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Risk assessment of antimicrobial resistance in the vegetable industry

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Appendix 1A

A review of evidence for antimicrobial resistance in Australian levy vegetable crops.

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1. Introduction

Antimicrobial resistance (AMR) is a critical, one health (i.e., crosses between human, animal and plant/environmental health sectors) global issue impacting all nations, including Australia. It refers to a constantly evolving phenomenon that can cause pathogens to become resistant to previously effective treatments. This is a highly complex challenge that poses an increasing threat to plant, animal, and human health and is of growing concern as a biosecurity, sustainability, production, and food safety issue. In Australia AMR threatens crop agriculture as resistant plant diseases lead to economic losses and market impacts. Although antimicrobial and pesticide use is regulated, the links between use and resistance in agricultural settings are not fully understood, and this can potentially result in overuse or sub-optimal use of chemicals in agriculture, with subsequent implications for disease pressure, health outcomes, and environmental impacts.

AMR presents a significant risk to Australia's vegetable growing industry which in 2024-25 produced 3.8 million tonnes (MT) of vegetables valued at \$A6.03 billion, up from \$A5.70 billion in 2023/24 (Hort Innovation 2026). Of the 3.8 million tonnes of levy vegetables produced in Australia in 2024/25 5% (180.4kt) went to fresh export, 36% (1.38 million tonnes) went to processing, and 2.23 million tonnes went to fresh supply. Imports of fresh vegetables totalled 35.7kt, of which 79% (28.2kt) went to fresh supply and 21% (7.5kt) went to processing. Of the 2.26 million tonnes of fresh vegetable supply available in 2024/25 (2.23 million tonnes of local production and 28.2kt fresh imports) 81% went to the retail market and 19% went to the food service market (Hort Innovation 2024).

Plants are subject to attack from a range of pathogens and parasites which have the potential to reduce yield and to impact market access arrangements between states or internationally. For instance, some 33 insect pests, 2 nematodes, 25 fungal pathogens, 5 bacterial diseases, and 7 viruses are known to affect cucurbit crops in Australia (Calvo & Ekman, 2024). The emergence of fungicide or bactericide resistance is influenced by the chemical structure of the antimicrobial, the evolution of resistance within the pathogen (by mutation, recombination or horizontal gene transfer), and by agronomic and post harvesting sanitation practices involved in producing a particular crop commodity (Brent and Hollomon, 2007).

As part of a larger project funded by Hort Innovation Ltd. and SAAFE^{CRC} a review of records of resistance to bactericides and fungicides in pathogens of Australian levy vegetable crops (beans, baby greens, broccoli & baby broccoli, cabbage, carrots, cauliflowers, celery, cucumber, kale, leafy Asian vegetables, lettuce, peas, pumpkin, radish, spinach, and zucchini) including bagged leafy salad vegetables was conducted by project staff. Understanding resistance patterns in plant pathogens and parasites in Australian levy vegetable production will provide valuable insights into the risks associated with AMR in these systems. Identifying where significant AMR risks might occur will allow the development of mitigation strategies, including pesticide/antimicrobial stewardship programs, to minimise potential financial losses and reputational damage to the industry. There are no substantiated records documenting the field failure of commercial nematocides in Australian levy vegetable crops due to resistance (<https://irac-online.org/documents/nematicides-poster/>), hence nematocide resistance is considered outside the scope of this review.

2. Method

The review of records of AMR in Australian levy vegetable crops was conducted by undertaking a literature review, by canvassing the agrochemicals industry whose products are directly affected by the development of AMR, and by seeking the cooperation of the Australasian Plant Pathology Society some of whose members are actively involved in testing plant pathogens for AMR. Informal discussions were also held with plant pathologists previously or currently involved in monitoring or testing for fungicide or bactericide resistance in plant pathogens affecting crop production in Australia.

2.1 Literature survey

A literature search was conducted using the descriptors 'fungicide resistance', 'bactericide resistance', crop common name, and 'Australia' through the University of South Australia library collection and Google Scholar. CropLife recognised in the early 1980s that resistance to fungicides could become an issue for the industry and responded by setting up the Fungicide Resistance Action Committee (FRAC), now known as the ECFR. CropLife's ECFR is linked to a global FRAC which operates under the auspices of CropLife International (<https://croplife.org/>). FRAC and ECFR have each published lists of plant pathogens and their risk of developing fungicide resistance based on information from international markets (<https://www.frac.info/media/glu3unn/frac-pathogen-list-2019.pdf>; <https://www.croplife.org.au/resources/programs/resistance-management/fungicide-resistance-management-strategies/>). This information was reviewed as a part of the literature survey.

2.2 Agricultural chemicals industry

CropLife Australia (CropLife) is the organisation which represents the agricultural and veterinary chemicals industry in Australia (<https://www.croplife.org.au/>). CropLife members develop and commercialise agrochemicals, including fungicides and bactericides, in the Australian market and become aware of the occurrence of AMR through feedback from farmers who have experienced crop failures. CropLife was approached and agreed to circulate to the members of their Expert Committee on Fungicide Resistance (ECFR) a short survey questionnaire seeking information regarding records of bactericide and fungicide resistance in plant pathogens in Australia.

2.3 Public sector researchers

The membership of the Australasian Plant Pathology Society (APPS) comprises plant pathologists in Australia and New Zealand, some of whom are employed in the academic or public sectors in testing plant pathogens for AMR. The participation of the APPS was sought in the review by contacting their membership, requesting researchers involved in the field of AMR detection and monitoring in vegetable crops in Australia to complete a short survey to identify reports or records of AMR in these crops.

2.4 Plant pathologists involved in resistance testing or monitoring

Several plant pathologists currently or previously involved in the broader field of fungicide or bactericide resistance testing or monitoring in Australia were identified. Discussions were held with these individuals with the aim of identifying plant pathologists currently or previously involved in testing for AMR in vegetable pathogens in Australia who might have records of resistance which have not been published.

3. Results

3.1 Literature survey

The literature survey identified 15 papers and articles reporting reduced sensitivity or resistance to bactericides or fungicides in Australian levy vegetable crops (Table 5). Seven of these reports are referenced by CropLife in a list of plant pathogens and fungicide groups for which resistance or reduced sensitivity has been confirmed or suspected under Australian field conditions as of June 2024 (<https://www.croplife.org.au/resources/programs/resistance-management/fungicide-resistance-management-strategies/>). To manage the development of resistance, all fungicide products sold in Australia are classified according to the chemical activity group of their active constituent by an alphanumeric code on the product label; the industry recommends a range of strategies on product labels and through various stewardship programs to manage resistance (<https://www.croplife.org.au/resources/programs/resistance-management/fungicide-activity-group-table/>).

Table 1. Published records of reduced sensitivity or resistance to bactericides or fungicides in Australian levy vegetable crops.

Crop	Pathogen	Selection agent(s) and ECFR fungicide activity group	Author(s) and year
Brassicas	<i>Peronospora parasitica</i> (downy mildew)	Metalaxyl (Group 4)	O'Brien (1994)
	<i>Mycosphaerella brassicicola</i> (ringspot)	Carbendazim (Group 1)	Wicks, Lomman & Rogers (1987)
Broccoli	<i>Albugo candida</i> (white blister)	Pyraclostrobin (Group 11)	Hailstones (2012)
Capsicum	<i>X. euvesicatoria</i> (bacterial leaf spot)	Copper sulphate (Group M1)	Gambley (2018), Martin <i>et al.</i> , (2004)
Carrots	<i>Erysiphe heraclei</i> (powdery mildew)	Azoxystrobin (Group 11)	Watson, Pung & Hall (2017)
Celery	<i>Pseudomonas syringae</i>	Copper sulphate (Group M1)	Hailstones (2012)
Chilli	<i>X. euvesicatoria</i> (bacterial leaf spot)	Copper sulphate (Group M1)	Gambley (2018), Martin <i>et al.</i> , (2004)
Cucurbits	<i>Sphaerotheca fuliginea</i> (powdery mildew)	Benomyl (Group 1)	Peterson (1973)
		Methyl benzimidazole carbamates (Group 1), Bupirimate (Group 8), Dimethirimol (Group 8), Fenarimol (Group 3), Penconazole (Group 3), Triadimefon (Group 3)	O'Brien, Vawdrey & Glass (1988)
		Benomyl (Group 1), Triadimefon (Group 3), Pyrazophos (Group 6), Bupirimate (Group 8)	O'Brien (1994)
		Azoxystrobin (Group 11), Bupirimate (Group 8), Carbendazim (Group 1), Triadimenol (Group 3)	Akem (2009)
	<i>Botrytis cinerea</i> (grey mould)	Benomyl (Group 1)	Luck & Gillings (1995)
	<i>Pseudoperonospora cubensis</i> (downy mildew)	Metalaxyl (Group 4)	O'Brien & Weinert (1995)
	<i>Pseudomonas syringae</i>	Copper sulphate (Group M1)	Hailstones (2012)
	<i>Acidovorax</i> spp. (cucurbit fruit blotch)	Copper (Group M1)	Hall & Tesoriero (2012)

Leek	<i>Pseudomonas syringae</i>	Copper sulphate (Group M1)	Hailstones (2012)
Lettuce	<i>Bremia lactucae</i> (downy mildew)	Metalaxyl (Group 4)	Hailstones (2012), O'Brien (1993), Wicks (1996)
	<i>Pseudomonas cichorii</i> (varnish spot)	Copper sulphate (Group M1)	Hailstones (2012)
Parsley	<i>Pseudomonas syringae</i>	Copper sulphate (Group M1)	Hailstones (2012)
Peas	<i>Peronospora viciae</i> (downy mildew); <i>Ascochyta pinodella</i> and <i>A. pinodes</i> (collar rot)	Metalaxyl (Group 4)	Pung, Cross & Falloon (2004)
Pumpkins	<i>Sphaerotheca fuliginea</i> (powdery mildew)	Benomyl (Group 1), Triadimefon (Group 3), Pyrazophos (Group 6), Bupirimate (Group 8)	O'Brien (1994)
	<i>Pseudoperonospora cubensis</i> (cucurbit downy mildew)	Metalaxyl (Group 4)	O'Brien & Weinert (1995)
Silverbeet	<i>Pseudomonas syringae</i>	Copper sulphate (Group M1)	Hailstones (2012)
A 'wide range of vegetables'*	<i>Botrytis cinerea</i> (grey mould), <i>Sclerotinia sclerotiorum</i> , <i>S. minor</i> (white mould)	Benomyl (Group 1), Iprodione (Group 2)	Hailstones (2012)
	<i>Botrytis cinerea</i> (grey mould)	Cyprodinil (Group 9), Boscalid (Group 7), Azoxystrobin (Group 11)	
	<i>Botrytis cinerea</i> (grey mould)	Azoxystrobin (Group 11), Boscalid (Group 11), Carbendazim (Group 1), Cyprodinil (Group 9), Iprodione (Group 2), Procymidone (Group 2)	Hall & Tesoriero (2012)
	<i>Sclerotinia sclerotiorum</i> (white mould)	Carbendazim (Group 1), Cyprodinil (Group 9), Iprodione (Group 2)	
	<i>Sclerotinia minor</i> (white mould)	Carbendazim (Group 1), Iprodione (Group 2)	
	<i>Pseudomonas</i> spp. (various leaf rots)	Copper (Group M1)	

*beans, brassicas, capsicums, cucurbits, herbs, lettuce, tomatoes, other vegetables.

The ECFR is linked to a global FRAC which operates under the auspices of CropLife International (<https://croplife.org/>). FRAC and ECFR have each published lists of plant pathogens and their risk of developing fungicide resistance based on information from international markets (<https://www.frac.info/media/qluf3unn/frac-pathogen-list-2019.pdf>; <https://www.croplife.org.au/resources/programs/resistance-management/fungicide-resistance-management-strategies/>). Inherent pathogen risk of developing resistance is related to disease epidemiology, field disease management, and genetic factors. Pathogens with a short lifecycle, high spore generation, high spore mobility, and mutation rates are among the inherent pathogen characteristics which favour the development of resistance (Brent & Hollomon, 2007, pp. 28-29). FRAC only rates pathogen risk as medium to high if resistance to more than one fungicide class has been reported in commercial use over the last 50 years. Pathogens of Australian levy vegetables identified in these lists as having a medium or high risk of development of resistance are shown in Table 6.

Table 2. Plant pathogens of Australian levy vegetables, ranked by their risk of developing fungicide resistance.

Risk level	Pathogen	Crop
High	<i>Botrytis cinerea</i> (grey mould)	Multiple (more than 200 host plants identified)
	<i>Sphaerotheca fuliginea</i> ; <i>Podosphaera xanthii</i> (powdery mildews)	Cucurbits
	<i>Pseudoperonospora cubensis</i> (downy mildew)	
Medium	<i>Albugo candida</i> (white rust)	Brassica vegetables
	<i>Ascochyta pisi</i> (Ascochyta blight)	Peas
	<i>Bremia lactucae</i> (downy mildew)	Lettuce
	<i>Erysiphe heraclei</i> (powdery mildew)	Carrots
	<i>Mycosphaerella pinodes</i> (blight; purple spot)	Peas
	<i>Phytophthora capsici</i> (damping off, leaf blight, fruit rot)	Cucurbits
		Solanaceous crops
		Snap beans; Lima beans

The inherent fungicide risk can be gauged by considering the chemical structure and mode of action of a particular fungicide, with each chemical class characterised by a resistance behaviour profile. This profile allows predictions to be made

regarding the propensity of specific fungicides to select for resistance in target pathogens and new pathogens (Brent and Hollomon, 2007, pp.6-11). Fungicide groups considered to have a high or medium-to-high risk of developing resistance are shown in Table 7.

Table 3. Fungicide/bactericide activity groups considered to be at high- or medium-to-high risk of selecting for resistance.

FRAC code, group name, and risk category	Comments
HIGH RISK	
Group 1 – Methyl benzimidazole carbamates (benzimidazoles & thiophanates)	Resistance common in many fungi; positive cross-resistance between group members; negative cross-resistance to N-phenyl carbamates. FRAC resistance management guidelines issued.
Group 4 – Phenylamindes (acylalanines, oxazolidinones & butyrolactones)	Resistance and cross-resistance well known in various Oomycetes. FRAC resistance management guidelines issued.
Group 10 – N-phenyl carbamates (diethofencarb)	Resistance known; negative cross-resistance to benzimidazoles. Resistance management required.
Group 11 – QoI fungicides (quinolone outside inhibitors: methoxyacrylates, methoxy acetamide, methoxy carbamates, oximino acetates, oximino acetamides, oxazolidinone diones, dihydrodioxazines, imidazolinones, benzyl carbamates)	Resistance known for several fungi; cross-resistance between all members of Group 11. Resistance management required; FRAC resistance management guidelines issued.
Group 11A – QoI fungicides (quinolone outside inhibitors: tetrazolinones)	Resistance not known; no cross-resistance with Group 11 fungicides. FRAC resistance management guidelines issued.
Group 25 – Glucopyranosyl antibiotic (streptomycin)	Bactericide resistance known. Resistance management required.
Group 41 – Tetracycline antibiotic (oxytetracycline)	Bactericide resistance known. Resistance management required.
Group 53 – Pyridazine	Resistance not known; no cross-resistance with Group 1 fungicides.
Group 49 – OSBPI fungicides (oxysterol binding protein homologue inhibition: piperidinyl thiazole isoxazolines)	Resistance risk assumed to be high (single site inhibitor). Resistance management required.
MEDIUM-TO-HIGH RISK	
Group 2 – Dicarboximides	Resistance common in <i>Botrytis</i> and some other pathogens. Cross-resistance common between group members. Resistance management required.
Group 7 – SDHI fungicides (succinate dehydrogenase inhibitors: 12 chemical groups)	Resistance known for several fungi. Resistance management required; FRAC resistance management guidelines issued.
Group 21 – Qil fungicides (quinone inside inhibitors: cyanoimidazole, sulfamoyl triazole, picolinamides)	Resistance risk unknown; assumed to be medium to high. Resistance management required.
Group 45 – QioSI fungicides (quinone inside and outside inhibitors)	Resistance risk unknown; assumed to be medium to high. Not cross-resistant to QoI fungicides. Resistance management required.
Group 47 – Cyanoacrylates (aminoacrylates)	Resistance known in <i>Fusarium graminearum</i> . Resistance management required.
Group 52 – DHODHI fungicides (dihydroorotate dehydrogenase inhibitors: phenylpropanol,	Resistance management required.

dihydroisoquinoline)

(Source: derived from <https://www.frac.info/media/kufnaceb/frac-code-list-2024.pdf> and Manabe *et al.*, 2023).

To estimate the risk of a particular fungicide selecting for resistance and to assist in developing strategies to delay selection for or to manage resistance FRAC has developed a risk matrix based on inherent fungicide and pathogen risks, incorporating agronomic risk associated with the crop/ pathogen interface (<https://www.frac.info/media/qluf3unn/frac-pathogen-list-2019.pdf>). Applying this rubric total risk is calculated by multiplying the relevant variables together (Table 8).

Table 4. Assessment of the risk of a particular fungicide selecting for resistance taking into account inherent fungicide risk, inherent pathogen risk, and agronomic risk.

Fungicide class	Fungicide risk	Combined risk			Agronomic risk
Benzimidazoles	High = 6	6	12	18	High = 1
Dicarboximides		3	6	9	Medium = 0.5
Phenylamides					Low = 0.25
QoI fungicides		1.5	3	4.5	
SDHI fungicides**	Medium to high (not quantified at this time)				High = 1 Medium = 0.5 Low = 0.25
SBI fungicides	Medium = 4	4	8	12	High = 1
Anilinopyrimidines		2	4	6	Medium = 0.5
Phenylpyrroles		1	2	3	Low = 0.25
Multi-site inhibitors (e.g., dithiocarbamates)	Low = 1	1	2	3	High = 1 Medium = 0.5 Low = 0.25
MBI-R inhibitors		0.5	1	1.5	
SAR inducers		0.25	0.5	0.75	
Pathogen risk		Low = 1	Medium = 2	High = 3	
Pathogen groups		Seed borne pathogens, soil borne pathogens, rust fungi, <i>Rhizoctonia</i> spp., <i>Fusarium</i> spp., <i>Sclerotium</i>	e.g., <i>E.necator</i> <i>G.fujikuroi</i> <i>Oculimacula</i> spp. <i>R.commune</i> <i>P.teres</i> <i>Z.tritici</i> <i>Monilinia</i> spp. <i>P.infestans</i>	e.g., <i>B.graminis</i> <i>B.cinerea</i> <i>P.viticola</i> <i>P.oryzae</i> <i>V.inaequalis</i> <i>P.fijiensis</i>	

(Adapted from (<https://www.frac.info/media/qluf3unn/frac-pathogen-list-2019.pdf>).

3.2 Agricultural chemicals industry

CropLife circulated to the ECFR a short survey asking members to report known instances of bactericide or fungicide resistance which they had recorded. This initial communication was followed by several prompts for recipients to respond. Unfortunately, only one member of the 10 contacted returned the completed survey; the sole respondent was not able to report any cases of fungicide resistance.

3.3 Public sector researchers

Unfortunately, the request to APPS was declined, potentially limiting the scope of responses to the review.

3.4 Plant pathologists involved in resistance testing or monitoring

Several plant pathologists currently or previously involved in the broader field of fungicide or bactericide resistance testing or monitoring in Australia were identified. Discussions were held with these individuals with the aim of identifying plant pathologists currently or previously involved in testing for AMR in vegetable pathogens in Australia who might have records of resistance which have not been published. The individuals contacted could not identify any plant pathologists currently involved with monitoring or testing pathogens of Australian levy vegetable crops for bactericide or fungicide resistance.

4. Discussion

The development of AMR in agriculture reduces disease control levels and disease control options resulting in reduced crop yields, causing significant economic impacts. This review indicates that the publicly available information regarding evidence of antimicrobial resistance in Australian levy vegetables is not current and is difficult to access. Additionally, the review identifies that members of the Australian agrochemicals industry, which should be at the forefront of bactericide and fungicide resistance monitoring, detection and recording, are loath to discuss their individual experiences and records. This latter situation may exist because of the commercial sensitivity of publicising the detection of resistance to proprietary molecules and the impact this could have on an individual company's sales.

The review also identifies that there is a lack of resources currently applied by or available in the public sector for monitoring and testing for bactericide and fungicide resistance in levy vegetable crops in Australia. This contrasts with other sectors of the agricultural economy. For example, in the Australian broadacre cropping sector (canola, cereal, and pulse crops) fungicide resistance in key pathogens is considered to pose a significant threat to production. In response the industry has established the Australian Fungicide Resistance Extension Network (AFREN; <https://afren.com.au/>), a network of plant pathologists, fungicide resistance experts, and extension specialists formed to address AMR in this sector. AFREN regularly publishes fungicide resistance management recommendations for the use of growers (<https://afren.com.au/resources/#management-guide>). Similarly, Wine Australia and CRC SAAFE have established a community of researchers to monitor and manage fungicide resistance in Australian grapevines (<https://www.crcsaafe.com.au/research/projects/fungicide-resistance-in-grapevine>). This collaboration has resulted in the publication detailing the status of fungicide resistance in grapevines in Australia (Ismail *et al.*, 2025). Unfortunately, no similar network for fungi, bacteria, virus or nematode plant pathogens exists in the levy vegetable industry, leaving the industry vulnerable.

Pathogens of Australian levy vegetables considered to pose a high or medium risk of developing resistance to fungicides are grey moulds of several crops, cucurbit downy mildew, cucurbit powdery mildews, white rust of brassicas, *Ascochyta* blight and blight or purple spot of peas, downy mildew of lettuce, and powdery mildew of carrots. In 2024-25 production of these crops was valued at \$A2,170.0 million, accounting for 36% of the total value of all fresh vegetable production for that year. The occurrence of resistance in any of these crops could cause significant economic damage to individual growers and to the industry.

The findings of this review argue for the establishment of an appropriate network of adequately resourced individuals to pro-actively monitor for bacterial and fungicide resistance in the high and medium combined fungicide x pathogen risk category and to recommend strategies aimed at reducing the risk of resistance arising.

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Appendix 1B

VegeNotes #1 (submitted to AusVEG in March for publication in the Spring 2026 edition of the magazine): **Staying Ahead of Antimicrobial Resistance (AMR): Protecting Australian Levy Vegetable Crops and Markets.** *Contacts:* Jessica Muller (AusVEG) and Rosalie Daniel (AusVEG)

Link to publication:

[Staying ahead of antimicrobial resistance \(AMR\): Protecting Australian levy vegetable crops and markets - AUSVEG](#)

Appendix 2A

Deliverable 2.1: Risk Assessment Frameworks for Antimicrobial Resistance and Chemical Co-selection in Ready-to-Eat Vegetables: A Critical Review

(CONFIDENTIAL UNTIL PUBLISHED)

Risk Assessment Frameworks for Antimicrobial Resistance and Chemical Co-selection in Ready-to-Eat Vegetables: A Critical Review

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Abstract:

Antimicrobial resistance (AMR) in ready-to-eat (RTE) vegetables is an emerging One Health concern, yet risk-assessment approaches for horticultural systems remain fragmented and are largely adapted from human foodborne-pathogen or chemical-safety frameworks. This scoping review systematically mapped and evaluated risk assessment methodologies relevant to AMR and chemically mediated co-selection across RTE vegetable production chains. Peer-reviewed and grey literature published between 2000 and 2025 was searched across major databases and institutional sources; 456 records were identified, 216 unique records were screened, and the included studies were synthesised across four domains: a) AMR and pathogen prevalence in fresh produce systems; b) Mechanisms of AMR and chemical co-selection; c) Current regulatory and voluntary frameworks, and d) Risk-assessment methodologies and applications. Antimicrobial-resistant bacteria and resistance genes were detected in vegetables, irrigation water, manure, soil, and post-harvest environments, with higher prevalence commonly reported in systems using untreated wastewater or raw manure. Horizontal gene transfer, mobile genetic elements, and co-selection by fungicides, herbicides, metals, and disinfectants were recurrent mechanisms associated with AMR persistence and dissemination. Existing regulations remained focused on conventional microbial indicators and rarely incorporated AMR determinants. Quantitative microbial risk assessment approaches were the most common modelling tools, but they were applied primarily to human foodborne pathogens, while AMR-specific dose-response data and crop-pathogen endpoints were largely absent. Overall, the evidence indicates that current frameworks are insufficient for horticultural decision-making and that integrated, horticulture-specific risk-assessment approaches are needed to integrate resistance mechanisms and exposure pathways with agricultural, environmental, and public-health outcomes.

Keywords: farm-to-fork; horticulture; chemical stressors; surveillance; exposure model; predictive.

1.0 Introduction

Antimicrobial resistance (AMR) is a critical global challenge that extends beyond clinical settings, posing significant threats to biodiversity, the sustainability of food production, and environmental integrity (FAO, 2023b). Its environmental dimension is driven by the widespread use of both antimicrobials and non-antimicrobial chemicals in crop and livestock production, as well as the presence of AMR in natural environments, irrigation water, and manure. In this review, antimicrobials refer to substances with intended activity against microorganisms, including antibiotics, antifungals, disinfectants, and other biocidal agents (McDonnell & Russell, 1999; McEwen Scott & Collignon Peter, 2018). Non-antimicrobial chemical stressors, including herbicides, metals, and other agricultural chemicals, are not primarily designed to target microorganisms, but can contribute to AMR emergence and persistence via co-selection, cross-resistance, and genetic linkage among resistance determinants (Murray et al., 2024). Both antimicrobials and non-antimicrobial chemicals can enter the environment from multiple sources, including treated and untreated human and animal excreta, as well as effluents from pharmaceutical manufacturing, healthcare facilities, and agricultural operations (WHO, 2022). These factors contribute to the diffuse and often non-point distribution of bioactive compounds across environmental matrices such as water, soil, and air (UNEP, 2023). Once released, these active compounds and their transformation products, generated through biotic (i.e., microbial-driven metabolism) or abiotic (i.e., physical and chemical) processes, may exert selective pressure on microbial communities (Montone et al., 2024). Such selective pressures may enrich resistant populations by promoting multiple resistance-associated mechanisms within microbial communities, including physiological stress responses, mutational adaptation, and horizontal gene transfer (HGT) of antimicrobial resistance genes (ARGs) (Baig et al., 2023; Gomes, 2024). Agricultural production and food processing activities may further amplify these selective pressures, reinforcing the environmental reservoirs of resistance that contribute to the global AMR crisis (Miller et al., 2022).

Among food commodities, ready-to-eat (RTE) vegetables such as leafy greens, carrots, cucurbits and other minimally processed produce, represent some of the most vulnerable vehicles for AMR transmission (Harrelson et al., 2025; Kläui et al., 2024). These products naturally host complex and dynamic microbial communities that constitute either an intrinsic or acquired resistome (Kiplimo et al., 2025). Environmental stressors, including exposure to agricultural chemicals, nutrient limitation, and temperature fluctuations, can induce HGT and mutations in stress-response genes, stimulating microbial adaptation and the co-selection of resistance to pesticides, biocides, metals and other related stressors alongside ARGs (Gao et al., 2025). In addition, RTE vegetables may become contaminated during pre-harvest stages through irrigation water, the application of biosolids or manure, and contact with soil, or during post-harvest handling and processing (Kalpana et al., 2024). Once established, resistant microbial populations either within the endosphere (e.g., vascular systems, (Li et al., 2024)) or on external niches such as the phyllosphere and rhizosphere, can persist under desiccation and storage stress, prolonging exposure potential along the farm-to-fork continuum (Giacometti et al., 2021).

Despite these risks, global AMR surveillance efforts remain predominantly human- and animal-centric. Programs such as the National Antimicrobial Resistance Monitoring System (NARMS) in the United States (USDA, 2025), the European Union's European Antimicrobial Resistance Surveillance Network (ECDC, 2023), and Canada's Canadian Integrated Program for Antimicrobial Resistance Surveillance (Government of Canada, 2025) primarily monitor AMR trends in meat, dairy, and clinical isolates. Comparable systematic surveillance for plant-derived foods remains fragmented, commodity-specific, project-based, or absent. Policy and monitoring frameworks addressing resistance to antimicrobials and co-selection by chemical stressors are even less developed.

Furthermore, existing quantitative microbial risk-assessment (QMRA) models used to inform management decisions were largely designed to assess enteric pathogen contamination and rarely capture gene transfer processes or co-selection dynamics relevant to the environmental dimensions of AMR (Nam et al., 2021; Pasalari et al., 2025). Conversely, risk assessments of agricultural chemicals, such as pesticides or fertilizers, largely focus on toxicological endpoints and maximum-residue limits (MRLs) without incorporating microbial selection pressures or adaptive mechanisms (Binet et al., 2025; D'Amore et al., 2025). The lack of structured data on AMR prevalence in vegetables, particularly within developing or export-oriented horticultural sectors, represents a major gap in global risk characterization and undermines the capacity to ensure food-safety equivalence under international trade frameworks (Brunn, Kadri-Alabi, et al., 2022). Addressing this gap requires robust, transparent, and scalable frameworks tailored to vegetable production systems that encompass pre-harvest, harvest, post-harvest, and consumption stages.

This scoping review was conducted as part of a broader collaboration with industry partners to develop a relative risk-assessment model for AMR in RTE vegetable production chains. The review systematically maps and evaluates risk-assessment methodologies applied or proposed for AMR and chemical co-selection in RTE vegetable systems, focusing on both antimicrobials and non-antimicrobial chemical stressors across the farm-to-fork continuum. Specifically, the objectives were to: (i) identify existing risk-assessment frameworks across AMR and chemically co-selected resistance contexts; (ii) evaluate their applicability to horticultural production systems and associated environmental matrices; (iii) identify

overlaps, complementarities, and methodological gaps relevant to RTE vegetables; and (iv) provide evidence to support the development of an integrated, One Health-aligned risk-prioritization framework consistent with international monitoring systems.

By synthesizing these approaches, this review aims to support the harmonisation of risk-assessment methodologies for AMR and chemically mediated co-selection within horticulture, strengthen regulatory and industry preparedness, and enhance global vegetable biosecurity.

2.0 Methods

2.1 Review Design and Objectives

This review was conducted as a scoping review, guided by the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR)*. The objective was to systematically map, describe, and evaluate existing risk assessment methodologies that have been applied or proposed for AMR and chemical co-selection within food systems, with a specific focus on RTE vegetables and associated farm-to-fork pathways. The review also sought to identify methodological gaps, overlap between microbial risk framework and conventional chemical assessments, and their applicability to risk prioritisation in horticultural production.

2.2 Search Strategy

A structured literature search was performed for peer-reviewed and grey literature published between 2000 and 2025. Searches were conducted across PubMed, Scopus and Web of Science, supplemented by targeted searches of institutional and regulatory repositories, including the The Food and Agriculture Organization (FAO), World Health Organization (WHO), Codex Alimentarius, Food Standards Australia New Zealand (FSANZ), United States Food and Drug Administration (FDA), Centre for the Promotion of Imports from Developing Countries (CBI) buyer-requirement database, the California Antimicrobial Resistance (CARB) National Action Plan, and relevant European Union food-safety frameworks.

Search terms combined controlled vocabulary (e.g., MeSH) and free-text keywords using Boolean operators, covering three thematic clusters:

- Resistance terms: “antimicrobial resistance” OR “AMR” OR “chemical resistance” OR “resistant pathogens” OR “biocide resistance” OR “pesticide resistance” OR “co-selection”
- Commodity terms: “vegetables” OR “fresh produce” OR “leafy greens” OR “horticulture” OR “salad crops” OR “ready-to-eat” OR “ready to eat” OR “RTE” OR “RTE vegetables”
- Framework terms: “risk assessment” OR “framework” OR “methodology” OR “surveillance” OR “exposure model”

Reference lists of included studies, systematic reviews, and key policy documents were also screened to identify additional eligible publications. The database searches yielded 87 records from PubMed, 127 from Scopus, and 139 from Web of Science, together with 103 additional documents identified through targeted searches of institutional and regulatory databases and grey-literature sources. In total, 456 records were retrieved for initial screening.

2.3 Eligibility Criteria

Publications were included if they met the following criteria:

1. Reported the occurrence, prevalence, or distribution of AMR-microorganisms, ARGs, or chemical-resistant pathogens in vegetables, fresh produce, or associated contamination pathways (e.g., soil, irrigation water, manure, harvest, post-harvest handling, or retail environments).
2. Examined mechanisms associated with antimicrobial resistance or chemical resistance in food-production systems, including co-selection by pesticides, fungicides, biocides, metals, or other environmental stressors relevant to vegetable production.
3. Described, evaluated, or referenced international, national, or regional regulatory, guidance, or voluntary

frameworks relevant to AMR or chemical-resistance risk management in fresh produce systems (e.g., Codex, FAO/WHO, FDA, FSANZ, EFSA, buyer-driven or certification schemes).

4. Described, developed, applied, or critically discussed qualitative, semi-quantitative, or quantitative risk assessment methodologies relevant to AMR, chemical-resistant pathogens, plant pathogens, or foodborne hazards in vegetables or comparable horticultural contexts.
5. Were available in English and provided sufficient methodological detail for data extraction.

Exclusion criteria included:

1. Studies exclusively targeting meat, dairy, or aquaculture (unless methodologies were transferable to horticultural produce).
2. Editorials, opinion pieces, or publications lacking methodological or data relevance.
3. Laboratory-only studies without real-world validation or field context.

2.4 Screening and Selection Process

All search results were imported into a central database, Zotero, for central management and deduplication, resulting in 216 unique records. Two reviewers independently screened titles and abstracts against inclusion criteria, followed by full-text assessment of potentially relevant papers. Discrepancies were resolved through consensus discussions.

To enhance transparency and efficiency, AI-assisted triage and data extraction were performed using Elicit (Elicit, 2025), an evidence-synthesis platform employing large-language-model–assisted screening. Elicit was used to identify papers relevant to specific domains (e.g., AMR in fresh produce systems, regulatory frameworks, risk-assessment models).

2.5 Data Synthesis and Domain Framework

Extracted data were synthesised thematically across four analytical domains reflecting the key dimensions of AMR and chemical-resistance risk assessment in RTE-vegetable systems:

1. AMR and Pathogen Prevalence in Fresh Produce Systems
2. Mechanisms of AMR and Chemical Co-selection
3. Current Regulatory and Voluntary Frameworks
4. Risk Assessment Methodologies and Applications

Each included study was mapped to one or more domains according to its methodological focus, framework type, and relevance to horticultural risk-assessment contexts.

3.0 Results

3.1 AMR and Pathogen Prevalence in Fresh Produce Systems

Across 216 screened sources, 29 studies were included in this domain, covering publications between 2013 and 2025 from multiple countries and regions. The geographic distribution included America (n = 5), Europe (n = 6), Africa (n = 6), Asia (n = 10), with an additional two global reviews. Studies from regions with wastewater irrigation and untreated manure application (Benin, Tunisia, Lebanon) consistently reported higher AMR prevalence, with 60-92% resistance rates on studied vegetables (Faour-Klingbeil et al., 2016; Moussé et al., 2015; Said et al., 2016), compared to regions with regulated agricultural practices (Netherlands, Finland) showing 3-5% prevalence (Kurittu et al., 2021; van Hoek et al., 2015).

Most studies assessed AMR and pathogen contamination at the level of the whole vegetable commodity, with lettuce being the most frequently investigated. Lettuce showed evidence of AMR and pathogen contamination across regions, with

prevalence ranging from 2.6% third-generation cephalosporin (3GC)-resistant *Enterobacteriaceae* in iceberg lettuce (van Hoek et al., 2015) to 50% relative abundance of ARGs on lettuce surfaces in a shotgun metagenomic study (Wind et al., 2021). Spinach also demonstrated high contamination rates, including 22.6% *E. coli* prevalence along South African supply chains, where multidrug-resistant (MDR) isolates clustered with irrigation-water isolates at >90% genetic similarity (Richter et al., 2022). Fresh-cut vegetables and RTE salads consistently exhibited higher bacterial loads and AMR prevalence than whole vegetables. These products harboured a wide range of resistant organisms, from 7% MDR *Enterococcus* spp. to 57.7% MDR *E. coli*, often with significant correlations between ARGs and plasmid replicons (Bai et al., 2024; Campos et al., 2013). Although less frequently studied, some root vegetables, including bunched carrots, also exhibited high resistance levels, with 8.9% to 83.3% 3GC-resistant *Enterobacteriaceae*, placing them among the studied commodities with the highest prevalence of resistant *Enterobacteriaceae* in retail settings (Blaak et al., 2014; van Hoek et al., 2015).

E. coli was the most frequently isolated species, reported in 18 studies, followed by *Listeria monocytogenes* (n = 6) and various other *Enterobacteriaceae*. High prevalence of MDR *E. coli* and 3GC-resistant *Enterobacteriaceae* was documented across most studies. A recent meta-analysis (Nkhebenyane et al., 2024) estimated the pooled prevalence of ESBL-producing *Enterobacteriaceae* (ESBL-E) in vegetables globally at 11.9% (95% CI: 9.1–15.5%), with high heterogeneity ($I^2 = 96.8\%$, $P < 0.001$). Regional prevalence varied substantially, with Spain reporting the highest estimate at 28.4%, while China showed the lowest at 6.4%. Temporal analysis demonstrated an upward trend in ESBL-E prevalence, increasing from 9.0% in 2018–2019 to 9.8% in 2020–2021 and 15.9% in 2022–2024.

Contamination sources were identified at both pre- and post-harvest stages. Water (including irrigation, general, and wastewater) was documented in 20 studies as a major pre-harvest driver, followed by manure in 17 studies and soil contamination in 7 studies. A scoping review characterising AMR in mixed food produce and crop-related agricultural inputs demonstrated irrigation water and manure to be highly contaminated with *E. coli*, *S. enterica*, *E. faecium* and *E. faecalis*, with a prevalence of 94% and 90% respectively (Brunn, Kadri-Alabi, et al., 2022). Richter et al. (2022) reported a higher prevalence of MDR *E. coli* (26.30%) on spinach irrigated with river water than those irrigated with borehole water systems (17.5%). Blaak et al. (2014) also demonstrated 100% contamination from 3GC-resistant *Enterobacteriaceae* in surface water used for lettuce irrigation while none was detected in ground water. Raw manure from livestock has also been identified as the main contamination source of antimicrobial resistant non-O157 *E. coli* (46% prevalence) in fresh produce systems, including leafy greens and cucumbers, compared to litter (24%) and insects (12%) (Glaize et al., 2020). Post-harvest contamination pathways including washing, handling, and retail practices were recorded in 14 studies as AMR amplification points. Datta et al. (2024) reported an overall high MDR *E. coli* prevalence on all studied vegetables and herbs from supermarkets (40.7%) and local markets (23.3%). Another cross-sectional market survey also demonstrated unsatisfactory *E. coli* counts, according to international guidelines as specified in the U.K., Australia and Canada, from various vegetable samples, including spinach, lettuce and cucumber, collected from both formal and informal markets (Richter et al., 2021). More details are documented in **Table 1**.

3.2 Mechanisms of Antimicrobial and Chemical Co-selection

Across the 31 studies meeting inclusion criteria for this domain, multiple interconnected mechanisms drove AMR emergence, persistence, and dissemination in leafy-vegetable production systems. Across studies, HGT was consistently highlighted as a dominant mechanism, facilitated by plasmid-mediated conjugation, mobile genetic elements (MGEs), and selective pressures from agricultural chemicals.

Plasmid-mediated conjugation was identified as a primary intercellular transfer route for AMR, with reported transfer frequencies ranging from 10^{-6} to 10^{-3} depending on host strain, environmental conditions, and selective pressures (Lopes et al., 2021; Zhang et al., 2023). Conjugation occurred most efficiently within the plant rhizosphere (approximately 10^{-3}), and donor strains such as *Klebsiella variicola* rapidly colonised both the lettuce rhizosphere and leaf endosphere (Riva et al., 2024). Recent evidence further suggests that protozoan grazing by free-living amoebae can substantially elevate plasmid conjugation frequency (4 – 5 times) in soil bacterial communities by inducing oxidative stress and SOS-linked responses that promote HGT (Lin et al., 2025). Genomic and targeted molecular evidence further suggests that AMR dissemination in vegetable production systems is facilitated by integrons and insertion sequences, highlighting the complementary roles of conjugative plasmids in intercellular transfer and MGEs in the capture, mobilisation, and redistribution of AMR across diverse plant-associated bacterial hosts (**Table 2**). Chromosomal mutations conferring target-site resistance were also reported alongside horizontally acquired resistance mechanisms (**Table 2**). Whole-genome sequencing of tetracycline-resistant *E. coli* isolates from store-bought RTE salads in Germany revealed the predominance of specific phylogenetic lineages, while point mutations in *gyrA* and *parC* were identified as major chromosomal determinants of quinolone resistance in *E. coli* (Reid et al., 2020). In fungal pathogens, multiple *cyp51A* coding-region and promoter mutations were

identified in *Aspergillus fumigatus*, including F46Y/M172V/E427K, F46Y/M172V/N248T/D255E/E427K, TR₃₄/L98H, and TR₄₆/Y121F/T289A, all of which are associated with reduced susceptibility or resistance to triazole antifungals. In the study of Arendrup et al. (2024), azole resistance in *A. fumigatus* is consistent with selective pressures favouring the propagation of pre-existing resistant genotypes rather than de novo emergence in sensitive isolates, with the TR₃₄/L98H promoter mutation as the dominant genotype, accounting for approximately 78% of azole-resistant *A. fumigatus* isolates, while TR₄₆/Y121F/T289A represented around 6%.

In addition to mutation-driven resistance, co-selection by agricultural chemicals emerged as a major driver amplifying antimicrobial resistance across studies (**Table 3**). Fungicides were identified as potent co-selective agents. Beyond selecting for azole-resistant *A. fumigatus*, sub-inhibitory exposure of *E. coli* to chlorothalonil, azoxystrobin, and carbendazim enhances plasmid-mediated conjugative transfer through reactive oxygen species generation, activation of the SOS stress response, and increased membrane permeability (Zhang et al., 2023). Azoxystrobin and carbendazim also upregulate plasmid-borne conjugation genes, increasing transfer frequencies at environmentally relevant residue concentrations (µg/kg–mg/kg) (Zhang et al., 2023). Similarly, herbicides including dicamba, 2,4-D amine, and glyphosate can alter bacterial antibiotic susceptibility by modulating efflux pump genes (*acrA*, *acrB*, *acrD*, *tolC*) and the permeability-associated influx gene *ompF*, even at or below recommended field application concentrations (Kurenbach et al., 2017).

Metals present in fertilisers, manure, sewage sludge, and other agricultural inputs further contributed to co-selection (Table 3). Cadmium, lead, nickel, chromium, copper, zinc, and tellurium were repeatedly associated with multidrug resistance, often through co-localisation of metal tolerance genes and ARGs on MGEs. Multiple-antibiotic-resistant endophytic bacteria exhibited resistance to all tested heavy metals and universally demonstrated biofilm-forming capacity, enhancing persistence and transfer potential. Notably, co-resistance between cadmium and benzalkonium chloride was observed in *Listeria monocytogenes*, with important implications for food processing environments where benzalkonium chloride is widely used (Avila-Novoa et al., 2024).

Finally, disinfectants and biocides used during vegetable processing imposed additional selective pressure (**Table 3**). For example, the phylloplane microbiomes isolated from RTE salad vegetables were found to carry chlorite dismutase (*cld*) gene cassettes embedded within class 1 integrons, which are associated with chlorite resistance (Qi et al., 2024). Given that class 1 integron-bearing MGEs often co-localize within *cld* cassettes alongside biocide tolerance determinants (e.g., quaternary ammonium compound [*qac*] cassettes) and other ARGs, this physical linkage provides a mechanistic basis for the co-selection and persistence of integron-mediated AMR during vegetable washing and processing, particularly in contexts where chlorine- or biocide-based sanitizers are routinely applied (Gadelha et al., 2019; Mohapatra et al., 2023; Zhao et al., 2025).

Collectively, these observations suggest that chemical exposures across both pre- and post-harvest stages synergize with genetic mechanisms to maintain and amplify AMR in vegetable production systems.

3.3 Current Regulatory and Voluntary Frameworks

Across the 36 sources included in this domain, approximately 24 were reviews or policy analyses, seven were empirical studies, and four were studies providing recommendation for framework development (**Table 4**). Most sources address AMR pathways more broadly through water reuse, wastewater treatment, or food production systems. Existing regulatory approaches remain indicator-based and focused on traditional faecal or pathogen-derived metrics such as *E. coli*, coliforms and *Clostridium perfringens*, rather than antibiotic-resistant bacteria or ARGs.

The European Union provided the most structured regulatory system through Regulation (EU) 2020/741, which established four reclaimed-water quality classes (A–D) for agricultural irrigation and mandated monitoring of *E. coli*, total coliphages and *C. perfringens* spores (European Parliament and Council of the European Union, 2020). Several southern EU Member States, including Spain, Italy, Greece and France, implemented additional national water reuse standards, while other Member States such as Germany relied entirely on EU-level guidance without national vegetable-specific provisions (Ho et al., 2025). In the United States, no federal regulation governed agricultural water reuse, and regulatory authority was delegated to individual states, resulting in considerable heterogeneity, with 17 states developing their own reuse standards (Jahne et al., 2024; WRAP, 2024). The U.S. Food Safety Modernization Act Produce Safety Rule established requirements for growing, harvesting, packing and holding produce, but sources consistently reported uncertainty among producers regarding its applicability and compliance obligations, and the rule did not include AMR monitoring (Hamilton et al., 2023).

In low- and middle-income countries (LMICs), regulatory coverage is limited and often precautionary. For instance, the

Palestinian Authority prohibits the use of treated wastewater for vegetable irrigation, while Israel applies ISO-based standards with national adaptations (Ben Mordechai et al., 2024). More broadly, socio-economic constraints, the absence of national reference laboratories, and limited monitoring capacity contribute to weak regulatory oversight of AMR in vegetable production systems (Samanta & Bandyopadhyay, 2020). In higher-income settings, jurisdictional overlap, such as among the FDA, USDA, and EPA in the United States, can further lead to inconsistent regulatory interpretation. Globally, plant-based production systems also lack surveillance frameworks comparable to those used for food animals, such as Colombia's Integrated Surveillance Program for Antimicrobial Resistance (Samtiya et al., 2022).

Regulatory attention has been concentrated on pre-harvest irrigation water, with comparatively limited provisions addressing soil, organic amendments, or post-harvest environments. Most pre-harvest regulations focus on irrigation water microbial quality, commonly defined through *E. coli* thresholds. In some jurisdictions, additional controls apply to manure or organic fertilisers; for example, Germany prohibits the application of liquid manure to vegetable crops (European Parliament and Council of the European Union, 2020; Hu et al., 2024). Recent studies indicate that *bla*_{TEM}, *tetA*, and *sul1* are among the most prevalent ARGs in antimicrobial-resistant bacteria isolated from RTE vegetables and salad crops (Brunn, Kadri-Alabi, et al., 2022; Castello et al., 2025; Kläui et al., 2024). Interestingly, reviews of ARGs prevalence in aquatic environments have also highlighted these genes as priority monitoring targets in water matrices (Keenum et al., 2022; Siri et al., 2023). However, the absence of systematic surveillance data, covering both the prevalence and dose-response data for antimicrobial-resistant bacteria and ARGs, contributes to the underdeveloped AMR monitoring framework in vegetable-specific surveillance programs. Moreover, post-harvest environments received minimal AMR-specific regulatory attention, despite evidence from a large metagenomic analysis of 1,780 samples collected from 113 food processing facilities across Europe showing that more than 70% of known AMR genes circulated throughout food production chains, with approximately 40% associated with plasmids and other MGEs (Quijada et al., 2025). To the best of our knowledge, neither pre- nor post-harvest systems incorporated AMR determinants into vegetable-specific monitoring or compliance requirements, despite evidence of their presence in both agricultural and processing environments.

3.4 Risk Assessment Methodologies and Applications

A total of 36 studies met the inclusion criteria for this domain (Table 5). Across these studies, quantitative approaches were most prevalent, with 26 studies applying quantitative or QMRA frameworks, compared with eight studies using qualitative methods and two employing semi-quantitative ranking or scoring systems. All studies performed hazard identification for AMR organisms, ARGs, or antibiotic residues, and 35 studies incorporated some form of exposure assessment, though comparatively few progressed to full risk characterisation, largely due to the absence of AMR-specific dose–response models. Several studies explicitly aligned with international guidance developed for enteric, human pathogens, including Codex CAC/GL 30-1999, FAO/WHO microbial risk-assessment frameworks, and WHO integrated surveillance principles (Bai et al., 2024; Brunn, Kadri-Alabi, et al., 2022; Wind et al., 2021). Others adapted FDA/EPA hazard quotient and acceptable daily intake methods originally developed for chemical contaminants (Matamoros et al., 2022; Patra & Dubey, 2024). Glaize et al. (2020) referenced NARMS for antimicrobial susceptibility testing and breakpoint interpretation, although its systematic structure has not yet been extended to produce-focused AMR surveillance.

Across methodological applications, QMRA frameworks were the most extensively developed and were applied primarily to foodborne pathogens associated with vegetable production systems (i.e., AMR-*E. coli*, *Salmonella* spp., and *L. monocytogenes*), whereas no included study applied a QMRA framework for plant (crop) AMR-pathogens. Reported illness probabilities varied widely depending on contamination source and exposure scenario, from 10^{-9} to 10^{-2} for AMR-*E. coli* on lettuce under controlled irrigation conditions (O'Flaherty et al., 2019), to 10^{-1} to 1.0 annually for consumption of vegetables irrigated with untreated wastewater (Cangola et al., 2025). Manure-to-crop models generally estimated very low consumer exposure, with concentrations of beta-lactamase-harboring *E. coli* reduced from 3.33 log₁₀ CFU/g in mixed fresh manure to -10.9 log₁₀ CFU/g in lettuce at harvest (Makita et al., 2024), whereas wastewater-based models and soil exposure scenarios yielded high counts of *L. monocytogenes* in irrigation water (mean: 12.0×10^2 CFU/100 mL) and agricultural soil (mean: 19.6×10^2 CFU/g) (Iwu et al., 2022). Existing risk quotient and hazard index approaches identified medium to high ecological risks from veterinary antibiotics in vegetable soils and highlighted increased health risks for children consuming sludge-amended vegetables (Patra & Dubey, 2024). Resistome-based scoring systems, including metagenomic risk indices and ARG–MGE co-occurrence metrics, revealed high resistome potential at multiple pre-harvest points, including 642 unique ARGs in manure amendments and 55 ARGs shared between amendments and lettuce surfaces (Wind et al., 2021). Large-scale genomic surveys of RTE vegetables further demonstrated widespread dietary exposure to ARGs, reinforcing the importance of integrated, multi-endpoint methodologies for AMR risk evaluation in fresh-produce systems.

Several studies have applied qualitative or semi-quantitative approaches to examine AMR risks in vegetable production

systems, often focusing on hazard identification and contextual exposure pathways rather than formal risk quantification. For example, Hölzel et al. (2018) identified vegetables as potential vectors for ESBL-producing *Enterobacteriaceae*, colistin- and carbapenem-resistant *Pseudomonas aeruginosa*, and vancomycin-resistant enterococci, but highlighted foundational gaps across risk-assessment components, including the absence of dose-response data and treatment-failure probabilities. Wang et al. (2021) emphasized the need for One Health-aligned risk frameworks that account for ARG co-occurrence with chemical contaminants and advocated for green mitigation technologies to reduce ARG dissemination across soil–water–plant systems. Other studies have generated quantitative resistance or exposure data without progressing to formal risk characterization. Micallef et al. (2013) combined antimicrobial susceptibility testing, genetic relatedness analysis, and statistical modelling to describe the distribution and dispersal potential of resistant *Enterococcus* spp. on tomato farms but concluded that public health risks could not be quantitatively defined. Blaak et al. (2014) referenced QMRA conceptually but relied on qualitative interpretation of health effects due to limitations in culture-based enumeration, while Rieux et al. (2025) qualitatively assessed potential consumer exposure to antibiotic-resistant bacteria in raw vegetables and identified the need for future, structured risk-assessment studies. Together, these findings underscore various persistent methodological gaps, particularly the lack of harmonized endpoints and vegetable-specific dose–response models, and the need for integrated, cross-sectoral approaches to AMR risk assessment. Most of these qualitative applications, however, still relate more directly to public-health exposure than to crop-protection outcomes.

4.0 Discussion

This scoping review demonstrates that AMR in RTE vegetable production systems represents a significant and underappreciated component of the global resistance burden. The geographic patterns identified across the included studies highlight how structural, environmental, agronomic, and food-processing factors shape AMR prevalence in RTE vegetable production systems. In particular, the level of sanitation and water treatment infrastructure emerged as a key determinant of contamination with human-associated AMR pathogens. Consistently higher contamination levels were reported in Africa and parts of Asia, intermediate levels in the Americas, and comparatively lower, though still notable, detection in Europe (Bai et al., 2024; Datta et al., 2024; Richter et al., 2021; Said et al., 2016; van Hoek et al., 2015). Regions with limited sanitation, variable or inconsistent wastewater treatment, and high reliance on surface water or raw manure application, such as Benin, Madagascar and Tunisia, showed higher burdens of multidrug-resistant (MDR) *Enterobacteriaceae* and *Enterococcus* spp. (Moussé et al., 2015; Rieux et al., 2025; Said et al., 2016). These patterns suggest that broader system-level characteristics, rather than isolated farm practices, determine the baseline of AMR entering horticultural systems. Factors such as inadequate or absent waste management infrastructure, antimicrobial use across human and animal sectors, and environmental discharge pathways contribute substantially to this baseline (Larsson & Flach, 2022). In contrast, regions with more robust water management, food safety, and regulatory frameworks (e.g., the Netherlands, Germany, and Japan) still report notable AMR signals, including extended-spectrum β -lactamase (ESBL)-producing *Enterobacteriaceae*, colistin resistance, and tetracycline-resistant *E. coli*. The persistence of resistance in these highly regulated settings indicates that hygiene-based food safety systems are effective at controlling acute enteric pathogens but are insufficient to prevent the ecological selection and dissemination of AMR. In addition, the intensive, high-input practices commonly associated with industrial agriculture in high-income countries may impose strong selective pressures and disrupt soil and plant-associated microbiomes, thereby facilitating the persistence and dissemination of antimicrobial-resistant bacteria and resistance genes (Graham et al., 2025). These regional contrasts parallel findings from the global ESBL-producing *Enterobacteriaceae* meta-analysis, which documented substantial heterogeneity and increasing temporal trends, suggesting that AMR dissemination in RTE vegetables production systems reflects both globalised transmission dynamics and local production practices (Klāui et al., 2024; Phan et al., 2024).

4.1 Adaptation and Integration of Risk Frameworks for AMR in Horticultural Production

As fresh produce consumption rises and vegetables are more frequently consumed raw (and inadequately washed), the need for systematic risk assessment methodologies specific to horticulture and RTE vegetable production has become increasingly urgent (Brunn, Kadri-Alabi, et al., 2022; Larsson & Flach, 2022; Murray et al., 2024). Microbial risk assessment (MRA) approaches in food safety exist along a continuum, from qualitative descriptive approaches, to quantitative probabilistic models (Bevilacqua et al., 2023). In this review, quantitative approaches were most prevalent, followed by qualitative and semi-quantitative approaches, primarily focusing on human/foodborne AMR hazards associated with fresh produce. The development of semi-quantitative and comparative risk assessment systems, such as the FDA-iRISK tool, marked a significant advancement, enabling the ranking of multiple food-hazard pairs from production to consumption (Chen et al., 2013). This move towards comparative assessment was complemented by frameworks designed to evaluate and rank both microbiological and chemical hazards using a common health metric like the pseudo-disability adjusted life year (pDALY), facilitating a more holistic view of food safety risks (LeJeune et al., 2021; Newsome et al., 2009). Concurrently,

risk assessments became more granular, focusing on specific on-farm stages such as water sources, pesticide application, worker hygiene, and packaging, with studies highlighting the significant risk contributions from human factors, particularly during packaging (Hölzel et al., 2018; LeJeune et al., 2021; Soon & Baines, 2012). However, across all included studies, only one implemented the full quantitative risk assessment, including hazard identification, exposure assessment, hazard characterisation (dose–response), and risk characterisation, estimating *Salmonella* infection risk from fresh salad vegetables in a consumer context using a beta-Poisson dose-response model (Habib et al., 2025). Most other studies addressed hazard identification and exposure assessment, but risk characterisation remained screening-level, largely due to the absence of AMR-specific dose–response relationships (Brunn, Kadri-Alabi, et al., 2022). Studies identifying AMR prevalence were concentrated largely on the phyllosphere or rhizosphere of fresh produce and associated pre-harvest pathways, particularly irrigation water (Liu et al., 2021; O’Flaherty et al., 2019). The evaluation of AMR within internal vegetable tissues remains difficult to interpret because the few available studies used different methods. Li et al. (2024) applied metagenomics and reported that the overall ARG abundances, including those conferring resistance to multidrug, beta-lactam, sulfonamide and tetracycline, in tomato xylem was up to 6.9 times higher than in rhizosphere soil, whereas Makita used culture-based enumeration of live beta-lactamase-producing *E. coli* and did not confirm internalisation of *E. coli* in tomatoes while reported very low beta-lactamase-producing *E. coli* abundances in the internal tissues of spinach and lettuce at harvest (-9.88 and $-10.9 \log_{10}$ CFU/g, respectively), compared with higher abundances of *E. coli* measured shortly after manure or slurry application (20.0 and 25.2 CFU/g, respectively). Accordingly, ARG detection should not be treated as equivalent to exposure to viable AMR bacteria, even though it remains informative for dissemination potential. Furthermore, post-harvest handling and processing environments were poorly represented, with few studies limited to measuring post-harvest prevalence on fresh produce (or in sanitation water) as a proxy for risk, and with little to no quantification of cross-contamination dynamics or critical control points in washing, processing, and packaging (Faour-Klingbeil et al., 2016; Salih & Mohammed, 2025). These neglected pathways are ubiquitous across real vegetable supply chains (e.g., wash systems, shared equipment, packaging lines, and transport/retail handling), yet they are rarely parameterised in current risk assessments (Kiplimo et al., 2025). As a result, the evidence base remains skewed toward pathways that are easier to measure or model (irrigation water, manure, soil), rather than those that may drive transmission at scale (post-harvest cross-contamination, vectors, and internalisation) (Possas & Perez-Rodriguez, 2023). This imbalance limits the industry’s ability to make informed, defensible trade-offs between sustainability and circular-economy priorities and One Health risk protection.

An additional challenge arises when the context shifts from human/foodborne pathogens to crop-associated pathogens. Existing frameworks were largely designed for acute human illness endpoints from the dissemination of enteric pathogens. Detection of resistant crop pathogens or associated genes currently has limited defined implication for crop health, yield loss, field persistence in a way that is analogous to human health dose-response (Miller et al., 2022) or even growth of environmental pathogens (Milligan et al., 2023). To note, only one scoping review (Brunn, Kadri-Alabi, et al., 2022) incorporated crop pathogens in its search strategy and reported *Xanthomonas* spp. resistant to gentamicin and oxytetracycline in lettuce, whereas none of the included studies explicitly assessed crop pathogens in their AMR risk assessments. Sustained and uncontrolled resistance selection in plant associated microbiomes may reduce the effectiveness of crop protectants, alter plant disease ecology, or sustain environmental reservoirs that re-enter production cycles (Gossen et al., 2014; Yin et al., 2023). Without crop- and industry-relevant endpoints, risk assessment remains anchored to human illness, despite horticulture functioning/plant production as the exposure system that maintains the hazard. A nationwide occupational cohort study in Taiwan (2004–2020) reported elevated risks of infections treated with WHO AWaRe “Reserve” antibiotics among vegetable and crop cultivators, reinforcing horticulture as part of the AMR exposure landscape (de Jong et al., 2026). Hence, developing industry-relevant endpoints is necessary not only to guide proportionate horticultural management, but also to support attribution of potential clinical origins and transmission interfaces (Kim et al., 2020). Current MRAs in horticulture therefore function primarily as scenario-comparison tools rather than robust decision-support tools for regulation, policy, or producers.

4.2 Mechanisms, Monitoring, and Integrated Management of Horticultural AMR

Early understanding of horticultural related AMR, mainly addressing fungicide resistance, began in the early 1990s with a shift away from reactive decision making toward proactive experience driven management (Staub, 1991). This included alternating active ingredients in fungicidal products to avoid sustained selection and subsequent resistance development. This process was formalised by the EU where resistance risk analysis was included as a key part of the authorisation procedure for new fungicides (Heimbach et al., 2002). This paradigm shift coincided with the development of molecular diagnostics to monitor resistance dynamics. For example, a real time PCR protocol detecting the *Cytb* G143A mutation that conferred resistance to broad spectrum fungicides from the strobilurin group in *Blumeria graminis* was developed (Fraaije et al., 2002). These tools provided a method to track the dynamics of resistant alleles under the selection pressure of specific

fungicide applications, such as the observed increase in the A143 allele frequency from 2.2% to 58% after three azoxystrobin sprays (Fraaije et al., 2002). Despite the growing recognition of the links between application strategies, selection pressure, and the measurable evolution of resistance in pathogen populations, continued intensive spray programs, often involving multiple applications per season, create significant selection pressure, particularly in high-risk pathogens like powdery mildews (Nuwamanya et al., 2023; Vielba-Fernández et al., 2020).

Commodity-level patterns further illustrate how AMR in vegetable production emerges from the interaction among crop types, production context, and exposure pathways. Across studies, leafy greens, particularly lettuce and spinach, were among the most frequently studied RTE vegetables and frequently showed a high prevalence of antimicrobial-resistant bacteria and resistance genes across both high- and low-income settings (Richter et al., 2022; Salih & Mohammed, 2025; Wind et al., 2021). Fresh-cut and RTE vegetable products demonstrated amplified AMR signals despite undergoing washing or sanitisation, suggesting that post-harvest operations may not adequately mitigate AMR contamination and may promote its dissemination through handling, wash-water recirculation, and shared equipment (Raffo & Paoletti, 2022; Rico & Falomir, 2020). From a consumer-risk perspective, these findings are most immediately relevant when viable AMR bacteria persist through post-harvest handling, whereas ARG-only detections are better interpreted as indicators of dissemination potential rather than direct proxies for infection risk (Bengtsson-Palme et al., 2023).

Importantly, resistance emergence in vegetable production systems cannot be solely explained using antimicrobials. The mechanistic evidence of AMR in the vegetable production systems, such as the co-occurrence of multiple resistance mechanisms, horizontal gene transfer, chromosomal mutation, and chemical co-selection, indicates that resistance dynamics within vegetable-associated microbiomes are shaped by continuous ecological and evolutionary processes operating across soil, plant, and processing environments (Davies & Davies, 2010; Merker et al., 2020). Non-antibiotic antimicrobial agents such as disinfectants, and non-antimicrobial chemical stressors such as herbicides and metals can reinforce AMR through shared stress-response pathways and genetic linkage mechanisms. Such combined exposures can produce additive, synergistic, or antagonistic effects on resistance selection, yet these interactions remain poorly characterised, as most experimental studies determine minimum inhibitory or selective concentrations based on human resistance endpoints, using single species and single compounds (Murray et al., 2024). However, understanding and prioritising industry endpoints in agriculture, especially the horticulture sector (e.g., crop yield, disease control, produce quality, and compliance with residue standards) and human health implications are not mutually exclusive (Mehmood et al., 2025). While crop protection inputs can select for resistance mechanisms that are relevant to human pathogens (e.g., broad efflux systems, stress-tolerance traits, and mobile elements carrying ARGs), clinically important resistance determinants can also persist in soils, irrigation water, composts, and processing environments and be redistributed across the vegetable supply chain, potentially undermining crop yield and sustainability (Graham et al., 2025; Kläui et al., 2024). From a risk-assessment perspective, mitigation strategies focused exclusively on antibiotic stewardship are unlikely to be sufficient to manage AMR in a horticultural context without parallel consideration of non-antibiotic co-selective agents and their combined ecological effects (Ifedinezi et al., 2024), along with stringent seed material screening/AMR inactivation. Consistent with this, the review highlights a paucity of robust data on AMR prevalence and dynamics across vegetable production chains, particularly for widely consumed RTE commodities that undergo minimal cooking prior to consumption, including leafy salad greens and popular snack-type vegetables.

These evidence gaps have direct economic implications on individual growers, regional and national economies, and international markets. At the farm level, resistance-driven loss of efficacy in disease-control inputs (e.g., fungicides and bactericides) can reduce crop yields and increase production costs through more frequent applications, increased labour and operator exposure, and the need to shift to more expensive or less effective alternatives (Varah et al., 2020). At the market level, these cost increases and any associated quality or safety concerns can affect consumer demand, buyer requirements, and trade competitiveness (Acosta et al., 2025). In parallel, the broader social costs of AMR are substantial, as treatment of resistant infections is associated with longer illness duration, increased diagnostic and hospital costs, the use of more expensive drugs, and higher mortality (Poudel et al., 2023). The OECD (2023) estimates that AMR is associated with average annual labour-market productivity losses of around 119,000 full-time equivalents (FTEs), corresponding to more than USD 6.6 billion per year, reflecting reduced labour-market participation and productivity at work.

In Australia, AMR represents a growing One Health threat for a vegetable sector valued at approximately A\$5.70 billion (Freshlogic, 2024). Preliminary stakeholder work conducted alongside this scoping review suggests that awareness is uneven and role-dependent: some participants were familiar with fungicide, herbicide, and insecticide resistance risks, whereas familiarity with AMR and the One Health framing was more variable across grower, adviser, and industry roles. This indicates a communication and surveillance gap that may delay adoption of proportionate mitigation measures and hinder preparedness for future market or regulatory expectations.

Together, these findings point to the need for comprehensive AMR risk assessment frameworks for horticulture that can integrate supply-chain data, define decision-relevant endpoints, and translate evidence into practical thresholds and interventions. Existing modelling in plant pathology has suggested that optimising fungicide mixtures and application timing to prolong the effective life of fungicides; for example, by balancing selection so that resistance to the component fungicides reaches similar frequencies at the point of control failure (Taylor & Cunliffe, 2022). However, there is an imperative to move beyond strategy optimisation toward broader risk assessment structures that can explicitly link resistance mechanisms and exposure pathways to horticulture-relevant outcomes (e.g., protectant performance, yield loss, field persistence, environmental release, and market access), while also capturing public-health implications where relevant (Gossen et al., 2014; Jayawardana & Fernando, 2024; Yang, 2006). This represents a critical next step for sustainable disease control and responsible antimicrobial stewardship in horticultural systems.

4.3 Research gaps/limitations/future directions

The convergence of findings across contamination pathways suggests that, within high-income country horticultural systems, AMR burdens are more likely to be problematic from interacting reservoirs, rather than dissemination from any single environmental source. Attention is unevenly distributed across the production chain, with a predominant focus on pre-harvest irrigation water and comparatively limited consideration of soil, organic amendments, and post-harvest processing environments. This imbalance persists despite evidence that late-stage contamination may pose the highest exposure risk. Future work must therefore adopt a systems thinking perspective that explicitly evaluates stage-specific risks and their cumulative contribution to AMR emergence and dissemination in horticulture systems.

Methodological limitations continue to constrain the translation of AMR research into operational risk management. While hazard identification and exposure assessment are well represented across studies for human pathogens, full risk characterisation remains rare due to the lack of AMR-specific dose–response relationships, colonisation thresholds and treatment failure estimates (Blaak et al., 2014; Castello et al., 2025; Hölzel et al., 2018; Huijbers et al., 2015). For plant pathogens, inoculum-response data may exist under controlled conditions, but field-relevant AMR endpoints linking resistant populations to protectant failure or yield loss are rarely parameterised in integrative risk models. Variability in detection, endpoints, and sampling design further limits comparability. Most existing studies employ "count and collect" approaches rather than functional investigations that would enable dose-response modelling and quantitative risk characterisation. As a result, current tools primarily support relative comparisons rather than derivation of actionable thresholds or regulatory benchmarks.

Future research should prioritise adaptation and adoption of existing source-tracking and risk-assessment approaches, rather than relying only on entirely new frameworks. For example, marker approaches already used to trace sewage contamination in irrigation water (e.g., pepper mild mottle virus and cucumber green mottle mosaic virus (Yasui et al., 2021)) could be combined with plant pathogen occurrence data and the cross-over between resistance development in plant and human pathogens of the same species (such as *A. fumigatus* (van Rhijn et al., 2024)) to improve source attribution. Also, integrated models should link microbial genomics, ARG/MGE dynamics, crop management practices, and environmental conditions to both agricultural and public-health endpoints (Ben et al., 2019; Gulzar et al., 2023). Crucially, these models should be capable of scenario-based evaluation of emerging sustainable disease-management options (e.g., biological control such as bacteriophages and plant growth-promoting rhizobacteria, nanotechnology-based antimicrobials, and biotechnology-enabled resistance), so that potential reductions in chemical inputs can be assessed together with changes in AMR selection and transmission risk (Mehmood et al., 2025). Equally important is the explicit definition of decision-relevant endpoints that reflect both sustainability and One Health performance, including crop health and yield stability, field persistence and mobility of resistant microbial populations, protectant efficacy and input intensity, market access and residue compliance, and environmental release to surrounding soil and water. Without these advances, AMR risk assessment for vegetables will remain descriptive rather than predictive, limiting its capacity to guide proportionate regulation and industry practice that align circular-economy goals with public-health protection.

5.0 Conclusions

This review indicates that AMR in horticulture should be framed within a One Health and circular-economy context. Vegetable, especially RTE vegetables, production systems represent a convergence point for multiple inputs that impose selective pressure and sustain AMR and chemical resistance reservoirs, including irrigation and reused water, soils and organic amendments, agrochemicals and disinfectants, and climate- and weather-driven ecological variation. It also constitutes a major downstream interface for subsequent animal and human exposure through fresh produce supply chains.

Across the literature, evidence is dominated by prevalence-based studies, whereas complete risk assessment remains scarce. Hazard identification and, in some cases, exposure assessment are well represented, yet quantitative hazard characterisation (e.g., dose–response, colonisation thresholds, treatment-failure estimates) and parameterisation of under-represented pathways, particularly post-harvest transmission dynamics, are limited. Consequently, current assessments rarely yield actionable thresholds, intervention trigger points, or regulatory benchmarks required for decision-making. Stakeholder consultations conducted alongside this review further underscore the practical and economic sensitivity of the sector, including some awareness of pesticide resistance but variable familiarity with AMR and One Health framing across different industry roles. Taken together, these findings suggest that antimicrobial discovery and stewardship, while important, are insufficient on their own to ensure durable control. Instead, effective long-term mitigation will require a multifaceted, sector-wide, multiple-barrier approach, supported by robust horticulture-specific risk assessment frameworks that align sustainability objectives with One Health risk protection.

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Tables and Figures

Table 1: Summary of studies reporting antimicrobial-resistant microorganisms, resistance determinants, and contamination routes in fresh produce systems

Study Type	Continents	Geographic Region	Primary Focus	Study Design	Produce Type	Contamination Pathway	Pathogen / Organism	AMR/Chemical Resistance Determinants	Prevalence/Concentration	References
Primary study	America	USA, Virginia	Metagenomic assessment of ARGs in lettuce production	Field trial with metagenomic analysis	Lettuce (organic/inorganic cultivation)	Manure, compost, soil amendments	<i>Pseudomonas</i> spp. (lettuce, soil and composts), <i>Pantoea</i> spp. (lettuce), <i>Clostridium</i> spp. (manure), <i>Enterococcus</i> spp. (manure)	<i>arnA</i> and <i>pmrF</i> (most abundant ARGs co-occurring with MGE), <i>bla_{CARB-14}</i> , <i>bla_{OXA-322}</i> and <i>vanA</i> (clinically-relevant ARGs with the greatest relative abundance overall), <i>amA</i> , <i>bacA</i> and <i>ermB</i> (most frequently co-occurring on the plasmids annotated on lettuce surfaces), <i>TriC</i> to plasmid (<i>Ralstonia solanacearum</i>) co-occurred 10 times on the lettuce surfaces grown in the compost and was the second most abundant ARG-MGE	642 unique ARGs in amendments; 55 unique ARGs found both in the soil amendments and on lettuce surfaces; total ARG abundance is up to 50% higher on lettuce surface grown in soil amended with compost or raw manure compared to inorganic chemical fertilizer; clinically relevant ARGs and most ARG-MGE co-occurrences were the highest in lettuce samples compared to amendment and soil. The lettuce grown in compost with antibiotics carried the highest clinically relevant ARG relative abundance, while the lettuce grown in inorganic fertilizer had the least	(Wind et al., 2021)
Primary study	Europe	Netherlands	ESBL/AmpC Enterobacteriaceae on retail vegetables	Cross-sectional retail survey	Blanched celery, bunched carrots, butterhead lettuce, chicory, endive, iceberg	Retail vegetables, soil, irrigation water	<i>E. coli</i> , <i>Enterobacter</i> spp., <i>Citrobacter freundii</i> , <i>Rahnella aquatilis</i> , <i>Serratia fonticola</i>	ESBL (<i>bla_{SHV-12}</i>), AmpC, <i>bla_{FONA}</i> variants, <i>bla_{RAHN-1}</i>	5.2% overall (3GC-resistant Enterobacteriaceae) on vegetables; bunched carrots 8.9%; butterhead lettuce 6.6%;	(van Hoek et al., 2015)

					lettuce, radish				ice-berg lettuce (2.6%)	
Primary study	Africa	South Africa, Gauteng	MDR <i>E. coli</i> on fresh vegetables from formal/informal markets	Cross-sectional market survey	Spinach, tomato, lettuce, cucumber, green beans	Retail (retailers, street traders, trolley vendors and farmers' markets)	<i>E. coli</i> (commensal)	Resistance to neomycin (73.13%), ampicillin (38.81%), amoxicillin (41.79%), cefepime (34.33%)	Overall 14.86% <i>E. coli</i> on with highest occurrence in farmers' market (25.3%), followed by retailers (10%). street traders (6%) and trolley vendors (3%); Highest <i>E. coli</i> from leafy green vegetables (14% and 30% of the farmers' market lettuce and spinach) 40.30% MDR <i>E. coli</i>	(Richter et al., 2021)
Primary study	Africa	South Africa, Gauteng	MDR <i>E. coli</i> throughout spinach supply chains	Supply chain study	Spinach (open field, tunnel cultivation)	River water, borehole water irrigation, post-harvest handling	<i>E. coli</i> , <i>Salmonella</i> spp.	Penicillins (66.3%), cephalosporins (61.3%), carbapenems (11.3%)	Spinach irrigated with river and irrigation water - 22.57% <i>E. coli</i> ; 3% <i>Salmonella</i> spp.; 43.75% MDR <i>E. coli</i> (26.3% on spinach irrigated with river water, 17.5% on spinach irrigated with borehole water)	(Richter et al., 2022)
Primary study	Africa	South Africa	MDR <i>E. coli</i> in lettuce and spinach supply chains	Supply chain study	Lettuce, spinach (GlobalG.A.P. certified)	Irrigation water (Klip River, Hartbeespoort dam), packhouses	<i>E. coli</i> (phylogroups B2, B1, A, D)	ESBL/AmpC(100%), ampicillin (70.6%), amoxicillin (68.6%)	11.8% leafy greens; 17.4% water; 2.5% soil; 64.7% MDR	(Ratshilingano et al., 2022)
Primary study	Europe	Germany	WGS of <i>E. coli</i> from store-bought produce	WGS-based retail study	Cilantro, arugula, mixed salad	Manure fertilizers, contaminated irrigation water, wildlife	<i>E. coli</i> (phylogroup B1 dominated (70%); B1-ST6186, C-ST165, B1-ST58, B1-ST641, C-ST88)	<i>tet(A)</i> , <i>bla</i> _{TEM-1B} , <i>qnrS1</i> , <i>sul2</i> , <i>strA-strB</i> , <i>dfrA14</i> , <i>bla</i> _{CTX-M-15/-14/-55} , <i>bla</i> _{OXA-10} , <i>intI1</i>	85% of TET-resistant <i>E. coli</i> from cilantro	(Reid et al., 2020)
Primary study	Asia	UAE	<i>Enterococcus</i> spp. in salad vegetables	Cross-sectional retail survey with WGS	Spinach, romaine lettuce (local and imported)	Retail outlets	<i>E. casseliflavus</i> (50%), <i>E. faecium</i> (20%), <i>E.</i>	<i>vanC</i> , <i>vanXY-C2</i> , <i>tetM</i> , <i>ermB</i> , <i>optrA</i> ; 19 distinct plasmids	85.5% <i>Enterococcus</i> spp. detection; 55.3%	(Habib et al., 2025)

							<i>faecalis</i> (16%)		resistant; 18.8% MDR	
Primary study	Asia	Thailand, Bangkok	<i>E. coli</i> prevalence in vegetables and herbs	Cross-sectional market survey	Spearmin t, leaf lettuce, coriander , Chinese cabbage, cucumber	Local markets, supermarkets, post-harvest handling	<i>E. coli</i>	Penicillin (100%), tetracycline (31.3%), ampicillin (31.3%)	32.0% <i>E. coli</i> overall, 40.7% in supermarkets vs 23.3% local markets; <i>E. coli</i> prevalence - leaf lettuce 36.7%, cucumber 35%, spearmint 35%, coriander 35%, Chinese cabbage 18.3%; 27.1% MDR	(Datta et al., 2024)
Primary study	Europe	Netherlands	ESBL/AmpC bacteria on fresh produce and agricultural environment	Farm-to-retail study	Blanched celery, bunched carrots, chicory, endive, iceberg lettuce, mushrooms, radish	Pig manure, surface/ground water irrigation, soil	<i>Rahnella aquatilis</i> , <i>Serratia fonticola</i> , <i>Citrobacter</i> spp., <i>Enterobacter</i> spp.	<i>bla</i> _{RAHN-1/-2} , <i>bla</i> _{FONA-1/-2/-3/6/-5} ; AmpC	3GC-resistant Enterobacteriaceae - 61.9% supermarket vegetables (33.3% in mushrooms, 83.3% in bunched carrots); 44.4% soil; 100% surface water	(Blaak et al., 2014)
Primary study	America	Brazil	Microbiological assessment of lettuce salads	Restaurant survey	Lettuce (prepared salads)	Post-harvest handling in restaurants	<i>Staphylococcus</i> spp., <i>E. coli</i>	<i>Staphylococcus</i> spp. - Penicillin (56.7%), oxacillin (46.7%), erythromycin (26.7%)	61.1% of salad samples thermotolerant coliforms; 5.6% <i>E. coli</i> ; 23.3% multi-resistant <i>Staphylococcus</i> spp.	(Gutierrez et al., 2020)
Primary study	Europe	Portugal	Ready-to-eat salads as vehicle for AMR	Retail supermarket study	Ready-to-eat salads (split/mixed leaves, carrot, corn)	Post-harvest processing, cross-contamination between production lines	<i>E. coli</i> (phylogroups A, B1, D; ST69), <i>Raoultella terrigena</i> , <i>Citrobacter freundii</i> , <i>Enterococcus</i> spp.	<i>tet(A)</i> , <i>aadA</i> , <i>strA-strB</i> , <i>sul1/sul2</i> , <i>bla</i> _{TEM} , <i>bla</i> _{SHV-2} , <i>qnrB9</i>	Ready to eat salads - 86% unsatisfactory aerobic counts; 74% unsatisfactory coliforms; 4% <i>E. coli</i> , 70% <i>Enterococcus</i> spp. (7% MDR isolates)	(Campos et al., 2013)
Primary study	Asia	Japan	mcr-9 carrying Enterobacteriaceae from vegetables	Retail vegetable survey	Bean sprouts, myoga	Wastewater, sewage irrigation from animal farms	<i>Enterobacter cloacae</i> ST738, <i>Raoultella ornithinolytica</i>	<i>mcr-9.1</i> , <i>bla</i> _{ACT} , <i>bla</i> _{PLA-1a} ; IncHI2/HI2A plasmids	308 colistin-resistant isolates from 200 fresh vegetables (bean sprouts and myoga); 0.65% mcr-9 positive	(Xedzro et al., 2023)
Primary study	Europe	Spain, Valencia	AMR Enterobacteriaceae in conventional/organic/fresh-cut vegetables	Comparative retail study	Carrot, arugula, lettuce, tomato (conventional, organic, fresh cut)	Manure, irrigation water, sanitizing methods	<i>Enterobacter cloacae</i> , <i>Klebsiella oxytoca</i> , <i>K. pneumoniae</i>	Most isolates from each vegetable type - Ampicillin (64-85%), amoxicillin/clavulanic (70-77%); self-transmissible	Fresh-cut highest contamination (1.05-1.10 isolates (non-coliform Enterobacteriaceae species	(Rico & Falomir, 2020)

							<i>Pantoea agglomerans</i> , <i>Serratia marcescens</i>	resistance plasmids	most frequent (62%)/sample; 80% multi-resistant in conventional produce (54% in fresh-cut produce, 52% in salads, 43% organic produce)	
Systematic review /Meta-analyses	Meta-analysis	Global (63 studies)	ESBL-producing Enterobacteriaceae prevalence in vegetables	Systematic review/meta-analyses	Carrots, lettuce, radish, spinach, sprouts, others	Wastewater, manure, animal intrusion	ESBL-producing Enterobacteriaceae (<i>E. coli</i> , <i>K. pneumoniae</i> , <i>Enterobacter</i> spp.)	<i>bla</i> _{SHV} (42.8%), <i>bla</i> _{CTX-M-15} , <i>bla</i> _{AmpC} (4.3%), <i>bla</i> _{VIM}	11.9% pooled prevalence of ESBL-producing Enterobacteriaceae (95% CI: 9.1-15.5%); Spain 28.4%; China 6.4%; ESBL-E increased by 9%, 9.8% and 15.9% in 2018-2019, 2020-2021 and 2022 to 2024	(Nkhebenyane et al., 2024)
Primary study	Africa	Benin, Cotonou	ESBL <i>E. coli</i> from market garden products	Market garden study	Lettuce, cabbage, great nightshades, carrots	Untreated wastewater, manure, chicken droppings, pond water	<i>E. coli</i> (STEC, VTEC)	All <i>E. coli</i> isolates - <i>bla</i> _{TEM} (67.5%), <i>bla</i> _{SHV} (10%), <i>bla</i> _{CTX-M} (22.5%); SLTI, SLTII toxin genes	34.95% samples with <i>E. coli</i> ; Cabbages 28.26% in dry season; lettuce 0.65×10 ⁶ CFU/g; 92% amoxicillin-clavulanic resistance	(Moussé et al., 2015)
Scoping review	Meta-analysis	Global (49 countries)	AMR pathogens in food crops globally	Scoping review	Salad crops, culinary herbs, fruit	Irrigation water, manure, post-harvest cross-contamination	<i>E. coli</i> , <i>K. pneumoniae</i> , <i>S. enterica</i> , <i>L. monocytogenes</i> , <i>E. faecium/faecalis</i>	ESBL genes (<i>CTX-M</i> , <i>SHV</i> , <i>OXA-TEM</i>), tetracycline genes (<i>tetA</i> , <i>tetB</i> , <i>tetM</i>)	<i>E. coli</i> , <i>S. enterica</i> and <i>E. faecium</i> or <i>E. faecalis</i> combined prevalence - 72% in vegetables, 71% in salad crops, 94% in irrigation water, 90% in manure; Carbapenem resistance 3%; fluoroquinolone 13%; aminopenicillin 20%	(Brunn, Kadri-Alabi, et al., 2022)
Primary study	Africa	Tunisia	<i>Enterococcus</i> spp. from vegetable food, soil, and irrigation water	Farm-to-market study	Fennel, lettuce, onion, carrot, parsley, radish, cabbage, pepper, tomato	Treated wastewater, irrigation, soil with raw animal manure, markets	<i>E. faecium</i> (52.3%), <i>E. hirae</i> (35.4%), <i>E. faecalis</i> (6.15%)	<i>erm</i> (B), <i>tet</i> (M), <i>tet</i> (L), <i>aph</i> (3')-III, <i>aac</i> (6')-aph(2''), <i>vanC2</i>	88.2% farm vegetables; 84.2% market; 51% soil and irrigation water ciprofloxacin resistance 60%; High level gentamicin-resistant	(Said et al., 2016)

									enterococci 15.5%	
Primary study	Africa	Madagascar	ESBL-producing Enterobacteriales from vegetable plants	Cross-sectional farm study	Spinach, lettuce, tomato, cabbage	Human sewage, animal manure, contaminated soil/irrigation water	<i>E. coli</i> (phylogroups A, B1, F; ST46, ST354), <i>Enterobacter asburiae</i>	<i>bla</i> _{CTX-M-15} , <i>bla</i> _{CTX-M-55} ; IncY, IncFIB, IncFII plasmids	27% of plants positive for beta-lactam antibiotics; 83% ESBL producers	(Rieux et al., 2025)
Primary study	Asia	India, Varanasi	ARG spread in vegetables cultivated with sewage sludge	Pot experiment	Carrot, spinach (sewage sludge-amended)	Sewage sludge (biosolids)	<i>Bacillus</i> spp., <i>Priestia</i> spp., <i>Pantoea</i> spp., <i>Pseudomonas</i> spp. (51% plant/human pathogens)	<i>bla</i> _{NDM} , <i>qnrS</i> , <i>sul1</i> , <i>bla</i> _{GES} , <i>ermF</i> , <i>int1</i> , IS26	ARGs 1×10 ⁵ to 3.2×10 ¹⁰ copies/kg; MARI 0-0.88; ampicillin and lead resistance 100%	(Patra & Dubey, 2024)
Primary study	Europe	Finland (imported products)	ESBL/AmpC <i>E. coli</i> and <i>K. pneumoniae</i> in global food products	Imported food survey	Coriander, chili pepper (from Malaysia)	Manure fertilization, contaminated irrigation water, cross-contamination	<i>E. coli</i> , <i>K. pneumoniae</i> (ST307), <i>Citrobacter</i> spp., <i>Hafnia alvei</i>	<i>bla</i> _{CTX-M-1/-15/-55/-65} , <i>bla</i> _{SHV-12/-81/-28} , <i>bla</i> _{TEM-1B/-52C} , <i>bla</i> _{CMY-2} , <i>bla</i> _{DHA-1}	3% vegetables ESBL/AmpC producing <i>E. coli</i> ; 1% ESBL/AmpC producing <i>K. pneumoniae</i>	(Kurittu et al., 2021)
Primary study	Asia	Malaysia	AMR <i>L. monocytogenes</i> and <i>S. Enteritidis</i> from vegetable farms	Farm-to-retail study	Organic and conventional vegetables	Irrigation water, soil, manure, farms, packing houses, markets	<i>L. monocytogenes</i> , <i>S. Enteritidis</i>	<i>L. monocytogenes</i> : penicillin G (100%), meropenem (70.7%); <i>S. Enteritidis</i> : ampicillin/amoxicillin/trimethoprim (100%)	Multiple Antibiotic Resistance index 0.11-0.56 (<i>L. monocytogenes</i>); up to 0.62 (<i>S. Enteritidis</i>)	(Kuan et al., 2017)
Primary study	America	USA, Tennessee/North Carolina	AMR <i>E. coli</i> transmission in sustainable farming	Sustainable farm study	Snap beans, cucumbers, lettuce, spinach, cabbage, broccoli, others	Raw and composted manure, irrigation water, insects, wildlife	<i>E. coli</i> (phylogroups A-G; serotype O45; aEPEC)	<i>bla</i> _{CMY} (n=5), <i>bla</i> _{TEM} (n=32); streptomycin, ampicillin, sulfisoxazole resistance	15.4% overall <i>E. coli</i> ; 46% raw manure; 14 produce isolates (6 from cucumbers and 3 from snap beans); 62% MDR	(Glaize et al., 2020)
Primary study	Asia	UAE	<i>Salmonella</i> spp. in salad vegetables	Retail risk assessment	Arugula, dill, spinach, cabbage, coriander, lettuce varieties	Cross-contamination, retail storage, water spraying post-harvest, display without refrigeration	<i>Salmonella</i> spp. (ST463, ST3760, ST64)	<i>aac(6)-Iaa</i> , <i>fosA7</i> ; pan-susceptible phenotype	1.25% <i>Salmonella</i> spp. (95% CI: 0.41-2.89%); arugula 3/51 positive, dill and spinach 1/51 each	(Habib et al., 2023)
Primary study	Asia	Lebanon	MDR <i>E. coli</i> from raw vegetables	Supply chain study	Cucumber, parsley, tomato, mint, lettuce	Polluted rivers (Litani), raw sewage irrigation	<i>E. coli</i> (EPEC; trivalent serogroups)	Streptomycin (100%), cephalothin (100%), ampicillin (78%); plasmid-	60% MDR <i>E. coli</i> ; trivalent serogroup 2 32%	(Faour-Klingbeil et al., 2016)

						n, wholesale/retail handling		borne sulfonamide genes		
Primary study	Asia	China, Beijing	Foodborne pathogens from fresh-cut fruits/vegetables	Retail survey	Fresh-cut fruits and vegetables	Irrigation with wastewater, organic fertilizer, retail cross-contamination	<i>S. aureus</i> (ST398-t34), <i>E. coli</i> (22 serotypes, 18 STs), <i>L. monocytogenes</i> (ST101)	<i>bla_z</i> , <i>mecA</i> , <i>floR</i> , <i>tet(A)</i> , <i>dfrA12</i> ; QRDR mutations (<i>GyrA</i> S83L)	<i>S. aureus</i> 15.38%; <i>E. coli</i> 9.23%; <i>L. monocytogenes</i> 1.85% (overall in fresh-cut fruits and vegetables) contamination rate for fresh-cut vegetables is 29.63% (14.81% <i>S. aureus</i> ; 12.96% <i>E. coli</i>); 57.67% MDR <i>E. coli</i>	(Bai et al., 2024)
Primary study	Asia	Turkey	AMR pathogens in ready-to-eat vegetable salads	Restaurant salad survey	Carrot, lettuce, parsley, purple cabbage (ready-to-eat)	Irrigation water, fertilizer, post-harvest handling, storage	<i>E. coli</i> (groups A, B1, C, E, F), <i>S. aureus</i>	<i>bla_{TEM}</i> , <i>bla_{CTX-M-8/25}</i> , <i>bla_{CTX-M-1}</i> ; ESBL production	In all ready-to-eat vegetable salads - <i>E. coli</i> 38.1%; <i>S. aureus</i> 2.4%; 35.7% ESBL <i>E. coli</i> ; <i>E. coli</i> is 100% aminoglycoside resistance	(Baran et al., 2022)
Primary study	Asia	Iraq	<i>L. monocytogenes</i> in selected food products	Retail food survey	Lettuce, cauliflower, cabbage, spinach, celery	Irrigation water, manure, transport, retail handling	<i>L. monocytogenes</i> (<i>prfA</i> , <i>inlA</i> , <i>hlyA</i> virulence genes)	Ampicillin (100% resistance); susceptible to gentamicin, tetracycline, ciprofloxacin	9.6% overall; lettuce 25%; celery 25%. <i>prfA</i> 41.6%, <i>hlyA</i> 33.3%	(Salih & Mohamed, 2025)
Primary study	America	Mexico	AMR <i>E. coli</i> from foodstuffs including vegetables	Retail food survey	Lettuce, spinach, chards	Poor hygiene practices, lack of refrigeration in groceries	<i>E. coli</i>	Multi-drug resistance patterns; higher resistance in groceries vs supermarkets	26.2% MDR <i>E. coli</i> in vegetables	(Miranda et al., 2010)
Primary study	America	Mexico, Jalisco	<i>L. monocytogenes</i> in fruits and vegetables	Retail supermarket study	Lettuce, parsley, cilantro, broccoli, cucumber	Phosphate fertilizer, antibiotics, residues in soil/irrigation water	<i>L. monocytogenes</i> (serotypes 1/2a, 1/2b; LIPI-1 to LIPI-4)	<i>lde</i> (52.9%), <i>tetM</i> (29.4%), <i>msrA</i> (17.6%); cadmium and benzalkonium chloride co-resistance	12.8% prevalence in overall fresh fruits and vegetables; MAR index ≥ 0.46 in 70.5%; 58.8% cadmium resistant	(Avila-Nova et al., 2024)

Table 2: Reported mechanisms and key genetic elements underlying antimicrobial resistance in vegetable production systems

Mechanism	Key Elements	Vegetable/production systems	Host Organisms	Reference
Fungicide-mediated enhancement of HGT via plasmid conjugation	RP4 plasmid carrying <i>trbBp</i> , <i>traF</i> , <i>trfAp</i> , <i>traJ</i> , <i>korA</i> , <i>korB</i> , <i>kilA</i>	Soil systems	<i>E. coli</i> , <i>P. putida</i>	(Zhang et al., 2023)
MGE-mediated HGT	<i>int11</i> , IS26	Carrot, spinach, sewage sludge amendments	Multiple genera including <i>Bacillus</i> spp., <i>Pseudomonas</i> spp.	(Patra & Dubey, 2024)
MGE-mediated HGT	<i>cld</i> gene cassette, <i>qacE2</i>	Vegetable phylloplane (spinach, mixed leaf salads)	<i>Pseudomonas</i> spp., <i>Erwinia</i> spp., <i>Chryseobacterium</i> spp.	(Qi et al., 2024)
Plasmid-mediated conjugation	pJK5::Plac::gfp	Lettuce rhizosphere	<i>K. variicola</i> , Pseudomonadaceae, Aeromonadaceae	(Riva et al., 2024)
Plasmid-mediated conjugation	IncHI2 / IncHI2A plasmids carrying <i>mcr-9.1</i> (e.g. pCST17-2_1)	Bean sprouts, myoga	<i>E. cloacae</i> , <i>R. ornithinolytica</i>	(Xedzro et al., 2023)
Plasmid-mediated conjugation (multi-replicon)	<i>mcr-1.1</i> , <i>bla_{CTX-M-15}</i> , <i>qnrB19</i> on IncHI2–IncQ1, IncF, ColE1-like plasmids	Soils collected from chicory, kale, mustard, parsley and chive crops	<i>E. coli</i> ST131-H22	(Lopes et al., 2021)
MGE-mediated HGT	Class 1 integron (In191) with <i>dfrA14</i>	Spinach, irrigation water	<i>E. coli</i> , <i>K. pneumoniae</i>	(Ritcher et al., 2021)
MGE-mediated HGT	IS26 with <i>tet(A)</i> , <i>bla_{TEM-1B}</i> , <i>qnrS1</i>	Store-bought produce (cilantro, arugula, mixed salad)	<i>E. coli</i> phylogroup B1	(Reid et al., 2020)
MGE-mediated HGT	ISCR2 mobile element with <i>tet(X4)</i>	Multiple sources including vegetables	<i>E. coli</i> ST542, ST10, ST761, ST48	(Fan et al., 2024)
Plasmid-mediated conjugation	IncFII, IncFIB plasmids with <i>bla_{CTX-M-15}</i>	Spinach, irrigation water	<i>K. pneumoniae</i>	(Ritcher et al., 2021)
MGE-mediated HGT	ISEc9, IS26, ISKpn19 with <i>bla_{CTX-M-1}</i> , <i>bla_{CTX-M14}</i> , <i>bla_{CTX-M15}</i>	Lettuce rhizosphere	ESBL-producing <i>E. coli</i>	(Richter et al., 2024)
Chromosomal mutation	F46Y/M172V/E427K with <i>cyp51A</i> ; F46Y/M172V/N248T/D255E/E427K with <i>cyp51A</i>	Tomatoes	<i>Aspergillus fumigatus</i>	(Madrid et al., 2024)
Chromosomal mutation	TR ₃₄ /L98H with <i>cyp51A</i> promoter; TR ₄₆ /Y121F/T289A with <i>cyp51A</i>	Agricultural environments (soil)	<i>Aspergillus fumigatus</i>	(Arendrup et al., 2024)
Chromosomal mutation	SNPs in <i>gyrA</i> , <i>parC</i>	Store-bought produce (cilantro, arugula, mixed salad)	<i>E. coli</i>	(Reid et al., 2020)

Table 3: Environmental co-selectors and mechanisms driving co-selection or amplification of antimicrobial resistance in vegetable production systems

Co-Selector	Mechanism of Co-Selection / Resistance Amplification	References
Chlorothalonil (fungicide)	Induces reactive oxygen species, activates SOS response, increases membrane permeability, resulting in enhanced plasmid-mediated conjugative transfer of ARGs	(Arendrup et al., 2024)
Azoxystrobin (fungicide)	Upregulates plasmid-borne conjugation-related genes, increasing conjugative ARG transfer	
Carbendazim (fungicide)	Enhances expression of conjugation-related genes, promoting ARG dissemination via plasmids	
Propiconazole (azole fungicide)	Acts as a potential selector for azole-resistant <i>A. fumigatus</i> ; no significant increase in bacterial ARG transfer observed	
Azole fungicides (general class)	Dual agricultural and clinical use creates environmental hot spots for azole resistance and cross-resistance selection	
Dicamba (herbicide)	Alters antibiotic susceptibility via modulation of efflux pump activity	
2,4-D (herbicide)	Induces adaptive resistance through efflux pump regulation	
Glyphosate (herbicide)	Triggers efflux pump-mediated changes in antibiotic susceptibility	
Tween 80 (co-formulant)	Induces resistance changes through non-specific stress responses, with weaker effects than active ingredients	
Carboxymethyl cellulose (co-formulant)	Causes adaptive resistance changes via stress-related mechanisms	

Cadmium		Co-selects for antibiotic resistance and benzalkonium chloride resistance via shared efflux and tolerance mechanisms	(Avila-Novoa et al., 2024)
Lead, Chromium	Nickel,	Select for multidrug resistance in endophytic and environmental bacteria, often coupled with biofilm formation	(Patra & Dubey, 2024)
Copper, Zinc		Promote ARG proliferation under manure-amended conditions	(Zhang et al., 2023)
Copper, Mercury	Silver,	Tolerance genes co-located with ARGs on mobile genetic elements, facilitating co-selection	(Lopes et al., 2021)
Tellurium		Co-localisation of tellurium tolerance determinants with colistin resistance genes (e.g. <i>mcr-9</i>), enabling genetic co-selection	(Xedzro et al., 2023)
Sodium chlorite (disinfectant)		Selects for chlorite dismutase-mediated resistance via <i>cld</i> gene cassettes embedded in class 1 integrons	(Qi et al., 2024)
Chlorine treatments)	(wash	Selects for tolerant bacterial populations through survival-based stress filtering	(Ratshilingano et al., 2022)
Free chlorine		Induces stress-response pathways and efflux pump upregulation	(Ding et al., 2025)
Benzalkonium chloride		Co-selects with heavy metal resistance (e.g. cadmium) via shared efflux mechanisms	(Avila-Novoa et al., 2024)

Table 4: Summary of regulatory frameworks, gaps, and recommendations relevant to antimicrobial resistance in vegetable production and related environmental systems

Study Context	Type of Vegetables	Regulatory Frameworks	Gaps and Limitations	Recommendations	References
Review and policy analysis; Global	Not applicable	Not mentioned (the paper does not provide specific information on regulatory frameworks or guidelines related to AMR in vegetables)	- Regulatory gaps: Not explicitly mentioned, but implied through the need for prioritization and strategic alignment. - Surveillance or monitoring limitations: Not explicitly mentioned in the quotes provided. - Data gaps or knowledge deficiencies: Implied through the need for prioritization and strategic alignment. - Methodological limitations in risk assessment: Not explicitly mentioned in the quotes provided. - Infrastructure or resource constraints: Implied through the discussion of funding and resource allocation challenges. - Coordination challenges between stakeholders: Highlighted by the need for agreement on positioning relative to pandemic preparedness and recovery agendas. - Future research priorities recommended: Not explicitly mentioned in the quotes provided, but implied through the need for strategic alignment and prioritization.	- Proposed regulatory changes or new frameworks: Strengthening national regulatory agencies and enforcing regulations. - Suggested improvements to risk assessment methods: Not specifically mentioned in the context of vegetables. - Recommended surveillance or monitoring approaches: Improving surveillance systems to capture actionable data. - Proposed interventions along the food chain: Not specifically mentioned in the context of vegetables. - Coordination mechanisms suggested: Global governance and national action plans (NAPs). - Precautionary measures recommended: Not specifically mentioned in the context of vegetables. - Implementation strategies discussed: Focus on WASH, infection prevention and control, therapeutic innovation, and surveillance.	(Wellcome, 2020)

Empirical research using a system dynamics model	Not applicable (study focuses on water treatment)	- Specific regulations, standards, or guidelines mentioned: U.S. EPA's Surface Water Treatment Rules, Ground Water Rule, NWRI's '12-10-9' framework, WHO guidelines for microfiltration. - Regulatory bodies or authorities responsible: U.S. Environmental Protection Agency (EPA), National Water Research Institute (NWRI), World Health Organization (WHO). - Scope of regulation: Pre-harvest and post-harvest, focusing on treatment process reliability and source water characterization. - Enforcement mechanisms described: Not explicitly mentioned. - Regulatory gaps or absence of guidelines noted: Not explicitly mentioned. - Comparison between different jurisdictions: Not applicable.	- Regulatory gaps or inadequacies noted: Importance of source water characterization. - Surveillance or monitoring limitations: Assumptions about UV failure probabilities may not reflect real-world rates. - Data gaps or knowledge deficiencies: Understanding failure probabilities, comprehensive characterization of treatment process failures and pathogen loads. - Methodological limitations in risk assessment: Model may overestimate failure severity, uncertainty in dose response models. - Infrastructure or resource constraints: Not explicitly mentioned. - Coordination challenges between stakeholders: Public health is only one consideration; broader evaluation needed. - Future research priorities recommended: Comprehensive characterization of treatment process failures and pathogen loads, improvement in dose response models.	Not mentioned (the paper does not address AMR in vegetables or provide recommendations for addressing it)	(Amoueyan et al., 2019)
Empirical research; EU	Milk, brine, fresh meat, cheese, fish, meat products	Not mentioned (the paper does not provide specific information on regulatory frameworks, standards, or guidelines related to AMR in vegetables)	- Methodological limitations: Challenges in recovering sufficient microbial DNA from low-biomass niches; sequences can originate from both dead and alive cells; limited sensitivity for detecting low-abundance microorganisms. - Data gaps: Study was unbalanced towards cheese and meat producers; limited to a few European countries; need for more facilities from diverse sectors and countries. - Future research priorities: Include more facilities from diverse sectors and countries to better understand resistome composition. - Infrastructure or resource constraints: Limited by current technology for detecting low-abundance microorganisms. - Coordination challenges: Not explicitly mentioned, but implied through the need for improved protocols and broader sampling.	- Proposed regulatory changes or new frameworks: Guide the appropriate use of biocides and antimicrobials in food production settings. - Suggested improvements to risk assessment methods: Consider linkages between resistome of final products and surfaces. - Recommended surveillance or monitoring approaches: Implement improved sampling and DNA extraction protocols. - Precautionary measures recommended: Ensure appropriate use of agents in food production settings. - Implementation strategies discussed: Address challenges in whole-metagenome sequencing for low-biomass niches.	(Quijada et al., 2025)

Empirical research; countries in Europe (Germany, Austria, Czech Republic, Slovakia, Hungary, Croatia, Serbia, Romania, Bulgaria, Ukraine, Greece, and Cyprus)	12 Wastewater effluent samples	The paper discusses the EU Chemicals Strategy for Sustainability, adopted by the European Commission in 2020, which aims to create a toxic-free environment. The NORMAN prioritisation scheme supports regulatory obligations by identifying pollutants in various environmental compartments. It has been used to provide recommendations for the European surface water Watch List and adopted by France and Slovakia for national studies. The scheme involves categorizing substances based on knowledge gaps and ranking them using exposure, hazard, and risk indicators. However, the paper does not specifically address regulatory frameworks related to AMR in vegetables.	- Regulatory gaps or inadequacies noted: Lack of knowledge on chemical exposure to humans and the environment; need for more comprehensive compilation of agreed quality targets by governmental authorities. - Surveillance or monitoring limitations: Insufficient information from target monitoring and uncertainty in the identification from suspect screening for a large number of substances. - Data gaps or knowledge deficiencies: Need for improvement in suspect screening to increase confidence in chemical occurrence data; lack of experimental effect data for many substances. - Methodological limitations in risk assessment: Limitations in analytical methods for certain substances; need for extension to other analytical techniques like GC-APCI-HRMS. - Infrastructure or resource constraints: Need for better sharing of existing data to improve prioritization efforts. - Coordination challenges between stakeholders: Not explicitly mentioned. - Future research priorities recommended: Enhancing the statistical framework and refining hazard scores to improve environmental risk assessment; improving suspect screening capabilities.	- Suggested improvements to risk assessment methods: Enhance suspect screening using machine learning models, refine the prioritization framework to match instrumentation with substance properties, and use QSAR models for ecotoxicity endpoints. - Recommended surveillance or monitoring approaches: Improve suspect screening data quality and availability. - Coordination mechanisms suggested: Improve data sharing and collaboration. - Implementation strategies discussed: Enhance the statistical framework and refine the hazard score.	(Dulio et al., 2024)
Review; Global	Not specified	- Specific regulations, standards, or guidelines mentioned: The "One Health" approach, WHO's Global Action Plan, FAO's Plan for Antimicrobial Resistivity, compulsory guidelines for antibiotic use in animals and humans. - Regulatory bodies or authorities responsible: WHO, FAO, OIE, national reference laboratories. - Scope of regulation: Pre-harvest (animal health), post-harvest (food safety), both (environmental impact). - Enforcement mechanisms described: Surveillance systems, advisory groups, veterinary legislation. - Regulatory gaps or absence of guidelines noted: Lack of national reference laboratories in many regions, need	- Regulatory gaps or inadequacies noted: Limited resources in LMICs for implementing 'One Health' initiative; need for revised research policies in developing countries. - Surveillance or monitoring limitations: Gaps in surveillance systems for antimicrobial use and AMR in the food chain; limited surveillance data on non-animal origin foods. - Data gaps or knowledge deficiencies: Insufficient development of new antibiotics; lack of surveillance data on non-animal origin foods. - Methodological limitations in risk assessment: Not explicitly mentioned. - Infrastructure or resource constraints: Limited resources in LMICs; need for investment in new antimicrobial treatments and vaccines. - Coordination challenges between stakeholders: Need for a collective global approach.	- Proposed regulatory changes or new frameworks: The "One Health" approach is recommended as a framework to address AMR, involving collaboration between WHO, FAO, and OIE. Regulatory changes should be policy-based and enforced globally. - Suggested improvements to risk assessment methods: Enhanced surveillance and adherence to guidelines are suggested to monitor and control antibiotic use in food production and human medicine. - Recommended surveillance or monitoring approaches: The WHO 'Advisory Group on Integrated Surveillance of Antimicrobial Resistance' used COIPARS methods for the regulation of AMR	(Samtiya et al., 2022)

			for revision of research policies in developing nations. - Comparison between different jurisdictions: Developed countries have established programs for monitoring AMR, while developing nations face regulatory gaps.	- Future research priorities recommended: Development of effective alternatives to antibiotics in agriculture; comprehensive plan to address AMR in communities.	and the use of antibiotics in food animals. - Proposed interventions along the food chain: A comprehensive plan is needed to reduce the challenge of AMR in the community and for the development of effective alternatives to the use of antibiotics in production agriculture. - Coordination mechanisms suggested: The "One Health" approach involves collaboration between WHO, FAO, and OIE. - Precautionary measures recommended: Proper hygiene and cleanliness by following necessary guidelines can help to decrease AMR issues. - Implementation strategies discussed: The developed approaches should be policy-based, enforced for all countries, and entirely backed by government regulations. A collective global approach is recommended rather than individual country actions.	
Policy analysis; Global	Not applicable		Not mentioned (the paper does not discuss specific regulatory frameworks or guidelines related to AMR in vegetables)	- Regulatory gaps or inadequacies noted: Lack of effective governance structures and guiding targets. - Surveillance or monitoring limitations: Mixed data on AMR burden and spread. - Data gaps or knowledge deficiencies: No means to synthesize global evidence on AMR. - Methodological limitations in risk assessment: Not explicitly mentioned. - Infrastructure or resource constraints: Need for a standing mechanism to review progress and update targets. - Coordination challenges between stakeholders: Lack of commitment to tangible action following political declarations. - Future research priorities recommended: Establishing an evidence panel and regular convening mechanisms.	- Proposed regulatory changes or new frameworks: Set a bold, unifying goal for a reduction in the global burden of AMR. - Suggested improvements to risk assessment methods: Establish a panel for scientific evidence and action on AMR. - Recommended surveillance or monitoring approaches: Establish a panel for scientific evidence and action on AMR. - Proposed interventions along the food chain: Not mentioned. - Coordination mechanisms suggested: Initiate mechanisms to regularly convene states to review progress, update targets, and maintain political momentum. - Precautionary measures recommended: Not mentioned. - Implementation strategies discussed: Not mentioned.	(Wellcome, 2024)

Review and policy analysis; US	Not applicable (study focuses on water reuse)	- Specific regulations, standards, or guidelines: No U.S. federal water reuse regulations exist; states are developing their own regulations based on health benchmarks and pathogen LRTs. - Regulatory bodies or authorities responsible: States are responsible for developing regulations. - Scope of regulation: Regulations are being developed for various water reuse applications, but specifics are not detailed. - Enforcement mechanisms described: Not mentioned. - Regulatory gaps or absence of guidelines noted: Lack of comprehensive federal regulations and updated summaries of LRTs. - Comparison between different jurisdictions: Not applicable as there are no federal regulations to compare.	- Regulatory gaps or inadequacies noted: Absence of U.S. federal water reuse regulations. - Surveillance or monitoring limitations: Uncertainties in characterizing reference pathogen densities and exposure volumes. - Data gaps or knowledge deficiencies: Limited data on pathogen densities in roof runoff and onsite sources; uncertainty in dose-response relationships. - Methodological limitations in risk assessment: Reliance on modelling due to data gaps; uncertainties in dose-response relationships. - Infrastructure or resource constraints: Challenges in operations management, monitoring, and oversight for decentralized onsite potable reuse systems. - Coordination challenges between stakeholders: Implied need for consistent regulatory frameworks and data sharing. - Future research priorities recommended: Improved understanding of dose-response relationships for enteric adenoviruses.	Not mentioned (the paper does not address AMR in vegetables or propose specific recommendations for addressing AMR in vegetables)	(Jahne et al., 2024)
Review	Not applicable	- Specific regulations: EC n° 1107/2009, EC n° 528/2012, REACH regulation - Regulatory bodies: European Union - Scope of regulation: Pre-harvest (use of pesticides in agriculture) - Enforcement mechanisms: Not mentioned - Regulatory gaps: Not mentioned - Comparison between jurisdictions: Applies in European Union, Switzerland, Norway, and the UK	- Regulatory gaps or inadequacies noted: Not explicitly mentioned. - Surveillance or monitoring limitations: The full potential of WBE to assess exposure through various routes remains underexplored. - Data gaps or knowledge deficiencies: Limited availability of metabolism data on humans and animals; lack of clear definitions for composite sampling methods. - Methodological limitations in risk assessment: Inconsistencies in reporting method performance metrics; need for improved QA/QC protocols. - Infrastructure or resource constraints: Not explicitly mentioned. - Coordination challenges between stakeholders: Not explicitly mentioned. - Future research priorities recommended: Integration of WBE with HBM; use of LC-HRMS techniques; inclusion of field blanks in QA/QC measures.	Not applicable (the paper does not address antimicrobial resistance in vegetables or propose specific recommendations related to AMR)	(Carneiro et al., 2024)

Retrospective cohort study; South Africa	Animals, environment and food products	Not mentioned (the paper does not discuss regulatory frameworks related to vegetables)	- Regulatory gaps or inadequacies noted: No single control measure has been effective in reducing NT-Salmonella contamination. - Surveillance or monitoring limitations: Potential bias in sample selection, lack of preservation of some isolates, incomplete laboratory records. - Data gaps or knowledge deficiencies: Incomplete entries in laboratory records and sample submission forms. - Methodological limitations in risk assessment: Lack of comprehensive data on all suspected cases and incomplete records. - Infrastructure or resource constraints: Not explicitly mentioned. - Coordination challenges between stakeholders: Need for better coordination between human medical diagnosticians and researchers. - Future research priorities recommended: Engage with human medical diagnosticians to access and analyze Salmonella isolates from the human health sector; adopt a One Health Approach for comprehensive surveillance.	- Recommended surveillance or monitoring approaches: Effective antimicrobial stewardship and surveillance to combat antibiotic resistance. - Proposed interventions along the food chain: Alternative approaches to antimicrobial resistance. - Coordination mechanisms suggested: Collaboration with human medical diagnosticians and researchers. - Implementation strategies discussed: Embracing the One Health Approach for comprehensive monitoring and surveillance.	(Matle et al., 2025)
Policy analysis/framework recommendation; Asia, particularly low- and middle-income countries (LMICs)	Not mentioned, focus on environmental matrices	Not mentioned (the paper does not provide specific information on regulatory frameworks related to AMR in vegetables)	- Data gaps or knowledge deficiencies: Information and knowledge of the environmental dimensions of AMR are scarce in Asian countries. - Surveillance or monitoring limitations: There is an urgent need for the design and implementation of AMR monitoring across this region. - Methodological limitations in risk assessment: Clarity is needed on what, how, and where to monitor. - Infrastructure or resource constraints: Cost-effective methods are critical due to resource limitations in LMICs; molecular-based methods require greater investment. - Coordination challenges between stakeholders: Selection of monitoring locations and sampling frequency depends on local needs and resource limitations. - Future research priorities recommended: Development of a globally compatible data reporting tool for environmental surveillance of AMR.	- Proposed regulatory changes or new frameworks: Integrated AMR surveillance system across human, animal, and environmental sectors. - Suggested improvements to risk assessment methods: Proposal of <i>Escherichia coli</i> as a target microbe for monitoring. - Recommended surveillance or monitoring approaches: Use of culture-based methods; selection of monitoring locations based on local needs and sources of AMR; priority locations include untreated wastewater discharges and potable source waters. - Proposed interventions along the food chain: Not mentioned. - Coordination mechanisms suggested: Development of a globally compatible data reporting tool. - Precautionary measures recommended: Not mentioned. - Implementation strategies discussed: Not mentioned beyond	(Honda et al., 2023)

environmental
monitoring framework.

Review; Global	Not mentioned	- Specific regulations, standards, or guidelines mentioned: Existing frameworks from WHO and USEPA, but these do not specifically address AMR. - Regulatory bodies or authorities responsible: WHO, USEPA. - Scope of regulation: General environmental contaminants, not specifically AMR. - Enforcement mechanisms described: Not mentioned. - Regulatory gaps or absence of guidelines noted: Lack of standardized surveillance and risk assessment strategies; applicability in LMICs unclear. - Comparison between different jurisdictions if applicable: Applicability in LMICs unclear compared to High Income Countries	- Regulatory gaps: Lack of standardized frameworks for environmental AMR surveillance and risk assessment. - Surveillance limitations: Complexity of natural environments, lack of sufficient data on ecological parameters. - Data gaps: Missing data from major economies and the private sector. - Methodological limitations: Non-standardized protocols, need for well-defined parameters in risk assessment models. - Infrastructure and resource constraints: Limited budgets, inadequate equipment. - Coordination challenges: Need for harmonized protocols, applicability in LMICs unclear. - Future research priorities: Development of standardized frameworks, integration of traditional ecotoxicology with modern 'omics' approaches, continuous monitoring for novel proxies and intervention evaluation.	- Proposed regulatory changes or new frameworks: Standardized, cost-effective risk assessment frameworks adaptable across different environments and regions. - Suggested improvements to risk assessment methods: Integration of traditional ecotoxicology with modern 'omics' approaches. - Recommended surveillance or monitoring approaches: Continuous monitoring to identify novel proxies and evaluate intervention effectiveness. - Proposed interventions along the food chain: Risk assessment models providing well-defined, actionable interventions. - Coordination mechanisms suggested: AMR-specific ecotoxicological guidelines. - Precautionary measures recommended: Use of indicator ARGs to minimize redundancies. - Implementation strategies discussed: Generating reproducible public health data for efficient risk assessment models.	(Makumbi et al., 2024)
Policy analysis; Global	Not applicable	Not mentioned (the paper does not provide information on regulatory frameworks related to AMR in vegetables)	- Gaps and inequities in the global response to AMR - Evidence gaps in current research on AMR - Need for future research to address identified gaps - Potential gap in representation and expertise from LMICs - Coordination challenges between member states, the quadripartite, and the wider AMR community	- Proposed regulatory changes or new frameworks: Creation of a scientific evidence panel with a clear mandate from member states. - Suggested improvements to risk assessment methods: Synthesizing and advancing the evidence base on AMR. - Recommended surveillance or monitoring approaches: Regular high-level summaries on global progress and future	(Wellcome)

				prioritisation. - Coordination mechanisms suggested: Panel to complement existing advisory bodies, draw experts from various disciplines and sectors. - Implementation strategies discussed: Panel to provide guidance on evidence gaps and needs for further research.	
Critical review; Global, with specific examples from the U.S. and Australia	Not specified	Not mentioned (the paper does not discuss regulatory frameworks specifically related to AMR in vegetables)	- Regulatory gaps or inadequacies noted: Lack of federal regulations, particularly in addressing microbial water quality during distribution. - Surveillance or monitoring limitations: Traditional focus on faecal indicator bacteria neglects other pathogens and exposure routes. - Data gaps or knowledge deficiencies: Limited studies on non-traditional exposure routes and emerging contaminants. - Methodological limitations in risk assessment: Need for quantitative microbiological risk assessments and epidemiological studies. - Infrastructure or resource constraints: Infrastructure issues are a major problem in managing recycled water systems. - Coordination challenges between stakeholders: Lack of comprehensive regulations and need for international coordination. - Future research priorities recommended: Tailoring treatment processes to specific end uses, developing best management practices for distribution systems, and addressing emerging concerns.	- Proposed regulatory changes or new frameworks: Adoption of the human exposome paradigm to guide risk management strategies. - Suggested improvements to risk assessment methods: Development of quantitative microbiological risk assessments (QMRA). - Recommended surveillance or monitoring approaches: Epidemiological studies to link human illness with microbial sources. - Proposed interventions along the food chain: Tailoring treatment processes to specific end uses and developing best management practices for distribution systems. - Coordination mechanisms suggested: Adoption of international guidelines like the Australian Guidelines for Water Recycling and the WHO's WSP. - Precautionary measures recommended: Emphasis on understanding risks and uncertainties and revising best management practices as knowledge gaps are addressed. - Implementation strategies discussed: Adoption of the human exposome paradigm and revision of best management practices.	(Garner et al., 2016)

Empirical research; US	Conventional potable, potable reuse and nonpotable reuse waters	Not mentioned (the paper does not discuss regulatory frameworks or guidelines related to AMR in vegetables)	- Regulatory gaps or inadequacies noted: Faecal indicator paradigms can fall short in water reuse contexts. - Surveillance or monitoring limitations: Not mentioned. - Data gaps or knowledge deficiencies: Need for further studies to refine the approach and fully understand microbiomes associated with different water types. - Methodological limitations in risk assessment: Not mentioned. - Infrastructure or resource constraints: Not mentioned. - Coordination challenges between stakeholders: Not mentioned. - Future research priorities recommended: Refining the approach demonstrated in the study to better support and optimize a 'fit for purpose' paradigm of water reuse.	Not mentioned (the paper does not address AMR in vegetables or provide related recommendations)	(Blair et al., 2024)
Policy analysis and RA framework tool development; Denmark	Various food types	- Specific regulations, standards, or guidelines mentioned: EU legislation for monitoring AMR in food-borne bacteria (Impl. Decision 2020/1729/EU), EU Food Law (Reg. 2073/2005/EU), WHO and FAO guidelines on microbiological risk analysis, European Medicine Agency framework for new medicines generating AMR. - Regulatory bodies or authorities responsible: European Union, WHO, FAO, European Medicine Agency. - Scope of regulation: Pre-harvest and post-harvest monitoring of AMR in food-borne bacteria. - Enforcement mechanisms described: Food recall, warnings to trade partners, labeling of specific foods. - Regulatory gaps or absence of guidelines noted: EU Food Law does not specifically address AMR, need for a consolidated approach to address AMR complexities. - Comparison between different jurisdictions: Not explicitly mentioned.	- Regulatory gaps: Existing risk assessment frameworks are limited for timely risk management. - Surveillance limitations: Routine surveillance data is not sufficient for assessing specific AMR genes. - Data gaps: Need for regular updates and reviews of fact sheets and treatment guidelines. - Methodological limitations: RRA-AMR-Food is not comprehensive and simplifies complex systems. - Infrastructure/resource constraints: Generation of fact sheets is resource demanding. - Coordination challenges: Need for further work on expert elicitation and consensus building. - Future research priorities: Expansion of the tool with additional questions and criteria.	- Proposed regulatory changes or new frameworks: Introduction of the RRA-AMR-Food tool for assessing AMR risk in foods. - Suggested improvements to risk assessment methods: Expansion and refinement of the tool over time. - Recommended surveillance or monitoring approaches: Use of routine surveillance data as a trigger for risk assessment. - Proposed interventions along the food chain: Food recalls, warnings to trade partners, labelling of specific foods. - Coordination mechanisms suggested: Development of fact sheets on antimicrobial use and resistance genes. - Precautionary measures recommended: Rapid assessment to enable timely withdrawal of high-risk foods. - Implementation strategies discussed: Use by scientific officers, review and validation over time.	(Korsgaard et al., 2022)

Review; Global	Not specified	- Specific regulations, standards, or guidelines mentioned: U.S. FDA's GenomeTrakr database, FAO and WHO's guidelines for microbiological risk assessment, EFSA's MRA models, CAC's frameworks for MRA. - Regulatory bodies or authorities responsible: U.S. FDA, FAO, WHO, EFSA, CAC. - Scope of regulation: Pre-harvest and post-harvest stages. - Enforcement mechanisms described: Use of databases like GenomeTrakr, guidelines from EFSA and CAC. - Regulatory gaps or absence of guidelines noted: European Union's GDPR limiting data sharing, FDA's stringent frameworks for WGS. - Comparison between different jurisdictions: Differences in regulatory frameworks between the U.S. and European Union.	- Regulatory gaps or inadequacies: Lack of unified international standards and regulations for food safety detection technologies; regulatory delays in approving new technologies. - Surveillance or monitoring limitations: Challenges in integrating datasets from different technologies; lack of communication between institutions leading to data silos. - Data gaps or knowledge deficiencies: Insufficient completeness and reliability of data; heterogeneity of data; need for standardization in sequencing platforms. - Methodological limitations: Uncertainty and complexity of models; reliance on simplified assumptions; need for more advanced statistical methods. - Infrastructure or resource constraints: High computational demands for sequencing technologies; economic burdens of implementing new technologies. - Coordination challenges: Lack of communication and data integration across different stages of the food supply chain. - Future research priorities: Advancements in detection technologies; standardization of data integration; international collaboration.	- Proposed regulatory changes or new frameworks: Advancement of standardization, refinement of policies and regulations to promote global food safety governance. - Suggested improvements to risk assessment methods: Integration of systems biology and multi-omics technologies, development of nano-biosensors, multi-scale coupling of Bayesian networks and predictive microbiology. - Recommended surveillance or monitoring approaches: Development of nano-biosensors for real-time monitoring, integration of Bayesian networks with predictive microbiology. - Proposed interventions along the food chain: Implementation of automation, AI, and cloud-based tools to improve detection technologies and reduce costs. - Coordination mechanisms suggested: Establishing multi-regional collaborative frameworks, promoting shared access to detection equipment, international collaboration and standardization. - Precautionary measures recommended: Establishment of core omics databases for highly pathogenic microorganisms. - Implementation strategies discussed: Government support through policy initiatives to lower implementation costs of new technologies.	(Xiao et al., 2025)
Empirical research; US	Leafy greens	- Specific regulations, standards, or guidelines mentioned: Food Safety Modernization Act (FSMA) Final Rule on "Standards for the Growing, Harvesting, Packing, and Holding of Produce for Human Consumption" or the Produce Safety Rule (PSR); Good Agricultural Practices (GAPs) - Regulatory bodies or	- Regulatory gaps or inadequacies noted: Minimal information on food safety practices in indoor, soilless environments; confusion about FSMA Produce Safety Rule applicability; lack of clear regulatory information. - Surveillance or monitoring limitations: Limited sample size and geographical distribution; incomplete characterization of operations due to low survey completion. - Data gaps or knowledge	- Proposed regulatory changes or new frameworks: Establishment of a centralized source of information for growers on regulatory requirements and best practices. - Suggested improvements to risk assessment methods: Additional grower education and training. - Recommended	(Hamilton et al., 2023)

		authorities responsible: FDA, USDA, EPA - Scope of regulation: Pre-harvest, post-harvest - Enforcement mechanisms described: Not mentioned - Regulatory gaps or absence of guidelines noted: Growers express uncertainty about regulatory requirements; perceived differences between USDA and FDA requirements - Comparison between different jurisdictions: Not applicable	deficiencies: Need for standardized methods to control algae growth; desire for science-based risk assessments. - Methodological limitations in risk assessment: Limited sample size and geographical distribution; incomplete characterization of operations. - Infrastructure or resource constraints: Need for concise, standardized training programs. - Coordination challenges between stakeholders: Lack of clear and concise regulatory information; confusion about regulatory requirements. - Future research priorities recommended: Development of standardized methods for algae control; science-based risk assessments; improved training programs; centralized source of regulatory information.	surveillance or monitoring approaches: Observational studies at indoor facilities and testing for microorganisms. - Proposed interventions along the food chain: Centralized information source and observational studies. - Coordination mechanisms suggested: Centralized information source. - Precautionary measures recommended: Additional education and training. - Implementation strategies discussed: Repeating the study after establishing centralized information sources and conducting observational studies.	
Policy analysis or review; California	Not mentioned	Not mentioned (the paper does not discuss regulatory frameworks related to AMR in vegetables)	- Regulatory gaps or inadequacies noted: Lack of US federal level water reuse regulations. - Surveillance or monitoring limitations: Not explicitly mentioned. - Data gaps or knowledge deficiencies: Varying chemical and pathogen concerns by source and application. - Methodological limitations in risk assessment: Complexity and variability of treatment standards across different sources and applications. - Infrastructure or resource constraints: Difference in capacity to develop treatment specifications by state. - Coordination challenges between stakeholders: Not explicitly mentioned. - Future research priorities recommended: Not explicitly mentioned.	- Proposed regulatory changes or new frameworks: Emphasis on "fit-for-purpose" treatment levels and the need for standardized federal regulations. - Suggested improvements to risk assessment methods: Need for a tool like the REUSExplorer to assess water reuse risks. - Recommended surveillance or monitoring approaches: Detailed specifications and monitoring requirements in tables. - Proposed interventions along the food chain: Not explicitly mentioned. - Coordination mechanisms suggested: Not explicitly mentioned. - Precautionary measures recommended: Not explicitly mentioned. - Implementation strategies discussed: Not explicitly mentioned.	(WRAP, 2024)

Review; (specifically countries Germany)	EU EU like	Roots, salads, and other vegetables commonly consumed raw	- Specific regulations: Germany prohibits the use of liquid manure for top dressing; UK Food Standards Agency discourages manure use in ready-to-eat crops. - Regulatory bodies: FAO provides guidelines for quantitative risk assessment; UK Food Standards Agency. - Scope of regulation: Pre-harvest (Germany's manure regulation). - Enforcement mechanisms: Not mentioned. - Regulatory gaps: Lack of comprehensive frameworks for identifying contamination sources and understanding intestinal processes.	- Regulatory gaps or inadequacies noted: Not explicitly mentioned. - Surveillance or monitoring limitations: Need for more comprehensive surveillance of contamination sources beyond irrigation water, organic fertilizer, and soil. - Data gaps or knowledge deficiencies: Lack of quantitative data and dose-response studies; need for data on processing and distribution steps as contamination sources. - Methodological limitations in risk assessment: Use of non-validated methods; focus on non-pathogenic bacteria or low clinical relevance data. - Infrastructure or resource constraints: Not explicitly mentioned. - Coordination challenges between stakeholders: Not explicitly mentioned. - Future research priorities recommended: Focus on clinically relevant antibiotics; evidence of transmission at clonal level; role of commensals in ARG transfer and extraintestinal infections.	- Proposed improvements to risk assessment methods: The authors recommend a shift from merely counting resistant bacteria to more functional approaches that provide dose-response data. - Recommended surveillance or monitoring approaches: Include processing and distribution steps in the search for plant-derived ARB; systematic studies on human contamination during production and processing are needed. - Proposed interventions along the food chain: Focus on clinically relevant antibiotics and the role of commensals in transferring resistance genes. - Coordination mechanisms suggested: Not explicitly mentioned, but implied through the need for comprehensive and systematic approaches. - Precautionary measures recommended: Not explicitly mentioned, but the emphasis on understanding AMR suggests caution in handling and consuming vegetables. - Implementation strategies discussed: Future studies should focus on clinically relevant antibiotics and the involvement of commensals in ARG transfer.	(Hölzel et al., 2018)
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Empirical research; EU	Water	- Specific regulations, standards, or guidelines mentioned: Revisions to the Urban Wastewater Treatment Directive (UWWTD), Environmental Quality Standards Directive (EQSD), Groundwater Directive, Water Reuse Regulation 2020 (WRR), EU One Health Action Plan. - Regulatory bodies or authorities responsible: European Union (EU), European Environment Agency (EEA), EU Council. - Scope of regulation: Pre-harvest and post-harvest, focusing on monitoring AMR in large WWTPs, surface waters, and groundwaters. - Enforcement mechanisms described: Reporting requirements under revised directives, integrated surveillance systems. - Regulatory gaps or absence of guidelines noted: Lack of standardized methods for AMR monitoring in aquatic environments. - Comparison between different jurisdictions: EU-wide regulations and recommendations.	- Regulatory gaps: Lack of harmonized nomenclature for targets/indicators. - Surveillance or monitoring limitations: Variability in national capabilities and resources; differences in experience with qPCR and culturing techniques. - Data gaps: Lack of certified reference materials for AMR targets and target bacteria. - Methodological limitations: Challenges in fully harmonizing protocols, especially for sample collection and qPCR assays. - Infrastructure or resource constraints: Timetable and funding constraints; delays in securing funding and approvals. - Coordination challenges: Need to adapt the initial scope to accommodate varying capacities and resources. - Future research priorities: Full harmonization of protocols; development of certified reference materials.	- Proposed regulatory changes: Revisions to Urban Wastewater Treatment Directive and Environmental Quality Standards Directive to include AMR monitoring. - Suggested improvements to risk assessment methods: Develop robust QA/QC procedures, use certified reference materials. - Recommended surveillance or monitoring approaches: Establish centralized data reporting system, integrate AMR surveillance into existing programs. - Proposed interventions along the food chain: Not specifically mentioned in the context of vegetables. - Coordination mechanisms suggested: Foster dialogue among stakeholders, promote effective communication and knowledge sharing. - Precautionary measures recommended: Define environmental quality criteria for AMR abundance, ensure data availability and sharing. - Implementation strategies discussed: Develop capacity-building initiatives, promote standardized methods.	(Schwermer et al., 2025)
Review; Global, with specific mentions of the EU and Japan	Crops in general	- Specific regulations: Banning of epoxiconazole and propiconazole in France due to endocrine-disrupting effects. - Regulatory bodies: EU, with regulations governed by hazard rather than risk. - Scope of regulation: Pre-harvest, with a focus on reducing chemical use and increasing organic farming. - Enforcement mechanisms: Not explicitly mentioned. - Regulatory gaps: Not explicitly mentioned. - Comparison between jurisdictions: EU's "Farm to Fork strategy" and Japan's "Strategy for Sustainable Food Systems, MeaDRI" indicate a global trend towards sustainability.	- Regulatory gaps: Stringent regulations hinder the introduction of new fungicides. - Surveillance limitations: Need for better monitoring of resistance development. - Data gaps: Limited data on the effectiveness of new fungicide classes and resistance inducers. - Methodological limitations: Challenges in translating research into practical applications. - Infrastructure constraints: Need for more resources to develop novel, safer fungicides. - Coordination challenges: Integration of biocontrol with chemical fungicides is needed. - Future research priorities: Development of new fungicide classes, acceleration of breeding for sustainable disease resistance, and integration of biocontrol with chemical fungicides.	- Proposed regulatory changes or new frameworks: EU's "Farm to Fork strategy" to reduce pesticide use and increase organic farming. - Suggested improvements to risk assessment methods: Use of non-fungitoxic resistance inducers. - Recommended surveillance or monitoring approaches: Success of probenazole in Japan. - Proposed interventions along the food chain: Integration of biocontrol and IPM, development of novel safer fungicides. - Coordination mechanisms suggested: Variety mixtures to reduce resistance selection. - Precautionary measures recommended: Speeding up breeding for sustainable disease resistance.	(Ishii, 2024)

- Implementation strategies discussed: Integration with biocontrol, development of novel fungicides.

Comprehensive review of existing data; Israel and the Palestinian Authority	Fresh fruits and vegetables, including leafy vegetables	- Specific regulations: Israel follows ISO regulations with local modifications; Palestinian Authority prohibits irrigation of vegetables with treated wastewater. - Regulatory bodies: Ministry of Health in Israel; Palestinian Authority guidelines not fully adopted. - Scope of regulation: Pre-harvest (irrigation practices). - Enforcement mechanisms: Governmental approval required in Israel; Palestinian guidelines not fully enforced. - Regulatory gaps: Lack of sensitivity for higher effluent quality; no account for emerging contaminants like PFAS and pharmaceuticals. - Comparison: Israel has more developed regulations and infrastructure compared to the Palestinian Authority.	- Regulatory gaps or inadequacies noted: Significant gaps in wastewater treatment infrastructure and regulations between Israel and the Palestinian Authority; prohibition on irrigating vegetables with treated wastewater in the Palestinian Authority; current regulatory systems lack sensitivity for higher effluent quality and do not account for emerging contaminants. - Surveillance or monitoring limitations: Need to establish official laboratories for monitoring emerging contaminants. - Data gaps or knowledge deficiencies: Need to review and expand guidelines for contaminants. - Methodological limitations in risk assessment: Recommendation to prohibit wastewater irrigation for leafy vegetables due to risk assessment limitations. - Infrastructure or resource constraints: Lack of treatment and reuse of wastewater in the West Bank; socioeconomic disparities affecting infrastructure. - Coordination challenges between stakeholders: Achieving uniform standards poses challenges due to socioeconomic, political, and cultural differences. - Future research priorities recommended: Reviewing and expanding guidelines for contaminants; establishing official laboratories for monitoring emerging contaminants; addressing socioeconomic, political, and cultural differences.	- Proposed regulatory changes or new frameworks: Unified regulatory strategy for wastewater reuse; inclusion of emerging contaminants in regulations; use of high-quality treated wastewater for fruit crops and lower-quality for non-edible crops. - Suggested improvements to risk assessment methods: Inclusion of emerging contaminants in regulations. - Recommended surveillance or monitoring approaches: Not explicitly mentioned. - Proposed interventions along the food chain: Interim prohibition on using treated wastewater for leafy vegetables. - Coordination mechanisms suggested: Agreed timeline for implementation; adoption of EU regulation system as a standard. - Precautionary measures recommended: Interim prohibition on using treated wastewater for leafy vegetables. - Implementation strategies discussed: Addressing scientific, legal, social, and economic challenges; agreed timeline for implementation.	(Ben Mordechay et al., 2024)
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Policy analysis and introduction to a new research initiative; Australia	Horticulture, viticulture, aquaculture and animal industries	Not mentioned (the paper does not provide specific information on regulatory frameworks, standards, or guidelines related to AMR in vegetables)	- Regulatory gaps or inadequacies noted: Unclear use of international antibiotic residue limits in Australia. - Surveillance or monitoring limitations: Uncertainties in indicator pathogens, surveillance design, and sustainability concerns. - Data gaps or knowledge deficiencies: Complexity of E. coli ecology, need for genomic surveillance, unclear implications of international antibiotic residue limits. - Methodological limitations in risk assessment: Current risk assessment approaches challenged by AMR. - Infrastructure or resource constraints: Premise plumbing and waterborne health burdens. - Coordination challenges between stakeholders: Need for cross-sectoral approach and data governance standards. - Future research priorities recommended: Developing interventions to mitigate AMR, improving risk assessment models, enhancing data governance and IT systems.	- Proposed regulatory changes or new frameworks: Development of standards for data governance and management. - Suggested improvements to risk assessment methods: Use of quantitative microbial risk assessment approaches and novel AMR-pathogen dose-response models. - Recommended surveillance or monitoring approaches: Not explicitly mentioned for vegetables. - Proposed interventions along the food chain: Development of new targeted AMR treatments and alternatives. - Coordination mechanisms suggested: Partner-based approach and collaboration across industries and government agencies. - Precautionary measures recommended: Not explicitly mentioned for vegetables. - Implementation strategies discussed: Not explicitly mentioned for vegetables.	(Donner et al., 2024)
Review/policy analysis; Global, with specific mentions of U.K. and U.S.	Not specified	- Specific regulations, standards, or guidelines mentioned: Evaluation of similar compounds in medical and non-medical applications; global action plans involving WHO, FAO, OIE, and UNEP; incorporation of fungi into JPIAMR agenda. - Regulatory bodies or authorities responsible: WHO, FAO, OIE, UNEP; international mycology societies like ECMM, ISHAM, MSGERC, EFISG. - Scope of regulation: Pre-harvest (authorization process); post-harvest (surveillance programs). - Enforcement mechanisms described: International surveillance programs; responsibility of fungicide producers. - Regulatory gaps or absence of guidelines noted: Lack of antifungal resistance in surveillance programs. - Comparison between	- Regulatory gaps or inadequacies noted: Limited attention to fungal resistance in AMR policies. - Surveillance or monitoring limitations: Current programs do not adequately incorporate antifungal resistance. - Data gaps or knowledge deficiencies: Need for increased emphasis on antifungal resistance in research and surveillance. - Methodological limitations in risk assessment: Challenge of developing antifungal drugs due to homology of drug targets. - Infrastructure or resource constraints: Need for fungicide producers to take responsibility for safeguarding human health. - Coordination challenges between stakeholders: Need for involvement of fungicide producers in discussions on managing antifungal resistance. - Future research priorities recommended: Incorporation of antifungal resistance into surveillance programs and addressing urgent questions related to fungal AMR.	- Proposed regulatory changes or new frameworks: Evaluating the use of similar compounds in medical and non-medical applications to prevent resistance selection. - Suggested improvements to risk assessment methods: Increased emphasis on antifungal resistance in research and surveillance programs. - Recommended surveillance or monitoring approaches: Global action plans and international surveillance programs to address risk assessment strategies and monitor AMR trends. - Proposed interventions along the food chain: Prioritize One Health antifungal resistance research and policies. - Coordination mechanisms suggested: Involvement of international mycology societies and fungicide producers. - Precautionary measures	(Verweij et al., 2022)

			different jurisdictions: Not explicitly mentioned.		recommended: Fungicide producers to take responsibility for safeguarding crop protection without unintended effects for human health. - Implementation strategies discussed: Prioritize One Health antifungal resistance research and policies to curb fungal AMR globally.	
Policy analysis and review; EU	Not applicable		Not mentioned (the paper focuses on the QPS process for microorganisms in food and feed chains and does not discuss regulatory frameworks related to AMR in vegetables)	The paper identifies several gaps and limitations in the QPS process: the QPS list is not exhaustive and only triggered by application dossiers, not new scientific evidence; it does not address specific exposure issues or potential allergenic components; and there are limitations in evaluating genetically modified microorganisms and their safety implications. These highlight regulatory gaps, data gaps, and methodological limitations in risk assessment.	Not mentioned (the paper does not address AMR in vegetables or provide recommendations for addressing it)	(Allende et al., 2025)
Review; Global (US, EU, China, India, Southeast Asia, Africa, Brazil, Argentina, Colombia, Ecuador, Bolivia, New Zealand, Australia)	Fruits and vegetables	and	- Specific regulations, standards, or guidelines mentioned: European Union's national strategic plans, US national strategy, Chinese ban on colistin as a growth promoter, WHO's 5-point action plan, MRLs for antibiotics in foodstuffs. - Regulatory bodies or authorities responsible: European Union, US, Chinese government, WHO. - Scope of regulation: Pre-harvest (banning antibiotics as growth promoters), post-harvest (MRLs for foodstuffs). - Enforcement mechanisms described: Implementation of national strategies and bans. - Regulatory gaps or absence of guidelines	- Regulatory gaps: Lack of implementation of measures to control ARB transmission in developing countries. - Surveillance limitations: Challenges in detecting antibiotics in foodstuffs efficiently and accurately. - Methodological limitations: Complexity, cost, and need for skilled labour in chromatographic techniques. - Infrastructure constraints: Need for more efficient and accessible methods for detecting antibiotic residues. - Coordination challenges: Need for international coordination and regulation to address ARB. - Future research priorities: Improving detection methods, implementing biosecurity measures, conducting large-scale clinical trials for new antimicrobial agents, and further research into proteomics, meta transcriptomics, and metabolomics.	- Proposed regulatory changes or new frameworks: Implementation of comprehensive strategies, WHO's 5-point action plan, EU and US national strategies. - Suggested improvements to risk assessment methods: Use of next-generation sequencing and omics technologies. - Recommended surveillance or monitoring approaches: Implementation of biosecurity measures, use of NGS and omics technologies. - Proposed interventions along the food chain: Phasing out antimicrobials as growth promoters, ban on colistin in China. - Coordination mechanisms suggested: WHO's action plan, EU	(Okaiyeto et al., 2024)

			noted: Lack of appropriate measures in developing countries. - Comparison between different jurisdictions: Developed countries like the EU and US have implemented strategies, while developing countries lack regulations.		and US national strategies. - Precautionary measures recommended: Basic food safety measures, development of novel isolation and detection methods. - Implementation strategies discussed: Use of thermal/non-thermal processes to prevent ARB spread.	
Policy analysis; US	Not mentioned	Not mentioned (the paper does not specifically address regulatory frameworks related to AMR in vegetables)	- Regulatory gaps or inadequacies noted: Need for compiling state regulations to support reuse adoption. - Surveillance or monitoring limitations: Need for research on antimicrobial resistance in water reuse. - Data gaps or knowledge deficiencies: Need for a coordinated national research strategy; gaps in understanding antimicrobial resistance. - Methodological limitations in risk assessment: Need for a more coordinated national research strategy. - Infrastructure or resource constraints: Challenges in implementing water reuse for irrigation; need for economic analysis to support private investment. - Coordination challenges between stakeholders: Need for coordination among regulators and stakeholders. - Future research priorities recommended: Study on public benefit of federal investment tax credit; research on antimicrobial resistance.	Not mentioned (the paper does not provide specific recommendations for addressing AMR in vegetables)	(WRAP, 2024)	
Critical review; Global	Not applicable, study focuses on water matrices	- Specific regulations, standards, or guidelines mentioned: WHO and EU Global Action Plans, National Action Plan, CDC initiatives, MIQE guidelines. - Regulatory bodies or authorities responsible: WHO, EU, CDC, EPA, FDA, USDA. - Scope of regulation: Environmental monitoring in water environments. - Enforcement mechanisms described: Collaboration among agencies, standardization of qPCR methods. - Regulatory gaps or absence of guidelines noted: Need for standardization in qPCR methods. - Comparison between different jurisdictions: Not applicable as the focus is on water	- Regulatory gaps or inadequacies noted: Need for standardization in qPCR protocols. - Surveillance or monitoring limitations: Lack of detailed reporting on quality assurance aspects like LOD, LOQ, and PCR inhibition. - Data gaps or knowledge deficiencies: Limited reporting of necessary parameters in studies. - Methodological limitations in risk assessment: Variability in qPCR workflows and reporting. - Infrastructure or resource constraints: Cost and need for specialized equipment for HT-qPCR. - Coordination challenges between stakeholders: Not explicitly mentioned. - Future research priorities recommended: Standardization of qPCR workflows and reporting; exploration of new technologies like ddPCR.	- Proposed regulatory changes or new frameworks: Standardization of qPCR-based monitoring of antibiotic resistance in water environments. - Suggested improvements to risk assessment methods: Harmonization of efforts through method standardization to enable comparison across studies. - Recommended surveillance or monitoring approaches: Use of specific assays and workflows for monitoring antibiotic resistance genes. - Proposed interventions along the food chain: Not mentioned. - Coordination mechanisms suggested: Standardizing reporting measures and using an array of ARGs to ensure	(Keenum et al., 2022)	

		environments rather than vegetables.		consistency across studies. - Precautionary measures recommended: Not mentioned. - Implementation strategies discussed: Standardization and harmonization of monitoring methods.	
Framework recommendation; US with international scope	Not specified	- Specific regulations, standards, or guidelines mentioned: WHO's GLASS, ESBL-EC Tricycle Protocol, EMBARK program by JPIAMR, NARMS in the U.S. - Regulatory bodies or authorities responsible: WHO, JPIAMR, U.S. multiagency program (NARMS) - Scope of regulation: Environmental monitoring, food chain, pre-harvest and post-harvest - Enforcement mechanisms described: Not explicitly mentioned - Regulatory gaps or absence of guidelines noted: Not explicitly mentioned for vegetables - Comparison between different jurisdictions: Not directly mentioned, but international efforts like EMBARK suggest global standardization efforts	- Regulatory gaps or inadequacies noted: Lack of agreed-upon targets and standardized methods for AMR monitoring in water environments. - Surveillance or monitoring limitations: Challenges in comparing metagenomic data, semiquantitative nature of NGS data, high cost of NGS. - Data gaps or knowledge deficiencies: Need to address critical questions about ARG levels, hotspots for resistance evolution, environmental factors, and epidemiological linkages. - Methodological limitations in risk assessment: Challenges in comparing metagenomic data, semiquantitative nature of NGS data, high cost of NGS. - Infrastructure or resource constraints: Need for regulatory requirements or incentives to encourage participation in AMR monitoring. - Coordination challenges between stakeholders: Need for a standardized framework and methods to support global surveillance goals. - Future research priorities recommended: Addressing identified gaps and limitations, particularly in standardizing methods and understanding environmental factors influencing AMR.	- Proposed regulatory changes or new frameworks: Development of a framework for standardized monitoring of AMR in water environments. - Suggested improvements to risk assessment methods: Standardized methods to establish baseline environmental occurrence data. - Recommended surveillance or monitoring approaches: Aligning target and method selection with monitoring objectives using a decision tree. - Coordination mechanisms suggested: Harmonizing with ongoing international efforts. - Implementation strategies discussed: Supporting data comparability through standard operating procedures.	(Liguori et al., 2022)

Hypothetical case study within a handbook on food safety risk analysis; Low-Income Countries/Low-Middle-Income Countries	Raw tomatoes	- Specific regulations, standards, or guidelines mentioned: Amended regulations requiring validated controls for preventing contamination; guidelines for antimicrobial use in pre-harvest stages. - Regulatory bodies or authorities responsible: Not specifically mentioned. - Scope of regulation: Both pre-harvest and post-harvest stages. - Enforcement mechanisms described: Increased inspections of facilities; providing technical assistance to ensure compliance. - Regulatory gaps or absence of guidelines noted: Not mentioned. - Comparison between different jurisdictions if applicable: Not mentioned.	- Data gaps: Lack of reliable data on foodborne hazards affects confidence in risk characterization and robustness of estimates. - Surveillance or monitoring limitations: Insufficient data from published sources; reliance on high-quality unpublished data. - Methodological limitations: Complexity of microbial risk assessment requires a comprehensive approach. - Infrastructure or resource constraints: Low- and middle-income countries lack resources and expertise for detecting food hazards and assessing risks. - Coordination challenges: Institutional challenges and inadequate resources and expertise in food safety risk communication. - Future research priorities: Addressing data gaps and improving risk assessment methodologies.	- Proposed regulatory changes: Amending existing regulations to require validated controls against Salmonella contamination; developing new guidelines for antimicrobial use. - Suggested improvements to risk assessment methods: Development of risk management action plans and enhanced regulatory measures. - Recommended surveillance or monitoring approaches: Increased inspections of processing and retail facilities. - Proposed interventions along the food chain: Proper use of antimicrobials; organic fertilization; fit-for-purpose water; worker hygiene; sanitation practices. - Coordination mechanisms suggested: Targeted training and education campaigns for producers, consumers, processors, and retailers. - Precautionary measures recommended: Ensuring hand hygiene and proper sanitation practices throughout the food chain. - Implementation strategies discussed: Availing guidance documents; providing technical assistance to ensure compliance.	(FAO, 2023a)
Desk review; Worldwide, with specific examples from North America (USA, Canada), Colombia, France, Germany, and the United Kingdom.	Not specified	- Specific regulations, standards, or guidelines mentioned: Rotterdam Convention, Annex III listing requirements, national monitoring systems in Canada, Colombia, France, Germany, and the United Kingdom. - Regulatory bodies or authorities responsible: Rotterdam Convention Secretariat, Health Canada's Pest Management Regulatory Agency (PMRA), Autoridad Nacional de Licencias Ambientales (ANLA) in Colombia, French Office National de la Chasse et de la Faune Sauvage (ONCFS), Federal Office of Consumer Protection	- Regulatory gaps: Lack of monitoring systems for pesticide impacts on wildlife in many countries. - Surveillance limitations: Under-reporting of fish kills; difficulty in detecting incidents due to lack of monitoring data. - Data gaps: Extent of pesticide impacts on aquatic life; indirect effects of herbicides and fungicides. - Methodological limitations: Difficulty in identifying main causative agent due to multiple pollutants and low residue levels. - Infrastructure constraints: Need for laboratory facilities to analyze carcasses and identify pesticides. - Coordination challenges: Lack of standardization and consolidation of incident reports.	- Proposed regulatory changes: Establish national pesticide incident monitoring and reporting systems. - Suggested improvements to risk assessment methods: Emphasize post-registration monitoring of real-life environmental impacts. - Recommended surveillance or monitoring approaches: Encourage regular monitoring and evaluation of poisoning impacts on migratory species. - Proposed interventions along the food chain: Adopt better pest and pesticide management strategies. - Coordination	(FAO, 2022)

		and Food Safety in Germany, Health and Safety Executive (HSE) in the United Kingdom. - Scope of regulation: Pre-harvest and post-harvest monitoring. - Enforcement mechanisms: Incident reporting databases, environmental management plans, regulatory agencies. - Regulatory gaps or absence of guidelines noted: Lack of standardization and consolidation of incident reports. - Comparison between different jurisdictions: National regulatory frameworks vary by country, with some having more comprehensive systems than others.	- Future research priorities: Improving pest and pesticide management strategies; enhancing post-registration monitoring.	mechanisms suggested: Foster cooperation between the Rotterdam Convention Secretariat, governments, FAO, UN agencies, NGOs, and other stakeholders. - Precautionary measures recommended: Strengthen regulatory and farmer advisory systems to prevent incidents. - Implementation strategies discussed: Share information and experiences related to environmental incidents among Convention Parties.
Qualitative through-chain analysis; Australia and New Zealand	Leafy vegetables, berries, melons	The regulatory framework involves FSANZ assessing microbiological food safety risks and guiding regulatory and non-regulatory measures. Specific standards include Chapter 3 of the Code for ready-to-eat minimally processed fruits and vegetables and Standard 4.2.6 for seed sprouts. The Codex Code of Hygienic Practice provides guidelines for GAPs and GHPs. FSANZ's previous Proposal P10151 was abandoned for non-regulatory measures. The Australia and New Zealand Ministerial Forum on Food Regulation has called for reassessment of food safety risk management for certain sectors. No specific enforcement mechanisms or regulatory gaps are mentioned, nor is there a comparison between jurisdictions.	- Regulatory gaps or inadequacies noted: Limited scope excluding ready-to-eat minimally processed fruits and vegetables and seed sprouts. - Surveillance or monitoring limitations: Qualitative nature of assessment limited comparative risk estimates. - Data gaps or knowledge deficiencies: Limited data availability for berries and melons. - Methodological limitations in risk assessment: Qualitative assessment limited detailed insights. - Infrastructure or resource constraints: Not explicitly mentioned. - Coordination challenges between stakeholders: Not explicitly mentioned. - Future research priorities recommended: Need for more data to reduce uncertainty; emphasis on starting risk management on the farm.	(FSANZ, 2021) Proposed regulatory changes or new frameworks: Development of a Primary Production and Processing Standard for fresh horticultural produce. - Suggested improvements to risk assessment methods: Standards to be based on risk analysis using the best available scientific evidence. - Recommended surveillance or monitoring approaches: Not explicitly mentioned. - Proposed interventions along the food chain: Applying good agricultural practices, good hygienic practices at harvest and postharvest, controlling inputs through-chain, and using effective sanitizers. - Coordination mechanisms suggested: Not explicitly mentioned. - Precautionary measures recommended: Not explicitly mentioned. - Implementation strategies discussed: Risk management to begin on farm, consistent and well managed through-chain approach.

Empirical research; Germany	Tomatoes, melons, celery, onions, lamb's lettuce, oak leaf lettuce	- Specific regulations: EU Regulation 2020/741 sets minimum quality standards for reclaimed water used for irrigation. - Regulatory bodies: EU; Southern EU countries like Spain, Italy, Greece, and France have their own regulations. - Scope of regulation: Pre-harvest; EU regulations focus on irrigation water quality. - Enforcement mechanisms: Not explicitly described in the paper. - Regulatory gaps: EU regulations do not address antibiotic-resistant bacteria and ARGs; Germany lacks specific national guidelines. - Comparison: Southern EU countries have implemented regulations, while Germany has not.	- Regulatory gaps or inadequacies noted: EU regulations do not address emerging concerns like antibiotic-resistant bacteria and ARGs; water reuse is underutilized in Germany due to regulatory concerns. - Surveillance or monitoring limitations: Need for long-term monitoring programs to ensure safe use of reclaimed water. - Data gaps or knowledge deficiencies: Long-term impacts of ARG dissemination in agriculture; fate of ARGs in soil after repeated irrigation. - Methodological limitations in risk assessment: Need for further research on ARG persistence and accumulation in soil. - Infrastructure or resource constraints: Not explicitly mentioned. - Coordination challenges between stakeholders: Not explicitly mentioned. - Future research priorities recommended: Understanding ARG persistence and risks; strengthening regulations and monitoring programs.	- Proposed regulatory changes or new frameworks: Strengthening regulations to ensure safe water reuse. - Suggested improvements to risk assessment methods: Future research on the long-term fate of ARGs in soil. - Recommended surveillance or monitoring approaches: Implementing long-term monitoring programs. - Proposed interventions along the food chain: Scalable ozonation and UV disinfection. - Coordination mechanisms suggested: Addressing environmental factors like soil contact and handling practices. - Precautionary measures recommended: Prioritizing water quality and treatment to prevent AMR spread. - Implementation strategies discussed: Informing regulatory developments and best practices for safe water reuse.	(Hof et al., 2025)
Policy analysis; EU	Food crops consumed raw, processed food crops, non-food crops	- Specific regulations, standards, or guidelines mentioned: Council Directive 98/83/EC, Regulation (EC) No 853/2004, ISO 20426:2018, ISO 16075:2015, WHO guidelines. - Regulatory bodies or authorities responsible: European Commission, Member States. - Scope of regulation: Pre-harvest and post-harvest, focusing on agricultural irrigation with reclaimed water. - Enforcement mechanisms described: Penalties for infringements, regular evaluations. - Regulatory gaps or absence of guidelines noted: Not explicitly mentioned. - Comparison between different jurisdictions if applicable: Encourages harmonization across EU Member States.	- Regulatory gaps or inadequacies noted: Need for financial incentives and investment in upgrading urban waste water treatment plants. - Surveillance or monitoring limitations: Need for regular evaluation and review of the Regulation. - Data gaps or knowledge deficiencies: Need for ongoing research and development in extending the scope and expanding requirements. - Methodological limitations in risk assessment: Empowerment of the Commission to adapt and supplement risk management elements. - Infrastructure or resource constraints: Need for investment in treatment plants and lack of financial incentives. - Coordination challenges between stakeholders: Need for cooperation and information exchange among authorities and stakeholders. - Future research priorities recommended: Support of research and development programs like Horizon Europe and the LIFE programme.	- Proposed regulatory changes or new frameworks: The paper suggests updating the Commission's action plan to prioritize water resources and creating an enabling framework for water reuse. - Suggested improvements to risk assessment methods: The paper recommends using qualitative or semi-quantitative risk assessment and quantitative risk assessment when necessary. - Recommended surveillance or monitoring approaches: The paper suggests using international guidelines and standards for risk assessment and management. - Proposed interventions along the food chain: The paper emphasizes the need for coordination mechanisms among different actors. - Coordination mechanisms suggested: The paper recommends establishing coordination	(European Parliament and Council of the European Union, 2020)

mechanisms to ensure safe water reuse.

- Precautionary measures recommended: The paper suggests using specific preventive measures as outlined in Table 1.
- Implementation strategies discussed: The paper discusses the need for upgrading urban waste water treatment plants and financial incentives for water reuse.

Review; Low- and middle-income countries (LMICs), specifically Southeast Asia (SEA), particularly Vietnam and Thailand	Not specified	- Specific regulations: Banning of prophylactic and growth-promoting use of antimicrobials in food animals by European countries and the FDA. - Regulatory bodies: FAO, WHO, FDA, and national governments. - Scope of regulation: Primarily focuses on food animals, with some mention of industrial farms. - Enforcement mechanisms: National targets to reduce AMU in livestock. - Regulatory gaps: Lack of stringent regulations in LMICs, socio-economic and administrative challenges. - Comparison: Developed countries have stronger regulations compared to LMICs.	- Regulatory gaps or inadequacies noted: Lack of stringent regulations and monitoring in LMICs. - Surveillance or monitoring limitations: Lack of national-level surveys and strict monitoring in LMICs. - Data gaps or knowledge deficiencies: Lack of species-level consumption data for antimicrobials in LMICs; limited knowledge about AMU in aquaculture. - Methodological limitations in risk assessment: Need for more farm-level molecular epidemiological studies. - Infrastructure or resource constraints: Lack of robust infrastructural support and financial constraints. - Coordination challenges between stakeholders: Need for a holistic one health approach involving local stakeholders. - Future research priorities recommended: More studies on AMU in LMICs, surveillance systems, and molecular epidemiology to address AMR.	- Proposed regulatory changes or new frameworks: Strong government legislation to address overuse, misuse, or abuse of antimicrobials; implementation of strong regulations by drug regulatory agencies to ban prophylactic and growth-promoting use of antimicrobials in food animals. - Suggested improvements to risk assessment methods: Not explicitly mentioned. - Recommended surveillance or monitoring approaches: Surveillance on AMR pathogens and AMU as a key driving force for controlling AMR. - Proposed interventions along the food chain: Reducing meat consumption; capping the amount of antimicrobials per year per kilogram of animal product; making antibiotics expensive by taxation; labelling meat from antibiotic-treated animals. - Coordination mechanisms suggested: A holistic one health approach incorporating local stakeholders. - Precautionary measures recommended: Raising awareness among farmers to adopt good hygienic farm	(Samanta & Bandyopadhyay, 2020)
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operations.
 - Implementation strategies discussed: Alternative anti-infective strategies; making meat from antibiotic-treated animals more expensive.

Framework development; conceptual and policy-oriented; EU	Not specified	The regulatory frameworks mentioned in the paper include EU Regulation (EU) 2020/741 on Minimum requirements for water reuse and Regulation (EU) No. 2019/1009 on EU Fertilising products. The paper notes regulatory gaps, such as the absence of specific regulations for certain products and reuse scenarios, and the lack of an EU legislative framework for renewable raw materials and bio-based, biodegradable, and compostable plastics. The proposed framework aims to bridge these gaps by leveraging existing regulations to ensure comprehensive oversight across unregulated scenarios. The framework is structured around three pillars: product quality, public health, and environmental protection.	- Regulatory gaps or inadequacies noted: Absence of regulations for specific products and reuse scenarios; lack of EU legislative frameworks for renewable raw materials and bio-based plastics. - Surveillance or monitoring limitations: Focus on single chemical contaminants; limitations in assessing chemical mixtures and pathogens without dose-response models. - Data gaps or knowledge deficiencies: Need for comprehensive data on chemical accumulation and incremental buildup in environmental compartments. - Methodological limitations in risk assessment: Inability to address broader issues of circularity, governance, and business models; need for probabilistic risk assessments. - Infrastructure or resource constraints: Need for cross-sector collaboration to secure market uptake; limitations in data collection. - Coordination challenges between stakeholders: Need for governance, regulation, and policy integration. - Future research priorities recommended: Integration of existing regulations; devising strategies for cleaner production and sustainable business practices; fostering cross-sector collaboration.	Not mentioned (the paper does not specifically address AMR in vegetables or provide recommendations related to it)	(Ardiyanti et al., 2024)
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Table 5: Summary of risk-assessment approaches applied to antimicrobial resistance in vegetable and fresh produce systems

Risk Assessment Type	Risk Assessment Components Addressed	Application Context	Reference to International Frameworks	References
Quantitative/QMRA risk-assessment approach	Hazard identification (AMR hazards), Exposure assessment (consumer exposure, food production chain), Risk characterization (scenario models, probability estimates)	The study applies risk assessment to food consumption, specifically through contamination at the slaughterhouse and during food preparation, with a focus on cross-contamination of vegetables.	The paper references the World Health Organization (WHO) and the Organization for Economic Co-operation and Development (OCDE) as international frameworks related to antimicrobial resistance. It does not explicitly mention other frameworks like Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or specific surveillance systems.	(Costa et al., 2022)
Qualitative	- Hazard Identification: AMR hazards, ARGs, resistant bacteria - Exposure Assessment: Environmental contamination (e.g., wastewater reuse, agricultural practices), consumer exposure (raw vegetable consumption) - Risk Characterization: Public health impact, increased morbidity and mortality rates	The study applies risk assessment to vegetables, fresh produce	Not mentioned (the paper does not reference any international frameworks for AMR or food safety)	(Castello et al., 2025)
Quantitative/QMRA risk-assessment approach	- Hazard identification: <i>L. monocytogenes</i> - Exposure assessment: Irrigation water, agricultural soil - Risk characterization: Probability estimates, scenario models	The study applies risk assessment to irrigation water, agricultural soil	Codex Alimentarius Commission (CAC)	(Iwu et al., 2022)
Qualitative risk assessment	Hazard identification (e.g., AMR hazards, ARGs, resistant bacteria, AMR proxies), Risk characterization (e.g., probability estimates, severity, scenario models)	The study applies risk assessment to fresh produce (specifically seven types of raw vegetables), soil, and irrigation water.	The study references national frameworks such as EARSS, MARAN, and Nethmap, and mentions the use of Quantitative Microbial Risk Assessment (QMRA) as a risk assessment tool. There is no direct reference to international frameworks like Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or other specific governance frameworks for AMR or food safety.	(Blaak et al., 2014)
Quantitative/QMRA risk-assessment approach	- Hazard identification: ESBL-and AmpC-producing Enterobacteriaceae on retail vegetables - Exposure assessment: Prevalence of these bacteria on different types of vegetables, raw consumption - Risk characterization: Public health implications, risk of disease and colonization, use of QMRA	The study applies risk assessment to vegetables, fresh produce	Not mentioned (the paper does not reference any specific international frameworks such as Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or other structured surveillance systems)	(van Hoek et al., 2015)
Quantitative/QMRA risk-assessment approach	Hazard identification (e.g., AMR hazards, ARGs, resistant bacteria, AMR proxies), Exposure assessment (e.g., irrigation water, soil, processing environments, consumer exposure), Risk characterization (e.g., probability estimates, severity, scenario models)	The study applies risk assessment to vegetables/fresh produce and irrigation water.	EU Regulation 2020/741	(Ho et al., 2025)

Quantitative/QMRA risk-assessment approach	- Hazard identification: Presence of antibiotic-resistant bacteria and ARGs in vegetables. - Exposure assessment: Estimation of human exposure to ABs and ARGs through vegetable consumption. - Risk characterization: Calculation of hazard quotients (HQ) and hazard indices (HI) to assess risk.	The study applies risk assessment to vegetables grown in soil amended with sewage sludge, focusing on the consumption of these vegetables as a pathway for human exposure to antibiotics and antibiotic resistance genes.	The study references the Joint FAO/WHO Expert Committee on Food Additives (JECFA) and the European Agency for the Evaluation of Medicinal Products (EMA) as sources for acceptable daily intake (ADI) values.	(Patra & Dubey, 2024)
Semi-quantitative (the study uses both qualitative and quantitative methods to assess the distribution and antibiotic resistance of <i>Enterococcus</i> spp., but does not conduct a comprehensive QMRA)	Hazard identification, Exposure assessment, Risk characterization	The study applies risk assessment to fresh produce (tomatoes), irrigation water, and soil on U.S. Mid-Atlantic farms.	The study references Good Agricultural Practices (GAPs) guidelines in the U.S. as recommended by the FDA and CFSA in 1998.	(Micallef et al., 2013)
Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards (resistance to ampicillin), resistant bacteria (<i>L. monocytogenes</i> with virulence genes <i>hlyA</i>, <i>prfA</i>, and <i>inlA</i>) - Exposure assessment: Prevalence in dairy, vegetable, and meat products - Risk characterization: Potential public health threat, need for improved food safety regulations and practices	The study applies risk assessment to vegetables (lettuce, celery), fresh produce (lettuce, celery), dairy products (traditional semi-hard cheese), meat products, irrigation water, soil, food processing environments (cross-contamination during transportation and retail handling), agricultural practices (faulty silage, unclean processing water, manual handling)	The study references the U.S. Food and Drug Administration's zero-tolerance policy for bacteria in food, which is an international framework related to food safety. It also suggests a broader reference to enhancing local food safety surveillance systems and contributing to global epidemiological characterization, which aligns with international frameworks for food safety and surveillance.	(Salih & Mohammed, 2025)
Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards, ARGs, resistant bacteria - Exposure assessment: Soil (sludge addition) - Risk characterization: Probability estimates (risk index), severity (increased risk with sludge addition)	The study applies risk assessment to vegetables (tomatoes), organic amendments (sewage sludge)	Not mentioned (the paper does not reference any specific international frameworks or structured surveillance systems for AMR or food safety)	(Li et al., 2024)
Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards (antimicrobial resistance genes and phenotypes), resistant bacteria (<i>Salmonella</i> isolates) - Exposure assessment: Consumer exposure (exposure through consumption of salad vegetables) - Risk characterization: Probability estimates (beta-Poisson dose-response model), scenario models (estimation of annual cases)	The study applies risk assessment to vegetables	- Clinical and Laboratory Standards Institute (CLSI) for antimicrobial susceptibility testing - WHO/FAO risk-assessment guidance for beta-Poisson dose-response formula	(Habib et al., 2023)
Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards, promotion of antimicrobial resistance - Exposure assessment: Soil fertilized with pig slurry - Risk characterization: Probability estimates (hazard quotient), severity (acceptable daily intake levels), scenario models (indirect threat to human health)	The study applies risk assessment to vegetables (lettuce) and organic amendments (pig slurry).	The study references EU regulations for Maximum Residue Limits (MRLs) in foodstuffs and uses the Hazard Quotient (HQ) and Acceptable Daily Intake (ADI) approach, which are part of international risk assessment frameworks. It does not explicitly mention other international frameworks like Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS,	(Matamoros et al., 2022)

EMBARK, or specific FDA or EPA guidelines.

Quantitative	- Hazard identification: Antimicrobial-resistant <i>E. coli</i> (MDR <i>E. coli</i>) - Exposure assessment: Irrigation water, post-harvest washing practices - Risk characterization: Potential for increasing antimicrobial resistance in humans, need for sanitation measures	The study applies risk assessment to fresh produce, irrigation water, and food processing environments along the supply chain from farms to restaurants in Lebanon.	Clinical and Laboratory Standards Institute's guidelines for antimicrobial susceptibility testing	(Faour-Klingbeil et al., 2016)
Qualitative	- Hazard identification (e.g., AMR hazards, ARGs, resistant bacteria, AMR proxies) - Exposure assessment (e.g., irrigation water, soil) - Risk characterization (e.g., probability estimates, severity, scenario models) - partially addressed due to lack of dose-response data and treatment failure estimates	The study applies risk assessment to vegetables, fresh produce, irrigation water, soil, organic amendments (manure fertilization)	FAO definition of quantitative risk assessment; FAO data on irrigation water usage	(Hölzel et al., 2018)
Qualitative with some quantitative elements (QMRA mentioned but not primary focus)	- Hazard identification: AMR hazards, ARGs, resistant bacteria - Exposure assessment: irrigation water, soil, processing environments, consumer exposure - Risk characterization: biological plausibility of AMR exposure risks	The study applies risk assessment to vegetables, fresh produce (salad crops, culinary herbs, fruit), irrigation water, soil, organic amendments (manure fertilizer, food processing environments)	- Codex Alimentarius Guidelines - FAO/WHO risk-assessment guidance - Global Antimicrobial Resistance Surveillance System (GLASS) - International Plant Protection Convention (IPPC)	(Brunn, Kadri-Alabi, et al., 2022)
Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards, ARGs, resistant bacteria, AMR proxies - Exposure assessment: irrigation water, soil, processing environments, consumer exposure - Risk characterization: probability estimates, severity, scenario models	The study applies risk assessment to vegetables, soil, organic amendments, and irrigation water. It evaluates the microbial safety and antibiotic resistance risks associated with large-scale open-air composting and composting toilet systems in a sustainable ecological farm setting.	- WHO recognition of antibiotic resistance as a major global public health threat - WHO's global priority list of antibiotic-resistant bacteria - European Union's Regulation (EU) 2019/6 - Standards for compost sanitization and biosolids treatment	(Liu et al., 2021)
Qualitative	- Hazard identification: AMR hazards, ARGs, resistant bacteria - Exposure assessment: irrigation water, soil, consumer exposure - Risk characterization: probability estimates, scenario models	The study applies risk assessment to soil, vegetables (soil-grown), organic amendments (manure), irrigation water, food chain (including vegetables and potentially other fresh produce)	One Health perspective	(Wang et al., 2021)

Quantitative/Q MRA risk- assessment approach	Hazard identification (AMR hazards, resistant bacteria, virulence markers); Exposure assessment (consumer exposure, geographical differences); Risk characterization (prevalence data, probability estimates, severity of infection)	The study applies risk assessment to retail raw foods including vegetables, edible mushrooms, raw meat, aquatic products, and quick-frozen products.	The study references the US zero-tolerance policy and the EU's limit of 100 cfu/g for <i>L. monocytogenes</i> as international frameworks related to food safety. It does not specifically mention Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or other structured surveillance systems.	(Wu et al., 2015)
Qualitative	- Hazard identification: AMR hazards, ARGs, resistant bacteria - Exposure assessment: Human activities leading to contamination - Risk characterization: Potential risk of human and animal exposure to antibiotic-resistant bacteria and genes	The study applies risk assessment to vegetables	Not mentioned (the paper does not explicitly reference any specific international governance frameworks for AMR or food safety)	(Rieux et al., 2025)
Semi- quantitative	- Hazard identification: The study identifies a diverse range of antimicrobial resistance genes (ARGs) in ready-to-eat (RTE) foods. - Exposure assessment: The study estimates the incidence of ARGs in average UK diets.	The study applies to risk assessment of ready-to-eat foods, specifically focusing on fresh produce, dairy products, and cooked meats. It does not explicitly assess risk in irrigation water, soil, organic amendments, or food processing environments.	Not mentioned (the paper does not reference any international frameworks or guidelines for AMR or food safety)	(Haynes et al., 2025)
Quantitative/Q MRA risk- assessment approach	- Hazard identification: AMR hazards (tetracyclines uptake by vegetables) - Exposure assessment: Irrigation water (synthetic wastewater spiked with tetracyclines) - Risk characterization: Ecological risk quotient (RQ), human health risk quotient (HQ), risk for antimicrobial resistance (RQ _{resistance}), estimated daily intake (EDI), acceptable daily intake (ADI)	The study applies risk assessment to vegetables, fresh produce, irrigation water, soil	- WHO (1997) for hazard quotient and EDI ratio approach - USDA (2019) for hazard quotient and EDI ratio approach - European Commission (2003) for risk quotient categorization - EUCAST for PNEC for resistance	(Gudda et al., 2023)
Quantitative/Q MRA	- Hazard identification: AMR hazards (antibiotic-resistant bacteria) - Exposure assessment: irrigation water, soil - Risk characterization: probability estimates, scenario models	The study applies risk assessment to vegetables irrigated with wastewater and accidental ingestion of contaminated wastewater and soil.	The study references the World Health Organization (WHO) guidelines for acceptable risk probability, specifically mentioning that the health risks found in the study exceed the WHO's maximum threshold. It does not explicitly reference any other international frameworks like Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or structured surveillance systems like NARMS or EFSA/ECDC monitoring.	(Cangola et al., 2025)
Quantitative/Q MRA risk- assessment approach	- Hazard identification: AMR hazards, antimicrobial resistance risks - Exposure assessment: Soil - Risk characterization: Probability estimates (RQ), scenario models (Σ RQ)	The study applies risk assessment to vegetable soils	Not mentioned (the paper does not explicitly reference any international frameworks like Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or other structured surveillance systems)	(Fang et al., 2023)

Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards (resistance to tetracycline and third-generation cephalosporins in Enterobacteriaceae isolated from food crops) - Exposure assessment: Contaminated inputs (manure, irrigation water, crop treatments), cross-contamination during processing - Risk characterization: Prevalence estimates and confidence intervals for AMR presence in food crops, implications for consumer and occupational exposure	The study applies risk assessment to food crops, specifically focusing on pre-harvest and post-harvest stages of the value chain, and considers contaminated inputs such as manure and irrigation water.	GLASS (WHO Global Antimicrobial Resistance Surveillance System)	(Brunn, Roustit, et al., 2022)
Quantitative	Hazard identification (antibiotic-resistant bacteria); Exposure assessment (consumer exposure through raw consumption); Risk characterization (discussion on potential spread and inefficiency of sanitizing methods)	The study applies risk assessment to fresh produce (vegetables).	Not mentioned (the paper does not explicitly reference any international frameworks such as Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or other structured surveillance systems)	(Rico & Falomir, 2020)
Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards, ARGs, resistant bacteria - Exposure assessment: soil, processing environments (lettuce), consumer exposure (snail) - Risk characterization: probability estimates (spread of ARGs), severity (impact on human health)	The study applies risk assessment to vegetables (lettuce), soil, and organic amendments (manure) in the context of a soil-lettuce-snail food chain.	Not mentioned (the paper does not explicitly reference any international frameworks such as Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or other governance frameworks for AMR or food safety)	(Zhang et al., 2024)
Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards, ARGs, resistant bacteria - Exposure assessment: Irrigation water, soil, processing environments, consumer exposure - Risk characterization: Probability estimates, severity, scenario models	The study applies risk assessment to fresh-cut fruits and vegetables, focusing on the entire production pathway from seed to consumption.	The study references FAO/WHO risk-assessment guidance (2008) and mentions the implementation of GAP, GMP, and HACCP systems. No explicit references to other international frameworks like Codex CAC/GL 30-1999, GLASS, EMBARK, or specific FDA or EPA guidelines are provided.	(Bai et al., 2024)
Quantitative/QMRA	Hazard identification (beta-lactamase-producing <i>E. coli</i>), Exposure assessment (manure, soil, vegetables, consumer exposure), Risk characterization (probability estimates, scenario models)	The study applies risk assessment to vegetables	The study references the World Organisation for Animal Health (WOAH) risk assessment framework.	(Makita et al., 2024)
Quantitative/QMRA risk-assessment approach	- Hazard identification: The study identifies antibiotic resistance genes (ARGs) and their distribution across different pre-harvest control points. - Exposure assessment: The study assesses the exposure of ARGs through different agricultural management practices. - Risk characterization: The study characterizes the risk by evaluating the relative abundance and diversity of ARGs in different samples, indicating the potential for ARGs to spread through the food chain.	The study applies risk assessment to vegetables (lettuce), soil, and organic amendments.	- WHO encouragement for holistic action plans (WHO, 2017) - European Commission's ban on antibiotics as growth promoters (European Commission, 2005) - Veterinary Feed Directive (FDA, 2013, 2017, 2018) - FDA Food Safety and Modernization Act (FSMA) recommendations for composting manure (FDA, 2015)	(Wind et al., 2021)

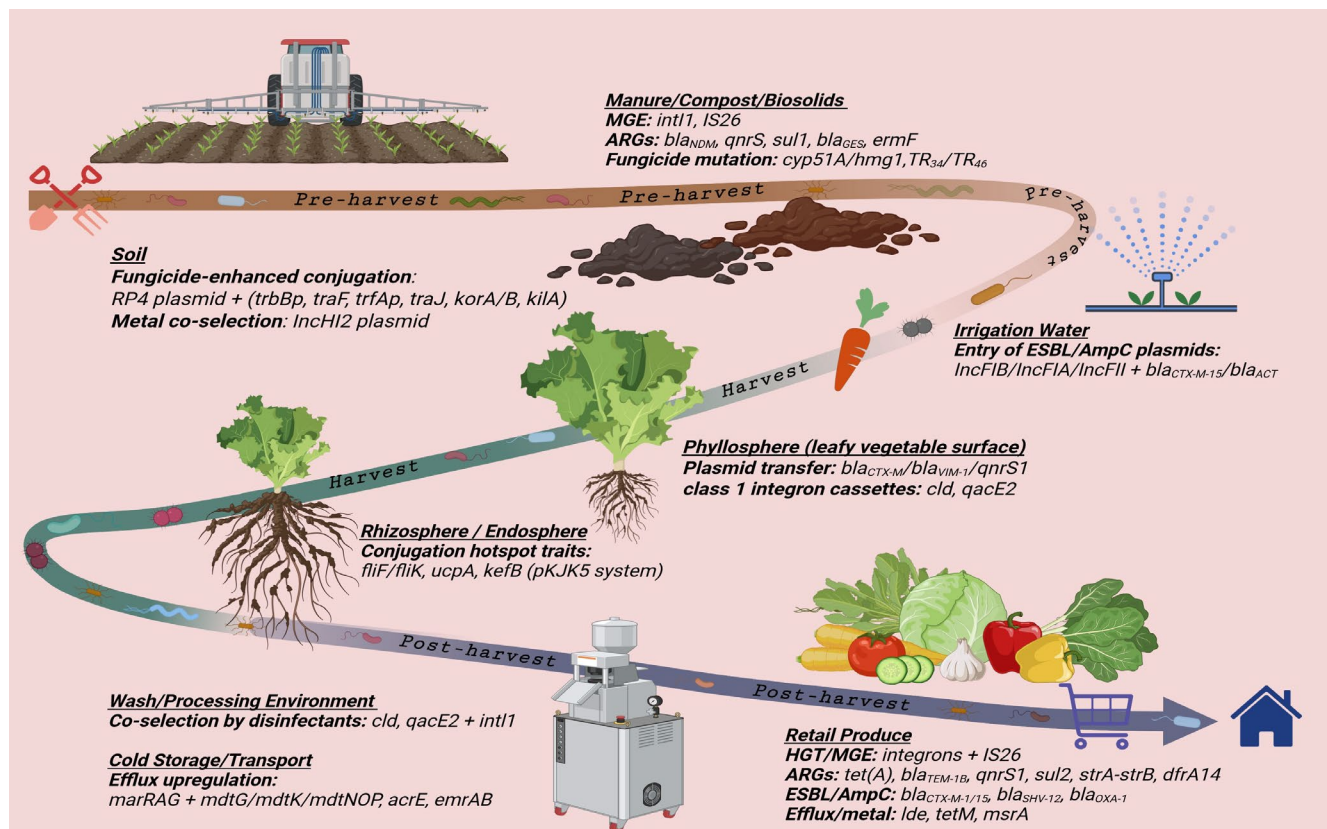
Quantitative/QMRA	- Hazard identification: AMR hazards, ARGs, resistant bacteria - Exposure assessment: irrigation water, soil - Risk characterization: potential for public health risk	The study applies risk assessment to fresh produce (lettuce), specifically focusing on the rhizosphere and phyllosphere, as well as soil and organic amendments (treated wastewater irrigation and poultry litter amendment), and considers postharvest processing environments.	The study references the "One Health" concept and discusses improving quantitative microbial risk assessment (QMRA) models but does not explicitly mention specific international governance frameworks like Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or other structured surveillance systems.	(Davidovich et al., 2025)
Qualitative	- Hazard Identification: AMR hazards, resistant bacteria - Exposure Assessment: irrigation water, soil, processing environments - Risk Characterization: Not explicitly addressed (no probability estimates or scenario models provided)	The study applies risk assessment to irrigation water and fresh produce (spinach) throughout the supply chain from farm to retail, focusing on the microbiological quality and presence of foodborne pathogens like Escherichia coli.	- World Health Organisation (WHO) recommendation of <1000 CFU faecal coliforms.100 ml⁻¹ in irrigation water used for minimally processed fresh produce. - European Union (EU) limit of 100 E. coli.100ml⁻¹ in irrigation water used for fresh fruit and vegetables. - Canadian standards' acceptable limit of <100 E. coli.100 ml⁻¹ for irrigation water used for produce to be consumed raw. - U.S. Food Safety Modernisation Act (FSMA) guidelines for water microbiological quality standards. - International guidelines for E. coli levels in pre-wash and final wash water. - EU guidelines for E. coli limits on RTE pre-cut fruit and vegetables.	(Richter et al., 2022)
Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards, ARGs, resistant bacteria, AMR proxies - Exposure assessment: Irrigation water, soil, processing environments, consumer exposure - Risk characterization: Probability estimates, severity, scenario models	The study applies risk assessment to agricultural settings like farms and abattoirs, horticulture, irrigation water, soil, and possibly organic amendments. It also considers the role of these environments in the development and dissemination of AMR.	- WHO Global Antimicrobial Resistance and Use Surveillance System (GLASS) - WHO frameworks for assessing environmental contaminants - USEPA frameworks for assessing environmental contaminants	(Makumbi et al., 2024)
Quantitative/QMRA risk-assessment approach	- Hazard identification: AMR hazards, ARGs, resistant bacteria - Exposure assessment: irrigation water, soil - Risk characterization: probability estimates, severity, scenario models	The study applies risk assessment to vegetables (lettuce as a model for vegetables eaten raw), irrigation water (reuse of treated wastewater), and soil (rhizosphere microbiome).	The study references the One Health context, which is an international framework. It does not explicitly mention specific international governance frameworks like Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or other structured surveillance systems like NARMS or EFSA/ECDC monitoring.	(Riva et al., 2024)
Quantitative/QMRA	- Hazard identification: AMR hazards, resistant bacteria - Exposure assessment: irrigation water, soil, processing environments, consumer exposure - Risk characterization: probability estimates, scenario models	The study applies risk assessment to vegetables, fresh produce, irrigation water, soil, and organic amendments (manure).	The paper references the World Health Organization (WHO) and its global report on surveillance of antimicrobial resistance, indicating a connection to international frameworks. It also mentions the use of Quantitative Microbial Risk Assessment (QMRA) and microbial source tracking, which could be aligned with international risk assessment guidelines. However, specific frameworks like Codex CAC/GL 30-1999, FAO/WHO risk-assessment guidance, GLASS, EMBARK, or other structured	(Huijbers et al., 2015)

surveillance systems are not explicitly mentioned.

Quantitative/Q MRA	- Hazard identification: AMR hazards (antibiotic-resistant <i>E. coli</i>) - Exposure assessment: irrigation water, consumer exposure - Risk characterization: probability estimates, scenario models	The study applies risk assessment to vegetables (lettuce), irrigation water	EC No 1441/2007 regulation; WHO guidelines for irrigation water quality	(O'Flaherty et al., 2019)
Quantitative/Q MRA risk- assessment approach	- Hazard identification: AMR hazards, resistant bacteria (STEC and AMR <i>E. coli</i>) - Exposure assessment: irrigation water, soil, raw chicken manure, insects - Risk characterization: probability estimates (transmission dynamics), severity (presence of AMR genes and MDR <i>E. coli</i>)	The study applies risk assessment to fresh produce, raw and composted manure, soil, and insects in sustainable farming environments.	- NARMS (National Antimicrobial Resistance Monitoring System) - WHO and FDA guidelines on antibiotic use in livestock - USDA National Organic Program (NOP) guidelines on manure application	(Glaize et al., 2020)

Figure 1: Farm-to-fork pathways contributing to the emergence and dissemination of antimicrobial resistance (AMR) in vegetable production systems.

AMR can be introduced and maintained along the vegetable supply chain through multiple environmental reservoirs and transmission stages. Pre-harvest sources include soil, manure/compost/biosolids, and irrigation water, which may introduce antimicrobial resistance genes (ARGs), mobile genetic elements (MGEs) such as *int11* and *IS26*, and resistant bacteria. Co-selection pressures from metals, fungicides, and other agricultural chemicals can enhance plasmid-mediated horizontal gene transfer (HGT) in soil, rhizosphere, and phyllosphere microbiomes. Harvest and handling may facilitate cross-contamination through plant surfaces and contact during cutting and handling. Post-harvest environments, including wash water and processing facilities, may promote persistence or co-selection through disinfectant exposure (e.g., integron-associated *cld* and *qacE2*). Cold storage and transport can favour survival through stress responses and efflux systems. Retail produce may therefore carry ARGs and resistance determinants (e.g., *bla*, *qnr*, *tet*, *sul*, *dfr*) associated with plasmids, integrons, and insertion sequences. Gene markers shown illustrate representative mechanisms reported across studies rather than universal occurrence.



Appendix 2B

Deliverable 2.2: Review of Data Systems and Data Governance Standards Across the Australian Vegetable Production Supply Chain

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1. Introduction

Data governance can variously be described as ‘the data management discipline that focuses on the quality, security and availability of an organization’s data’ (Holdsworth & Kosinski 2025), ‘the process of managing the availability, usability, integrity and security of the data in enterprise systems, based on internal standards and policies that also control data usage’ (Stedman 2024), or ‘the documented structures and activities...that provide confidence and control in managing the data created in...systems and processes, as well as the insights that come from the data, over the life of the data’ (Australian Government 2025). Data governance aims to ensure data is consistent, trustworthy and secure by defining and implementing policies, standards and procedures for data collection, ownership, storage, processing, and use within a business enterprise. Robust data governance ensures traceability and provides analytics which can assist in optimising operations and drive business decision-making.

There are a number of quality assurance programs available to producers and packers of vegetables in Australia, all of which impose a significant burden in terms of data governance on those seeking to comply with the schemes. These quality assurance programs require the development of operational procedures and protocols, ongoing review of these standards in the pursuit of continuous improvement and subjecting the business to internal and external audits. The overarching program with which businesses must comply is the Food Standards Code for Australia and New Zealand (FSANZ) which is a set of legislated standards applicable to vegetable producers, packers, processors, and sellers. FSANZ is complemented by a number of on- and off-farm food safety and quality certifications, the grocery retailer post-farm certification scheme (HARPS), and several on- and off-farm ethical and social compliance certifications. Each of these schemes is discussed herein in terms of data governance requirements placed on vegetable production and packing businesses to achieve and maintain certification and to continue to operate. Table 1 shows the certification required by small producers, packers, small growers who pack their own produce, and large grower-packers; grower-packers can pack product for other farmers or contactors as well as their own produce.

Table 1. Certification required by scale and nature of vegetable producing enterprise (source: AUSVEG 2025, p. 12).

	Small producer		Packer	Small grower-packer	Large grower-packer
Target market channels	Wholesale & local/ farmer market	Wholesale & local/ farmer market; packers	Supermarkets	Supermarkets & wholesale markets	Supermarkets
On-farm food quality and safety		YES		YES	YES
Post-farm food safety and quality			YES	YES	YES
Post-farm grocery retailer-led			YES	YES	YES

certification				
Ethical and social certification	Generally, YES (various assessments)	YES (some online assessment)	YES (some in-person audit)	YES (generally in-person audit)

In September 2025 AUSVEG released a report entitled ‘Horticulture compliance and regulation: reducing the burden by 2030’ (AUSVEG 2025). The report is based on a review of 17 vegetable producing enterprises conducted by Corporate Value Associates Australia (CVA) and provides an excellent and comprehensive review of the regulatory systems with which Australian vegetable growers must comply to maintain market access.

The compliance burden on vegetable producing enterprises is complex and evolving and has grown over recent years; much of the burden falls to individual producers (AUSVEG 2025, p. 9). Based on a value chain analysis (Fig. 1) CVA identified 48 separate areas across the value chain with which Australian vegetable producers must comply (Fig. 2).

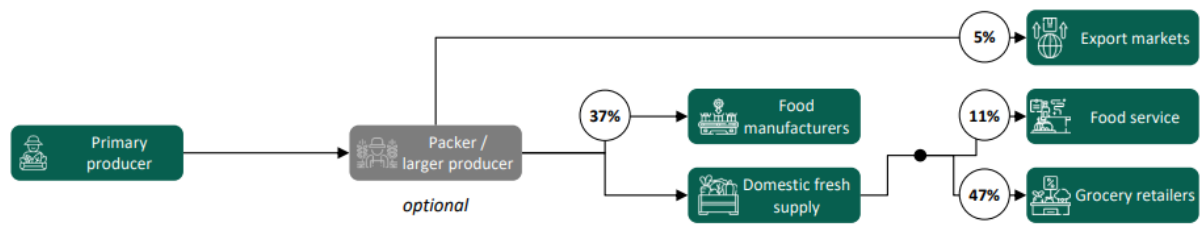


Figure 1. Australian vegetable industry supply chain and production flow; percentages indicate what proportion of produce flows to which end consumer interface; a significant amount of the 37% of produce which goes to food manufacturers flows through to grocery retailers and food service outlets (source: AUSVEG 2025).

Vegetable producers often need to obtain multiple, sometimes overlapping, certifications to maintain market access (AUSVEG 2025, p. 11). Compliance requires undertaking such diverse activities as obtaining relevant certifications, staff training, keeping spray diaries, and submitting to regular audits by a range of stakeholders, including governments (Federal, State, and local), supply chain partners, and utility suppliers.

Key areas of compliance ¹		Others ¹						
Key compliance areas	Value Chain							
	Inputs	Labour	On-farm processes	Outputs	Transportation	Export	Asset planning	Others
	Water (e.g., licenses, testing)	International workforce	Food safety and quality assurance certification	Post-harvest treatment	Chain of responsibility	Export certification	Business registration and structuring	Income tax (e.g., accounting)
	Pesticides and ag-chemical (storage, handling, records)	Accommodation for Workers on PALM scheme	Organic (standards, inputs, certification)	Post-harvest testing	Cold chain	Export logistics	Foreign investment	Insurance
	Pesticides and ag-chemical (application, testing, records)	Industrial relations	Protective farming	Weights and measures	Transportation restrictions		Land purchase	Payroll tax
	Fertiliser and soil additives (storage, handling, records)	Labour hire	Biosecurity	Packaging			Land transfer	Workers' compensation insurance
	Fertiliser and soil additives (application, testing, records)	Training	River health and waste water management	Food labelling			Land use and zoning	
	Equipment	Workplace health and safety	Waste disposal and recycling	Traceability			Biodiversity	
	Weapons and dangerous tools	Ethical and social certification	EPA	Sustainability reporting			Building approvals	
			Emergency plan, response and recovery				Site access	
		Use of tech				Access to utilities		

Figure 2. Map of compliance areas across the vegetable growing businesses value chain; ¹Key areas of compliance reflect the frequency of occurrence for each area and associated compliance activities undertaken by vegetable growers/packers; (source: AUSVEG 2025, p. 5).

The main certification schemes encompass food safety, food quality, and compliance with ethical and social norms. They can be classified as either government regulations (e.g., FSANZ), on-farm and off-farm food safety and quality certifications (e.g., BRCGS, Freshcare, Global GAP, SQF), retailer-driven post-farm certifications (e.g., HARPS), and on-farm and post-farm ethical and social certifications such as Fair Farms and Sedex (AUSVEG 2025, p.11). It should be noted that the CVA analysis does not consider in detail certification or registration requirements for inputs to the field growing phase of the production process such as composts and other soil amendments, agricultural chemicals, fertilisers, and seeds, or inputs to the packing and processing stages of the value chain such as sanitisers, disinfectants, and products designed to prolong shelf life. A number of the on-farm and off-farm certification schemes address these issues. Table 2 summarises the main compliance schemes for vegetable producers.

Table 2. Key industry certification schemes for vegetable producers (source: AUSVEG 2025, p. 11).

Focal area			
Food safety	Food Standards Australia and New Zealand: Standard 2.3.1 Fruit and vegetables; Standard 3.2.1 Food safety programs. Enforced by state governments	Mandatory requirements for all food sold in Australia and New Zealand to ensure safety, quality, and accurate labelling (https://www.foodstandards.gov.au/).	
	PPP standard for leafy vegetables; State government Primary Production and Processing Standard for Leafy Vegetables	All schemes require processes and procedures to be documented and annual audits; specified documents must be retained in written or form, including audit reports and responses thereto.	
On-farm and post-farm		BRCGS	

food safety and quality standards	Freshcare
	Global GAP
	SQF
Post-farm, grocery retailer certification	HARPS
On-farm and post-farm ethical and social certifications	Fair Farms Sedex

2. Quality assurance schemes for vegetable producers and packers

2.1 FSANZ - Government legislated food safety code

The Food Standards Code for Australia and New Zealand (the Code; FSANZ 2025; <https://www.foodstandards.gov.au/>) is comprised of a set of legislated Standards and is the reference document which Australian vegetable growers, packers, processors, and sellers must comply with. The Code applies to food that is sold, processed or handled for sale in Australia, or imported into Australia. Sections of the Code also apply to New Zealand. The FSANZ Standards which are applicable to vegetable production are summarised in Table 3.

Table 3. Standards under the Food Standards Code for Australia and New Zealand applicable to the production of vegetables in Australia (source: The Food Standards Code for Australia and New Zealand; <https://www.foodstandards.gov.au/>)

Standard Number	Comments
Standard 3.1.1 - Interpretation and Application	This Standard sets out the interpretation and application provisions that apply to the other food safety standards the objective of which is to ensure that only safe and suitable food is sold in Australia. The Standard also provides relevant definitions, including the definition of what comprises ‘safe and suitable food’ and ‘primary food production’, and of what comprises a ‘food business’, a ‘food handling operation’, a ‘food handler’, ‘handling of food’ and ‘food premises’ (see Glossary).
Standard 3.2.1 - Food safety programs	This Standard applies to food businesses in Australia and enables States and Territories to require food businesses to implement a food safety program based on HACCP (Hazard Analysis and Critical Control Point) concepts. The Standard requires that food safety programs are implemented and reviewed by food businesses and are subject to periodic audit by a suitably qualified food safety auditor.
Standard 3.2.2 - Food safety practices and general requirements	This Standard sets out specific requirements for food businesses and food handlers. It specifies process control requirements to be satisfied at each step of the food handling process, some of which relate to the receipt, storage, processing, display, packaging, distribution disposal and recall of food. Other requirements relate to the skills and knowledge of food handlers and their supervisors, the health and hygiene of food handlers, and the cleaning, sanitising, and maintenance of premises and equipment.
Standard 3.2.3 - Food Premises and Equipment	The objective of this Standard is to ensure that, where possible, the layout of the premises minimises opportunities for food contamination. Food businesses are required to ensure that their food premises, fixtures, fittings, equipment and transport vehicles are designed and constructed to be cleaned and, where

	necessary, sanitised. Businesses must ensure that the premises are provided with the necessary services of water, waste disposal, light, ventilation, cleaning and personal hygiene facilities, storage space and access to toilets. Food businesses that operate from a farm, vineyard, orchard or aquaculture facility are referred to the definition of 'food business' in Standard 3.1.1 to determine if they must comply with this Standard. If they are involved in the substantial transformation of food or the sale or service of food directly to the public then they must comply with this Standard.
Standard 4.1.1 - Primary production and processing standards – preliminary provisions	This Standard sets out provisions which apply to the Primary Production and Processing Standards of the Code. Where the Code provides that a person or business is required to comply with the general food safety management requirements, that person or business must – (a) have a food safety management statement; and (b) operate according to its food safety management statement. A person or business required to comply with the food safety management requirements must also – (a) systematically examine its operations to identify potential hazards and implement control measures to address those hazards; and (b) have evidence to show that a systematic examination has been undertaken and that control measures for those identified hazards have been implemented; and (c) verify the effectiveness of the control measures.
Standard 4.2.8 - Primary Production and Processing Standard for Leafy Vegetables	This Standard requires primary horticulture producers and primary horticulture processors in Australia to comply with the general food safety management requirements stated in Division 2 of Standard 4.1.1 in the production of leafy vegetables. It does not apply to the retail sale of leafy vegetables and does not apply to manufacturing of harvested leafy vegetables which includes the cooking, freezing, drying, preserving, blending or juicing of harvested leafy vegetables or the addition of other foods to harvested leafy vegetables. The Standard itemises the responsibility of producers and processors to ensure traceability of produce, the suitability of inputs such as seed, seedlings, soil, fertiliser, water, and growing sites, management of adverse weather events, premises, equipment, and harvest temperatures, washing and sanitisation of harvested produce, and minimising the presence of pest animals and vermin throughout the production chain in order to ensure that leafy vegetables are not made unacceptable. Under the Standard producers and processors are also required to ensure that persons who engage in relevant activities, or who supervise a person who engages in a relevant activity, have: (a) knowledge of food safety and food hygiene matters; and (b) skills in food safety and food hygiene matters commensurate with their work and take all reasonable measures to ensure that personnel and visitors exercise personal hygiene and health practices that do not make leafy vegetables unacceptable. The Standard prohibits a primary horticulture producer and a primary horticulture processor from selling or supplying leafy vegetables for human consumption if they ought reasonably know, or ought reasonably suspect, that the leafy vegetables are unacceptable.

The Code differentiates between vegetable production (primary food production) and food businesses (see Table 4 for definitions), with different Standards applying to each activity. Specifically, primary food production under the Code does not include processes which involve the substantial transformation of food (e.g., manufacturing or canning) regardless of where they are carried out, the sale or service of food directly to the public, or any other food production activity prescribed under the Act.

Table 4. Definitions of ‘primary food production’ and ‘food business’ under the Code

Activity	Definition under the Code
Primary food production	The growing, cultivation, picking, harvesting, collection or catching of food, including the transportation or delivery of food on, from or between the premises on which it was grown, cultivated, picked, harvested, collected or caught; packing, treating (for example, washing) or storing of food on the premises on which it was grown, cultivated, picked, harvested, collected or caught; and any other food production activity that is regulated by or under an Act prescribed by the regulations.
Food business	A business, enterprise or activity (other than primary food production) that involves one or both of following: the handling of food intended for sale or the sale of food regardless of whether the business, enterprise or activity concerned is of a commercial, charitable or community nature or whether it involves the handling or sale of food on one occasion only or is a cell culturing food business or a cell line supplier.

A vegetable producer may be required to comply with the Standards applicable to primary food production or to Standards which are applicable to both primary food production and food businesses depending on the structure of their operations. Compliance with FSANZ by small-scale growers who supply wholesale markets or sell through road-side stalls or local farmers markets may be variable.

2.2 QA schemes operating under the Global Food Safety Initiative

GFSI, the Global Food Safety Initiative is part of the Consumer Goods Forum. It is a network of food industry stakeholders which provides leadership and guidance on food safety management systems by setting globally recognised standards necessary for maintaining food safety along the supply chain, from the grower to the retailer. The organisation ensures consistency and fosters continuous improvement in food safety practices through its benchmarks for food safety management systems.

There are several quality assurance programs which can be applied to vegetable production and packing enterprises, including BRCGS, Freshcare, GlobalGAP, and SQF. Each of these programs is discussed in some detail below. Common factors between the programs are the need for producers and packers to commit to improving food safety, document procedures, undertake staff training, conduct and respond to regular risk assessments, undergo and respond to the findings of regular announced and unannounced audits, and keep extensive records of these processes. To ensure compliance and assure ongoing operation of their businesses vegetable producers and grower-packers require efficient data capture and recording systems and effective data governance standards to maintain the integrity of their information so that they can meet the standards set by the different schemes for compliance.

Table 5. Applicability of food quality and safety assurance schemes to different business enterprises (source: HARPS)

Food safety standard	Applicable to
BRCGS	Packers
Freshcare	Growers and packers

Freshcare supply chain standard	Packing, handling, storage, ripening, storage, distribution, wholesale, brokerage, provedore
GLOBALG.A.P.	Growers and packers
SQF	Growers, packers, manufacturing, distribution

2.2.1 BRCGS:

BRCGS is a global company that operates rigorous third-party quality control certification schemes designed to build confidence in supply chains across both food and non-food categories. The schemes specify processes which, when followed, allow a business to obtain certification for good manufacturing practice (GMP) and help provide assurance to customers that products are safe, legal, and of high quality. BRCGS Global Standards operate for food safety, packaging materials, storage and distribution, consumer products, agents and brokers, retail, gluten free, plant-based, and ethical trading supply chains.

The BRCGS food safety quality assurance certification scheme is an independent, globally managed scheme which was developed in the UK. The scheme seeks to harmonise food safety standards across the supply chain and is applicable to vegetable production and packaging operations. The food safety certification scheme has been established for over 25 years and has been adopted by over 22,000 sites in more than 130 countries. The Standard emphasizes the importance of creating a culture of safety and striving for continuous improvement and is used by leading global brands and retailers (<https://www.brcgs.com/our-standards/food-safety/>), food service companies, and procurement companies to assess their suppliers. The current version of the scheme is the Global Standard Food Safety Issue 9 (the Standard; BRCGS 2022) and is applicable to vegetable packaging and processing enterprises. The Standard provides a framework which specifies the safety, quality, and operational criteria required to be implemented within food manufacturing organisations to fulfil their legal compliance and consumer protection obligations, to assist them in the production of safe food, and to manage product quality to meet customers' requirements (<https://www.brcgs.com/media/ihpl2wk5/guide-to-certification-foodsafety-screenready.pdf>).

The Standard supports businesses in developing, implementing, maintaining, and improving their food safety management systems and is underpinned by the principle that food businesses need to have a full understanding of the products they manufacture, distribute, and sell. This requires businesses to have systems in place which allow the identification and control of hazards which could impact product safety, authenticity, legality, and quality. The Standard covers the functional areas of manufacturing, processing, and packaging of processed foods, raw materials for use by food service companies, catering companies, and/ or food manufacturers, primary products such as fruit and vegetables, and some commodities destined for animal feeds or derived from animal products. Companies seeking BRCGS certification are required to have written documentation of all relevant procedures, processes, plans, and records, and are required to submit these for annual internal and independent assessment and audit as detailed in the various clauses of the Standard. Production facilities are also required to be audited for adherence to GMP.

The Standard lists certain requirements as 'fundamental'. Those requirements are that senior management are committed to implementation of the Standard and to continual improvement within their organisations, the development and implementation of a food safety plan based on HACCP, operationalisation of internal audits, supplier management (particularly for suppliers of raw materials and packaging), the identification and implementation of corrective actions within the business, having traceability of products, mapping and implementing efficient plant layout, product flow and product segregation, and establishing housekeeping and hygiene protocols.

Requirements for certification are listed in Part II of the Standard under the headings Senior management commitment, The food safety plan – HACCP, Food safety and quality management system, Site standards, Product control, Process control, Personnel, Production risk zones – high risk, high care and ambient high care, and requirements for traded products.

The Senior management commitment section requires that senior site management demonstrate their full commitment to the implementation of the requirements of the Global Standard Food Safety and processes which facilitate continual improvement of food safety, quality management, and the food safety and quality culture of the site. This commitment is to be documented, signed and socialised across the site, with the document regularly reviewed and updated. The company

is also required to have a clear organisational structure documented showing lines of communication to allow effective dissemination of information regarding product safety, authenticity, legality, and quality to staff. The business is required to establish and maintain environmental and operational programs suitable for the business to produce safe and legal food products. These programs cover areas such as cleaning and disinfection, pest management, equipment and building maintenance, personal hygiene, staff training, purchasing and supplier approval, transportation arrangements, cross contamination control protocols, and allergen management protocols.

To comply with the HACCP requirement under the Standard a business must develop, document, and operationalise a food safety plan under the guidance of a suitably qualified team leader. The HACCP team is mandated to identify and record all potential hazards reasonably expected to occur in the business's production chain, including microbiological contamination, physical contamination, chemical and radiation contamination, food fraud (e.g., substitution, deliberate adulteration), malicious contamination, or risks of introduction of allergens. The team is required to conduct an analysis for hazards most likely to occur at an unacceptable level and develop and document a corrective action plan to each. The food safety plan is to be regularly reviewed and updated.

To meet compliance standards under Section 3 of the Standard (Food safety and quality management system) the business must operate an effective document control system to ensure that only current versions of manuals and forms are available. Additionally, the business is required to document its processes and procedures in the form of a hard or soft copy quality manual to allow their consistent application, to facilitate training, and support due diligence in production chains. Relevant sections of the manual are required to be readily available to staff. Specifically, Clause 3.2.1 of the Standard states that:

The company shall have a procedure to manage documents which form part of the food safety and quality system. This shall include: a list of all controlled documents including the latest version number, the methods for the identification and authorization of controlled documents, a record of the reason for any changes or amendments to documents, the system for the replacement of existing documents when these are updated'.

Records are required to be legible, maintained in good condition and retrievable, with changes documented, justified, and authorised, and retained for a defined period with due regard to legal requirements. Where documents are stored in electronic form the business is required to store them securely (e.g., with authorized access required, amendment control authorization, or password protection) and to have back-up procedures in place to prevent document loss.

This section of the Standard also documents requirements for supplier assessment and approval and inwards of goods receipts, monitoring, and management. Relevance to vegetable producers Section 3.5.4. addresses the use of contractors in the production chain, specifically in Section 3.5.4.3 'Where any processes are outsourced, including production, manufacture, processing or storage, the risks to the product safety, authenticity and legality shall form part of the site's food safety plan (HACCP plan)' and Section 3.4.5.4 'Requirements for outsourced processing shall be agreed and documented in a service specification (similar to a finished product specification). This shall include any specific handling requirements for the products. Section 3.4.4.5 requires that 'Any outsourced processing shall: be undertaken in accordance with established contracts which clearly define any processing requirements and maintain product traceability' and Section 3.4.4.6 requires that 'The company shall establish inspection and test procedures for products where part of the processing has been outsourced, including visual, chemical and/or microbiological testing.'

Section 3 further addresses the issues of product specifications, corrective and preventive actions, control of non-conforming products, traceability, complaint handling, and incident management (including product withdrawal and recall procedures).

Clause 4 of the Standard addresses the size, location, design of sites and buildings, and site access protocols to reduce risk. Considerations include reviewing activities established or planned for surrounding sites and the site environment, taking into account the potential for product contamination from the surrounds, and putting measures in place or required to reduce risk, such as flood plans or mitigation strategies. Clause 4.5, entitled 'Utilities - water, ice, air and other gases' requires that utilities used within the production and storage areas be monitored to control the risk of product contamination. Clauses 4.6, 4.7, and 4.8 require that all production equipment be suitable for purpose, that it be used to minimise the risk of product contamination, that an effective maintenance program to prevent product contamination be implemented and that suitable staff facilities be available, operated in such a way as to avoid contamination, and properly and regularly cleaned and maintained.

Clause 4.9 requires that appropriate facilities and procedures are in place to control risks of chemical or physical contamination of products, including contamination by chemicals, metal objects, glass, brittle plastics, ceramics and similar materials, wood, and other potential physical contaminants. This requires having processes in place to manage use, storage and handling of non-food chemicals to prevent contamination, including having an approved list of chemicals for purchase, ensuring the availability of Material Safety Data Sheets for each chemical, confirmation of the suitability for use in food processing environments, adequate and appropriate labelling of chemicals, availability of a designated storage area, access and use limited to appropriately trained personnel, spill procedures and disposal protocols in place for products and empty containers. Clause 4.10 requires that the risk of contamination of food products by foreign bodies be reduced or eliminated, where necessary through the effective use of suitable detection and removal equipment following documentation and execution of a risk identification and assessment procedure. Clause 4.11 specifies that housekeeping and cleaning systems be implemented in order to ensure that appropriate hygiene standards are documented and implemented to minimise the risk of product contamination. Clause 4 also addresses undertakings and actions required to ensure appropriate plans are developed, documented, implemented, reviewed, and updated for environmental monitoring (Clause 4.11.8), waste and waste disposal (Clause 4.12), management of surplus food and products for animal feed (Clause 4.13), pest management (Clause 4.14), management of storage facilities (Clause 4.15), and management of despatch and transport (Clause 4.16).

Clause 5 of the Standard addresses product design and development controls, including the need to have design and development procedures in place for new products or processes, or changes to existing products, packaging, or manufacturing processes. The Standard specifies that the HACCP methodology of risk assessment be used in developing the necessary processes, procedures, and protocols (Clause 5.1). Clause 5 also deals with product labelling (Clause 5.2), management of allergens (Clause 5.3), product authenticity, claims made for products, and chain of custody (Clause 5.4), packaging (Clause 5.5), quality control (product inspection, on-site testing, laboratory analysis; Clause 5.6), and product release (Clause 5.7). Clause 5.8 deals with sites which produce pet foods or animal feed and primary animal conversion (Clause 5.9).

Clause 6 addresses the area of process control, requiring that all plants operate to process specifications and work instructions or procedures which ensure production in compliance with the established HACCP or food safety plan for the site. Process specifications and work instruction or procedures are required to be available for key processes, including recipes, mixing instructions (inclusive of speeds and times), equipment settings, cooking and cooling times and temperatures, labelling instructions, coding and shelf-life markings, required storage conditions (including temperatures), and any other critical variables identified through the HACCP plan or food safety plan. As with all documentation required under the Standard, the specifications and procedures developed and documented must be reviewed prior to any changes being operationalised. This Clause also governs product labelling and pack control (Clause 6.2), weight, volume, and quantity control (Clause 6.3), and calibration of measuring and monitoring equipment (Clause 6.4).

Clause 7 specifies requirements designed to ensure that staff and visitors to the site are competent to carry out their work through appropriate training, work experience, or qualification. The Clause documents requirements which apply to personnel, including training and assessment commitments on the part of management (Clause 7.1), documentation and implementation of personal hygiene standards for staff and site visitors (Clause 7.2), and medical screening for staff, agency staff, contractors, and visitors to ensure that individuals do not introduce or transmit diseases, including foodborne diseases) to products (Clause 7.3). Clause 7.4 details the need for policies which specify requirements for personal protective equipment (PPE) to be worn by staff and visitors across the site, and management of soiled PPE.

Clause 8 addresses production risk zones, which are classified as high risk, high care, and ambient high care, at sites where an assessment indicates that the production process requires such classification. The overall requirement is that the production facilities and controls are suitable to prevent pathogen contamination of products.

Clause 9 (Requirements for traded products) covers the situation where food products which would normally be covered by the scope of the Standard but are not manufactured, processed, reworked, packed or labelled at the site are stored at the site. Under these circumstances, the site is required to operate a HACCP or food safety plan, and to have a documented supplier approval procedure which allows initial and ongoing approval of suppliers for the traded products and the products themselves. The site is required to have an inwards quality assurance program to verify that all traded products meet pre-agreed specifications and safety requirements and meet any relevant legal requirements. Traded products must meet the traceability requirements set for the overall site and production systems.

Part III of the Standard defines the audit protocols which underpin the food safety quality assurance certification scheme. The Standard provides companies seeking BRCGS certification with several options with regard to the structure of audits.

In principle, compliance with the Standard is established by annual announced and unannounced audits of certified premises typically lasting 2-3 days. Audits are carried out by independent audit firms. Dates for annual announced audits are agreed between the facility and the audit body; unannounced audits are conducted every 3 years within an agreed time window. The audit consists of several different audit techniques including an opening meeting, inspection of the site/facility, a review of all relevant documents, a 'vertical audit' comprising a traceability challenge and a mass balance exercise, a final review of audit findings, and a close-out meeting. Following the audit businesses are expected to document and implement any corrective actions identified by the audit, including conducting a root cause analysis, development of a preventive action plan for nonconformities. These activities must be completed within 28 days of the audit, with evidence of compliance being reviewed by the certifying body within 14 days. If all is considered satisfactory then a certificate, audit report, and a corresponding grade are issued within 42 days of the audit. Following the audit the business is expected to maintain the Standard and to identify areas for continual improvement and to schedule the next audit.

2.2.2 Freshcare:

Freshcare is an Australian-owned and operated company which provides internationally recognized quality assurance standards for the fresh produce and wine grape industries in Australia (<https://www.freshcare.com.au/>). Freshcare offers two auditable certification programs for the growing and harvest of fruits, vegetables, nuts, flowers, and foliage. These programs cover the areas of food safety and quality, and sustainable production and environmental management.

The food safety and quality program is administered through the Freshcare Food Safety and Quality Standard which has been developed specifically for Australian producers (the Standard; Edition 4.2 November 2020; FSQ; <https://www.freshcare.com.au/wp-content/uploads/2023/08/20230622-Freshcare-Food-Safety-Quality-Standard-Edition-4.2-and-Rules-Amendments.pdf>). The Standard underpins a certification and compliance program, providing growers and grower-packers with good agricultural practice (GAP) guidelines, best management criteria, specific food safety requirements based on HACCP, and post-harvest food safety criteria for the production and packing of safe, quality, fresh produce on-farm. The Standard defines 'Grower' as a business involved in the production and harvest of a crop, pre-farm gate; the definition 'Grower-Packer' includes businesses involved in receiving, handling, packing, and repacking of fresh produce but does not include further processing of whole products. Compliance with the Standard requires growers and grower-packers to generate, store, periodically review, and subject to internal and external audit a range of documents to support their accreditation. This process assures buyers of the quality and safety of fresh produce produced under the Standard.

The Standard provides templates and a detailed explanation of the obligations on a business seeking to comply with the Freshcare Rules and Freshcare Standard(s), which are in addition to its obligations to comply with regulatory requirements and the law. Businesses can apply to be registered for the Freshcare Program either through participation in approved Freshcare training or via application to Freshcare. Businesses with multiple sites operating under different management systems or in geographically distant locations are required to register each site with Freshcare separately. Each business participating in the program is required to have least one management representative complete approved training. Where this person leaves, the business is required to have a new representative commence training within three months.

Certification is contingent on a business complying with the undertakings documented in the Standard, including extensive, detailed documentation of processes, the generation and maintenance of comprehensive records relating to the business, and audit requirements. To achieve and maintain Freshcare accreditation businesses must submit to annual audits, including one unannounced audit every 4 years, to be carried out during harvest/ operational months. The onus is on individual businesses to schedule audits. To be compliant, businesses are required to provide unimpeded access for auditors to sites and premises, to full documentation and records, and to product, and to provide all reasonable assistance to auditors while audits are conducted. All corrective actions identified from an audit must be closed out within the time frames indicated for certification to be issued.

To initiate Freshcare certification, management is required to define the scope of the business and the scope of certification sought, and to identify property areas, infrastructure and local activities on a property map. Any changes to a business's profile, key contact information, or other relevant details need to be notified to Freshcare in writing within 28 days. Management is also required to document the business's commitment to food safety and quality and to the Freshcare program by documenting a Food Safety and Quality Policy, including setting up measurable food safety and quality objectives for the business. The Food Safety and Quality Policy must be communicated to all workers and reviewed at least annually, or when changes occur that may impact food safety or quality. Roles, responsibilities, and reporting relationships of workers responsible for food safety and quality management must be defined, and procedures and/or work instructions

need to be documented. Documents must be maintained for all activities that impact food safety or quality: compliance with the Standard must be demonstrated through the maintenance and availability of relevant documents and records.

To achieve certification a management representative is required to complete approved Freshcare Food Safety & Quality training, and the business must train all workers involved with tasks relevant to the Standard to ensure a base level of food safety awareness. The owner or appropriate senior manager is required to complete a review of training to support food safety and quality, to identify worker needs for re-training, identify opportunities for professional development, and to ensure appropriate qualifications and licenses are maintained. A review of training must be conducted at least annually or when processes and/or workers change. The business must also ensure that internal audits of all activities and records relevant to the Standard are conducted at least annually, or when changes occur, that may impact food safety. Workers responsible for completing sections of the internal audit must be identified and, where possible, must be independent of the practices being assessed.

A Corrective Action Record (CAR) must be completed when the requirements of the Standard, Freshcare Rules, or legislation are not met. A CAR must include a description of the problem and identify the cause of the problem. The CAR must also state whether the problem has occurred before and identify short and long-term fixes taken to prevent the problem from recurring. Confirmation that short-term and long-term actions are completed and effective, including the name and signature of the person completing the review, and the date of the review, must be documented. Evidence must be kept on record that recurrences of non-compliance have been reviewed by the owner or appropriate senior manager.

A management review of compliance must be conducted at least annually and a record of the review kept, including as a minimum internal and external audits, corrective and preventative actions taken, customer feedback, complaints, training undertaken, the business's food safety and quality policy, and measurable objectives. Businesses are required to notify the certification body and Freshcare of any serious food safety incident resulting in a product recall or a customer applying a stop supply within 48 hours of the incident. Additionally, businesses are required to notify Freshcare and their nominated certification body of any prosecutions brought or likely to be brought against the business within the scope of their Freshcare certification.

The Standard also requires that risk assessments be conducted annually or when changes occur which may impact the significance of identified hazards and records kept for persistent chemicals, heavy metals, fertilisers and soil additives, for pre-harvest water, and for any additional food safety hazard identified within the scope of the Standard. Where risks are identified, they are required to be addressed and remedial actions recorded. If the assessment determines the risk of the hazard identified is high, relevant control measures, monitoring and verification activities must be implemented. A risk assessment must be conducted, and records kept supporting any aspect of the Standard that is not implemented and must clearly detail the reason for any exclusion.

Freshcare certification also requires that complying businesses manage growing sites to minimise risks of contaminating produce, including through spray drift, flood events, animal ingress to growing areas, and physical contamination. Risk management includes ensuring planting materials are purchased from suppliers that are managed in accordance with supplier requirements. Compliance also requires the documentation and implementation of a plan for managing pests. With regard to agrochemicals, businesses are required to obtain properly labelled chemicals from approved suppliers, to ensure labels remain legible, and to store, manage and dispose of chemicals to minimise the risk of contaminating produce. Workers must be trained and authorised to store, handle, apply and dispose of chemicals, avoiding spray drift; chemical use must comply with regulatory, label and market requirements. Application equipment must be maintained and calibrated and mixing and disposal of chemical solutions must be managed to minimise the risk of contaminating produce. All chemical applications must be recorded and produced tested annually for chemical residues to verify that chemicals are applied correctly; withholding periods are observed and that produce complies with established Maximum Residue Limits (MRLs). Similarly, the Standard requires that fertilisers and soil amendments, pre-and post-harvest water, and potential sources of allergens be managed to minimise risk.

To be compliant, businesses must maintain product release procedures for the final check of produce to prevent unintended use or delivery of produce found non-compliant. Documentation demonstrating compliance with any written or agreed customer specifications and that product is checked to ensure it meets the agreed specification before despatch must also be generated and kept. If product does not meet the agreed specification, the customer must be informed and an agreed course of action implemented and recorded. An incident management plan is required to ensure produce that does not meet food safety requirements is effectively managed and a product identification and traceability system must be maintained to enable produce to be traced from production to its destination. A product recall and withdrawal plan is

also required.

The Freshcare Environmental Program is a comprehensive, outcomes-based environmental assurance program focused on best practice. The program is aimed at providing Australian growers and grower-packers with a pathway to demonstrate sustainable production and environmental management, including stewardship of their land, natural resources and communities in which they operate. The program is underpinned by the Freshcare Environmental Code of Practice (ENV3; <https://www.freshcare.com.au/our-standards/environmental/>).

Certification to ENV3 is achieved through independent third-party auditing by approved auditors. Similar to the Freshcare Food Safety and Quality program, ENV3 has two components (Management and Environmental) which must be met to achieve certification. The management requirements under ENV3 are similar to those under the food safety and quality program, particularly with regard to the need to fully document and keep current the business profile, develop and socialise an Environmental Action Plan (EAP) which describes the practices required on farm to provide assurance that produce has been grown and packed with care for the environment and to identify planned future actions to manage environmental issues and improve the property's environmental values. Where a customer requires compliance with specific environmental, sustainable agriculture or greenhouse gas emission practices not covered in ENV3, a written copy of these practices must be kept. Ongoing compliance with these customer requirements must be documented and included in internal audits.

The EAP requires businesses to assess their property and business operations and identify any environmental issues and assess environmental values. The EAP comprises 12 components of environmental management: environmental action planning, land and soil management, biosecurity, chemicals, fertilizers, soil additives, water, biosecurity, waste management, air quality management, and management of energy and fuel.

Under the environmental action planning component businesses seeking certification are required to document the actions planned to address any environmental issues identified and to improve the environmental values of the property, including the date of plan development, the environmental issue/value being addressed, location on the property of the environmental issue/value, actions planned to address the issue and/or improve the value, identity of worker/s responsible and target date of completion for each action. The business is required to elucidate a plan for evaluating action/s undertaken, including the date, name and signature of the person verifying action has been completed. Evidence of progress towards and/or changes to any planned actions is required to be kept, and the EAP must be reviewed and updated at least annually. The name of the person completing the review and the date of the review are also to be documented.

The EAP addresses land and soil management strategies to minimize degradation, erosion compaction and contamination, and requires that a Biosecurity Management Program be documented and implemented. The Biosecurity Management Program is required to include the date the program was developed and the name of the person documenting the program. Biosecurity threats related to crops grown, strategies/practices to minimize risk (including quarantine regulations and requirements) need to be identified, identity of worker/s responsible for implementing the Biosecurity Management Program needs to be recorded, and a plan for restricting access to the property by unauthorized individuals needs to be documented. The property covered by the EAP must be monitored for the presence of any unusual plant pest, disease or weed and any such pest identified on the property must be reported to the local department of agriculture or Plant Health Australia.

Pest and disease control strategies implemented on the property must be documented and selected to minimize risk to the environment (e.g., biological, chemical, cultural, mechanical and technological control strategies) before a control program is chosen. A record of control methods used must be kept and, when it is deemed necessary to apply agricultural chemicals, less environmentally hazardous beneficial organisms and/or strategies which have a lower environmental impact must be considered. Any decision to use agricultural chemicals must be based on one or more of crop and/or weather monitoring for pest and disease pressure, external agency pest and disease alerts, documented preventive pest and disease control programs, or industry preventive control programs or phytosanitary specifications. Records must be kept recording decision-making variables and responses. With regard to the use of agricultural chemicals, fertilizers, soil amendments, and water, the EAP imposes similar record-keeping, documentation, and audit requirements to the FSQ Standard.

The compliance program requires that a Biodiversity Management Plan be developed, documented, implemented, and annually updated and audited for the property covered by the EAP. The Biodiversity Management Program must use strategies and practices to protect areas of biodiversity identified on the property map, reduce processes which threaten biodiversity, and manage feral animals, invasive species, pests, environmental weeds and diseases. Additionally, the

Biodiversity Management Program must include the date the plan was developed, the name of the person documenting the program, identification of any biodiversity issues or values, strategies to deal with these, and identify the worker/s responsible for implementing the plan.

A documented Waste Management Program is mandated and must include the date the program was developed, the name of the person documenting the program, itemization of the waste type identified and location, management methods identified to rectify the situation, and the worker/s responsible for remediation. Any waste that cannot be avoided, reused or recycled, must be disposed of in approved off-site facilities, and records of waste transport and disposal of controlled waste must be kept. The program must specify that all stored waste is managed to minimize the risk of contaminating onsite and off-site areas and must be reviewed and updated annually. The name of the person completing the review and the date of the review must also be documented.

The EAP also mandates that an Air Quality Management Program be developed and implemented, with similar documentation, recording, and audit requirements as accompany the above programs, and that energy and fuel efficiency be optimized throughout the production system. With regard to energy and fuel efficiency, the EAP requires that electricity and fuel consumption is reviewed at least annually and that efficient operating practices for premises, vehicles, machinery and equipment are identified and implemented. Compliance requires that servicing and maintenance records be kept for vehicles, machinery and equipment and that energy and fuel efficiency be considered in the selection and/or design of new premises, vehicles, machinery and equipment. The EAP requires that bulk fuel storages be located, constructed and maintained to minimize the risk of environmental contamination and to contain spillage, and that current Safety Data Sheets (SDS) be kept for all bulk fuel stored on the property.

2.2.3 GLOBALGAP:

GLOBALG.A.P. is a compilation of farm quality assurance programs developed in Germany for the certification of agriculture, aquaculture, and floriculture production processes targeted at fostering safer and more responsible farming practices. The program has been implemented in over 130 countries worldwide (<https://www.globalgap.org/>). GLOBALG.A.P. standards and add-ons can be applied to the production processes of more than 700 different plant and aquatic species. Each species belongs to a product category with its own checklist that details the certification requirements.

The reference document for the GLOBALG.A.P. certification process for vegetable production is the Integrated Farm Assurance Smart Principles and Criteria for Fruit and Vegetables (IFA, GLOBALG.A.P 2022). IFA is a global standard that aims to promote responsible primary production, from preharvest activities to postharvest handling by addressing the key topics of food safety, environment, workers' health, safety, and welfare, production processes, and traceability to provide producers with clarity on market requirements. IFA has been operational for over 20 years, with IFA-certified production processes for fruit and vegetables covering more than 4.2 million hectares annually

In common with BRCGS and Freshcare, the GLOBALG.A.P. IFA certification program requires compliance with a series of modules, with compliance being confirmed through annual audits conducted by independent certified auditors. GLOBALG.A.P. specifies 33 modules for compliance: Internal documentation; Continuous improvement plan; Resource management and training; Outsourced activities (subcontractors); Specifications, suppliers, and stock management; Traceability; Parallel ownership, traceability, and segregation: Mass balance; Recall and withdrawal; Complaints; Non-conforming products; Laboratory testing; Equipment and devices; Food safety policy declaration; food defense; Food fraud; Logo use; GLOBALG.A.P. status; Hygiene; Workers' health, safety, and welfare; Site management; Biodiversity and habitats; Energy efficiency; Greenhouse gases and climate change; Waste management; Plant propagation material; Genetically modified organisms; Soil and substrate management; Fertilizers and biostimulants; Water management; Integrated pest management; Plant protection products; and Postharvest handling.

From the perspective of data systems and data governance standards, the over-riding principle of the GLOBALG.A.P. certification system is that there must be a procedure in place in the business to generate and control documents and records affecting the implementation of the system. This begins with a framework which demonstrates how documents and records are created, reviewed, approved, and updated, including how reviews are conducted and changes are made, how version tracking is implemented, and how relevant documentation is made available to relevant staff. Documents are required to be identified using issue numbers, dates, and pagination, the level of detail which is considered adequate must be specified, and how documents are to be periodically reviewed within timeframes nominated by GLOBALG.A.P. to demonstrate ongoing compliance needs to be specified. Documents are required to be available to nominated staff members, approved by authorized staff prior to distribution, and effectively removed from circulation when made

redundant.

Records required for auditing purposes must be kept up-to-date and kept for a minimum of two years. All such records must be readily available and kept securely; electronic versions must be valid and backed up and cover the longer of 3 months of activity prior to the date of first certification or begin on the day of registration. Documents must reference full details of each of the 33 functional areas, as listed above, and, where an individual record is missing the respective principle addressing those records is considered non-compliant such that a non-compliance will be issued against that principle in an audit.

Businesses seeking certification under the GLOBALG.A.P. quality assurance system are required to complete at least one internal audit/ self-assessment annually against the Integrated Farm Assurance Smart Principles and Criteria for Fruit and Vegetables (the Standard). The internal audit must be conducted prior to the external certification body audit and is required to evaluate compliance, review the implementation of the necessary criteria, and support identification of self-improvement opportunities. All applicable sites and products must be included in the internal audit and all topics covered by the Standard must be assessed, including subcontracted activities, harvest, and post-harvest handling. Corrective actions taken in response to identified non-conformances must be documented and necessary changes implemented.

Compliance with the Standard requires that a continuous improvement plan be documented following an evaluation of the farming operation by the producer, identifying improvement opportunities for implementation over a three-year period. The suggested structure of the improvement plan is to describe the improvement objective and current status, list the activities required to reach the objective, and specify the target outcome and delivery date.

Every audit is conducted against the relevant checklist and in accordance with the GLOBALG.A.P. general regulations – a set of certification rules for checklist implementation. Certification is gained and maintained through regular audits of registered producers performed by independent and accredited third-party certification bodies.

2.2.4 SQF:

The SQF Program, a US-based food safety and quality certification and management system is administered by SQFI (Safe Quality Food Institute), a division of FMI (the US Food Industry Association; www.fmi.org). The SQF quality assurance system was developed by the Western Australian Department of Agriculture in 1994 and sold to FMI in 2003; it is currently employed across 14,000 certified sites in 40 countries (www.sqfi.com). The 11 industry-specific Food Safety Codes are based on CODEX Alimentarius HACCP Guidelines, and ISO 17065, and are designed to meet industry, customer, and regulatory requirements for all sectors of the food supply chain from the farm to retail stores and food services businesses. SQF certification is site specific and provides an independent and external verification that a product, process, or service complies with international, regulatory, and other specified standard(s) and enables a food producer to give assurances that food has been produced, prepared, and handled according to the highest possible standards.

The SQF standards governing vegetable production are part of the Food Safety Code: Primary Plant Production Edition 9, dated 2020 (the Code; <https://www.sqfi.com/the-sqf-code/choose-your-code/library-of-codes/primary-plant-production>). Specifically, Food Sector category (FSC) 2 – Indoor Growing and Harvesting of Fresh Produce and Sprouted Seed Crops and FSC 3 – Growing and Production of Fresh Produce and Nuts apply to growing and packing of vegetable crops. FSC 2 applies to the production, harvesting, preparation, packaging, and on-site storage of products grown in indoor operations, including greenhouses, mushrooms, and sprout production. The standard also applies to tomatoes, peppers, cucumbers and lettuce produced in protected cropping systems. FSC 3 applies to the production, harvesting, preparation, field packing, and on-site storage of fresh whole fruit, vegetables, and nuts, including all produce grown under broadacre, intensive horticultural production systems, and external nursery operations. Crops covered by this standard include all ‘ready to eat’ fruit and vegetables, carrots, beets, potatoes, berries, all forms of leafy greens, spring mix, tomatoes, peppers, herbs and spices, baby spinach, lettuce, and melons.

Standard FSC 14 applies to the processing, packaging, and on-site storage of all processed fruit, vegetables, and nut products, including freezing, fermenting, drying, slicing, dicing, cutting, and modified-atmosphere processing. This Standard includes preparation of salad mixes and juicing but does not include canning.

In the Code document the requirements for compliance with FSC 2 are addressed in Module 18: GAP for Indoor Farming of Plant Products, requirements to meet FSC 3 are addressed in Module 7: GAP for Outdoor Farming of Plant Products, and requirements to meet FSC 14 are addressed in Module 11: GMP for Processing of Food Products. The Code also sets out the steps necessary to implement and maintain certification under the SQF Food Safety Code: Primary Plant Production. It details the SQF system elements for vegetable production that must be met (Module 2 – The SQF Food Safety Code: Primary Plant Production), and the relevant Good Agricultural/Operating Practices (GAP/ GOP) for growing, harvesting, and packaging of plant products (Module 7 – Good Agricultural Practices for Outdoor Farming of Plant Products; Module 10 – Good Operating Practices for Pre-processing of Plant Products (Packhouses); Module 18 – Good Agricultural Practices for Indoor Farming of Plant Products). A flowchart of the steps required to achieve SQF accreditation are shown in Fig. 3.

The scope for SQF certification is site specific: the entire site, including all premises, support buildings, silos, tanks, loading and unloading bays, and external grounds must be identified and included in the scope of certification. If activities are carried out in different premises but are overseen by the same senior, operational, and technical management and are covered by the one SQF System, the site can be expanded to include those premises. If operations or business premises are changed successful certification of the new site or premises is required, beginning with an initial certification audit. If the ownership of a certified site changes within the new owner is required to notify the certification body and apply to retain the SQF certification. If there are significant changes in site management and personnel, the certification body is required to complete an initial certification audit and issue a new certificate and a new certification number.

SQFI has a list of food sector categories to classify product groups and ensure that the nominated site has the requisite knowledge and skills. The FSCs that apply to vegetable production are specified in the Code under Primary Plant Production as FSC 2: Indoor Growing and Harvesting of Fresh Produce and Sprouted Seed Crops, FSC 3: Growing and Production of Fresh Produce and Nuts; FSC 4: Fresh Produce, Grain, and Nut Packhouse. Certification is product specific and requires that all products for which certification are sought are specifically nominated and audited for compliance with the Code.

Achieving SQF food safety certification is a two-stage process: first, the policies, procedures, work instructions, and specifications that meet the system elements and GAP/GOP modules of the Code need to be documented and implemented.

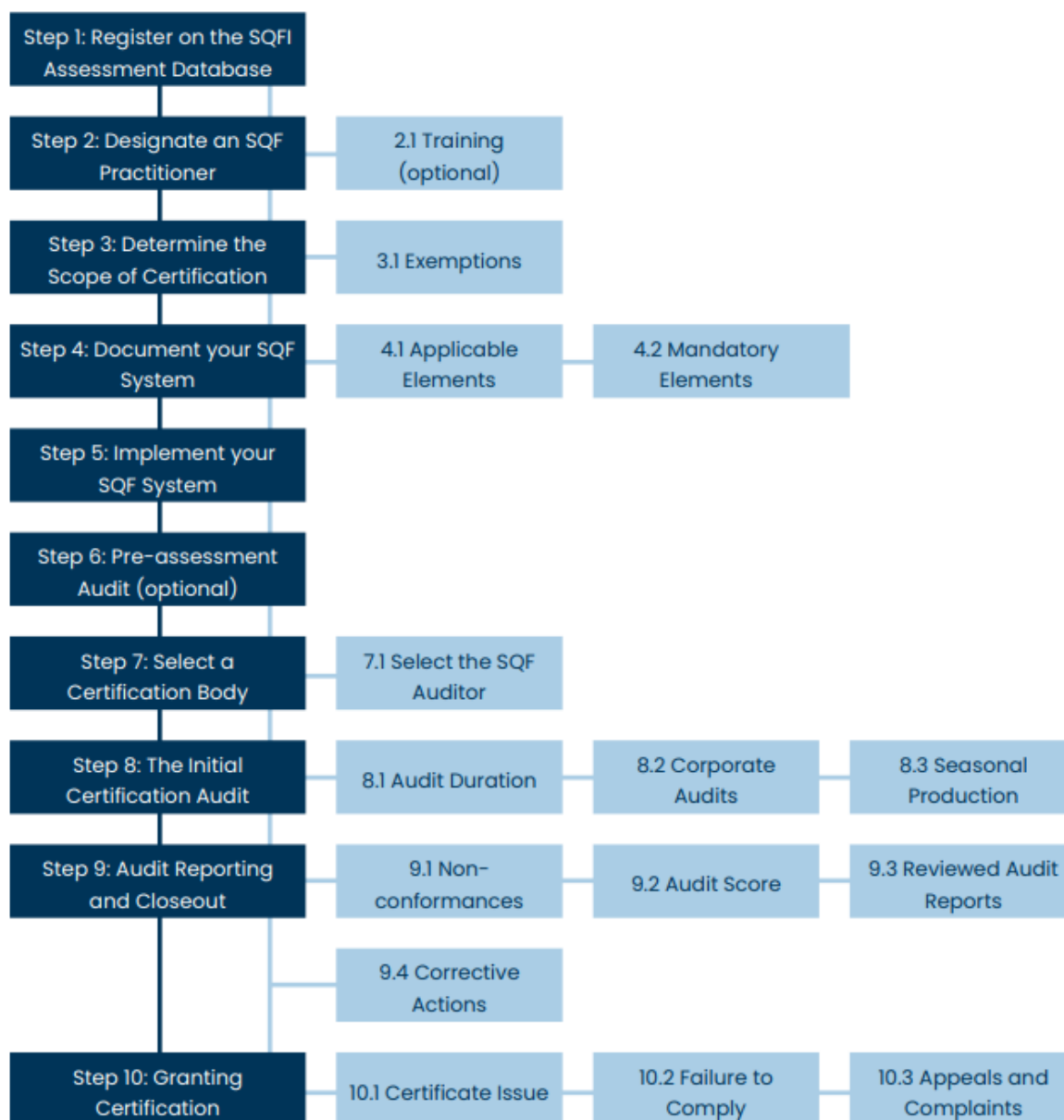


Figure 3. Steps required to achieve SQF accreditation (source: <https://www.sqfi.com/the-sqf-code/choose-your-code/library-of-codes/primary-plant-production>).

The auditable elements of Module 2 (system elements) and Modules 7, 8, or 10 (operational elements; whichever are applicable to the business enterprise) must be documented, implemented, and audited for a site to achieve SQF certification. The key elements of Module 2 are: Management Responsibility, Validation and Effectiveness, Management Review, Verification Activities, Complaint Management, Corrective and Preventative Action, Food Safety Management System, Internal Audits and Inspections, Document Control, Product Identification, Records, Product Withdrawal and Recall, Approved Supplier/Input Purchasing Program, Food Defence Plan, Food Legislation, Food Fraud, Good Agricultural/Operating Practices, Allergen Management, Food Safety Plan, and Training Program.

Management is responsible for ensuring that the policies, procedures, work instructions, and specifications are in place to meet the SQF requirements, that all documents are being followed, and records are being kept demonstrating compliance to the relevant modules of the Code. SQFI recommends that a minimum of ninety (90) days of records is available before a

site audit is conducted

An Initial Certification Audit is conducted to ensure that documentation complies with the Code and that food safety, hygiene, and management activities are carried out according with documented policies, procedures, and specifications. The audit may have off-site and on-site components. The on-site component is conducted only when the main processes are operating. Off-site audit activities can include a review of the qualifications of the SQF practitioner(s) and the food safety (HACCP) team, a review of policies, procedures, food safety plans, work instructions, and registers/listings, interviews with key personnel, a review of food safety plans, HACCP programs, and food safety management personnel, a review of internal audits, corrective actions, complaints, and recalls, an assessment of traceability policies and conduct of a mock recall exercise, and threat and vulnerability assessments for food defence and food fraud programs.

If the site is involved in seasonal production (defined as a period in which the major harvest activity is conducted over not more than five consecutive months) the initial certification audit must be conducted during the peak operational season. If products from more than one season or commodity are to be included in certification, the initial certification audit must be conducted during the highest risk and/or highest volume crop activities. Documentation and records for other seasonal production are reviewed as part of the certification audit. Re-certification audits in subsequent years should be scheduled during other crop harvesting or packing times so that all crops or commodities within the scope of certification have been audited within at least three years.

Annual re-certification audits are conducted to verify the continued effectiveness of a site's SQF System. A minimum of 50% of the allocated audit duration must be on-site. As with initial audits, remote activities dependent on ICT capability and information security requirements. Unannounced audits are conducted every three years.

2.3 Grocery retailer-led post-farm certification (HARPS)

The Harmonised Australian Retailer Produce Scheme (HARPS; <https://harpsonline.com.au/>) is a program owned by Hort Innovation and managed by One Direction ANZ; it includes the HARPS Standard, Scheme Rules, and associated technical documentation. The HARPS Standard is a set of criteria that provide an additional level of prescription above the basic Food Safety Global Food Safety Initiative (GFSI) Standards, which Retail Customers have agreed are fundamental for the delivery of safe produce to Australian consumers. (<https://harpsonline.com.au/wp-content/uploads/2022/11/HARPS-Standard-Version-2.0-2022-11-02.pdf>). The HARPS standard is not as comprehensive as the GFSI requirements but, in addition to food safety requirements, HARPS includes requirements related to trade and legal compliance (issues that can lead to customer complaints, product withdrawals and product recalls that concern the retailers) that are not covered in the GFSI programs which focus on food safety requirements alone.

Ongoing development of the HARPS Standard and associated technical documents is undertaken by the HARPS Technical Advisory Group. Current HARPS membership is comprised of a broad cross-section of industry representatives, including grower-packers (large and small businesses), marketers, certification bodies, food safety scheme representatives, and industry association representatives and consultants. Retailer members of HARPS are ALDI, Coles, Costco, Harris Farm Markets, Hellofresh, Metcash (IGA), and Woolworths.

The scope of the HARPS Standard covers the growing and packing of whole produce (fruit, vegetables and in-shell nuts); it does not include the processing or value-adding of produce. The scope covers all operations from site selection and preparation, growing, harvesting, packing, storage, ripening and distribution.

HARPS has three tiers of classification: Tier 1 comprises businesses which have a vendor or supplier number issued by one of the participating retailers; Tier 2 includes businesses which pack or repack any of loose products with PLU or DataBar stickers as required by a participating retailer, retail branded repacks, retail returnable plastic crates, proprietary branded prepacks, loose product in final retail packaging, packed to a retail specification as required by a participating retailer, or is an approved supplier to a Tier 1 business who supplies participating retailers in final retail packaging, or a supplier of ancillary services including ripening, brokerage, storage and cooling; Tier 3 businesses supply bulk produce for further packing to a Tier 1 or Tier 2 business. Businesses which process fresh produce, such as bagged salads, fresh cuts, or sliced carrots, are not considered to be in the scope of HARPS but these businesses do require food safety certification such as BRCGS, Freshcare, GlobalG.A.P., or SQF depending on their customers' specifications (<https://harpsonline.com.au/wp-content/uploads/2022/10/Decision-Graphics-v10.jpg>).

Tier 1 and Tier 2 businesses require HARPS certification in addition to certification to an approved GFSI certification scheme.

Tier 3 businesses do not require HARPS certification but they do require certification under a GFSI-approved certification scheme.require

If a business has already achieved Certification under a GFSI approved program it needs to undergo a HARPS audit (In addition to the GFSI audit) in order to become HARPS Approved. The HARPS elements integrate with the GFSI program audit, hence the audit is required to take place as one, seamless audit: the two audits are integrated and cannot be conducted separately unless prior approval is sought. Ongoing HARPS audits must occur concurrently with the GFSI Program audit. HARPS auditors require objective evidence that demonstrates compliance with the GFSI program chosen by the grower or grower-packer.

HARPS provides an 11-page pre-audit checklist for businesses which indicates the breadth of data systems and governance required to achieve compliance (<https://harpsonline.com.au/wp-content/uploads/2025/10/17.-HARPS-Example-Internal-Audit-Checklist-Rev-1.0.pdf>).

The requirements to be met by growers and grower-packers and document development, updating, and retention under HARPS are addressed in detail in the Standard, including data governance requirements. They are: scope and identity of GFSI schemes applied to the business and maintenance of a register of approved suppliers, finished product specifications register and testing protocols, retention samples policy and validation of shelf life, HACCP training status (a Statement of Attainment, or equivalent, confirming successful completion must be maintained and include, as a minimum qualification under Units of Competency FBPF SY2002 Apply Food Safety Procedures and FBPF SY3002 Participate in a HACCP Team), verification of labelling and packaging claims and label approval processes, personal hygiene protocols and availability of facilities, product recall and withdrawal policies (including the requirement to notify customers of a product recall from sale within sixty minutes of the decision to recall or withdraw a product being made, and evidence of mock recall exercises being held), allergen labelling requirements, documentation around premises, equipment registers, and maintenance protocols, cleaning protocols and procedures, foreign object control protocols, product testing standards, regimes, and records (a documented microbiological, chemical and heavy metal assessment and testing program that meets the requirements detailed in the Food Standards Code must be implemented), documentation of growing conditions with regard to use of manures and biosolids, water, and flood management planning, policies regarding calibration and weight checks for products, policies regarding product sold or given to staff, and retention of Certificates of Currency for Product and Public Liability Insurance must be maintained as a controlled document.

2.4 Ethical and social certifications

2.4.1 Fair Farms:

Fair Farms is a business which supports growers and related parties in the fresh produce supply chain to navigate employment laws and regulations, ensuring that all workers are treated with fairness and respect (<https://www.fairfarms.com.au/>). Fair Farms is governed by the Queensland Fruit & Vegetable Growers (QFVG) Board of Directors and provides practical support, targeted training, and independent, third-party audit and certification. The Fair Farms program is supported by an independent Technical Committee and an External Stakeholder Reference Group (ESRG) which provide expert guidance, stakeholder feedback, and ongoing evaluation.

Fair Farms offers audited and non-audited pathways to accreditation for businesses in the horticulture, viticulture, agriculture and nursery industries which grow or pack produce for wholesale or retail, or who operate as aggregators, distributors, brokers, or agents supplying to wholesale or retail. The non-audit pathway is designed for growers and businesses not supplying major retailers or their agents; The audit pathway is for growers and businesses that supply major retailers or work with wholesalers and agents who do. The audit pathway ensures businesses meet responsible sourcing requirements through an independent third-party audit, giving customers confidence in the business's commitment to ethical and fair farming practices. Fair Farms also offer audited certification for labour hire firms, and coordinate with buyers to aid suppliers in meeting their compliance obligations.

The Fair Farms program is governed by the Fair Farms Standard (<https://www.fairfarms.com.au/certification#fairfarmspathways>) which describes fair and responsible employment practices. Compliance with the Standard provides an assurance that the participant engages and remunerates their staff in accordance with all applicable state and federal laws, rules and Awards. The elements of the Fair Farms Standard are grouped into two sections: 'Management', comprising 4 sections and 'Fair and responsible employment' which comprises 12 sections. Demonstrable compliance with all elements is required for Fair Farms Certification. Each element describes

the outcomes required, the practices needed to ensure compliance and records used to demonstrate compliance with the Standard. The management component of the Standard addresses training requirements, internal audit and rectification processes; the Fair and responsible employment component addresses employment policies and procedures, the Fair Work system, employment of overseas workers, employment of minors, labor hire providers, conditions of employment, record keeping, induction, communication, training and qualifications, supervision and performance management, termination and redundancy, safe working conditions, and safe accommodation and living conditions.

Audited compliance demonstrates that the participant understands and appropriately discharges their responsibilities towards workers engaged through labor hire providers, they ensure a safe work environment and, where applicable, provide legally compliant and reasonable standards of on-farm accommodation for workers, and they follow a zero-tolerance approach towards any form of forced labor, bonded labor or modern slavery.

Data governance begins with the requirement for the business to have a policy statement outlining its commitment to professional business practice and ethical conduct, and intolerance of any forms of bribery, inducement, or corruption. The business is also required to have a code of conduct that identifies unacceptable behaviors within the business and trains its workers in that code. It must disclose any current or past legal action/investigations relating to employment, WHS or immigration matters, including any enforceable undertakings entered, noting any unresolved issues. The business must also document its commitment to fair employment practices and compliance with all applicable laws, to regularly reviewing its policy statement which outlines its commitment to adhere to all laws that apply to its workforce, in particular the Fair Work Act (for National system employers) or relevant State laws, relevant Awards, the Migration Act, and work health and safety legislation, maintain a cooperative and consultative approach with its employees, recognize and respect workers' right to freedom of association and to collectively bargain. The policy statement must be signed by the owner or general manager and must communicated to all workers.

The business must appoint a person with primary responsibility for human resource management who must maintain a working knowledge of workplace relations laws. Additionally, the business must define the organizational structure of the business and key responsibilities in the areas of human resource management and compliance with workplace relations laws and work health and safety; the reporting relationships between workers and supervisors/managers, including where supervisors/managers are engaged through Labor Hire Providers must be clearly stated.

To verify compliance with the Fair Farms Standard through relevant documents and records the business unit is required to demonstrate that it has access to current editions of the Fair Farms Standard and the Fair Farms Rules; all records and documents required to verify compliance to the Standard need to be legible and must include title, date of issue or version number, business name, and name of person completing record and date of completion. As documents and records change or are superseded out of date versions must be replaced.

To complete a self-assessment of workplace relations compliance the business owner or appropriate management representative must complete the Fair Farms Online Self-Assessment (OSA) to establish the business' level of compliance with the Standard and to identify any associated training needs and have the identified training completed. The business owner or appropriate management representative must complete approved Fair Farms training (where required) to address matters of noncompliance identified through the OSA. Training modules are to be completed within 3 months of the training needs being identified and evidence of completion of training must be kept.

A Corrective Action Record (CAR) must be completed when the requirements of the Standard, Fair Farms Rules or legislation are not being met, as identified by routine activities, annual OSA, internal audits (where applicable) and external audits (where applicable), or when a valid complaint is received. CARs must include a description of the problem, the cause of the problem, whether or not the problem has occurred before, short term fix (action taken to fix the problem) employed, long term fix (action taken to prevent the problem recurring) employed, confirmation that short term and long term actions are completed and effective, name and signature of person completing the review, and date of the review.

As with the FSANZ and on-farm and post-farm food safety and quality certification schemes, it is the responsibility of the business owner or senior management to ensure that all policies and procedures in the business designed to meet compliance under the Fair Farms system are documented, regularly reviewed and updated, stored appropriately, retrievable, and auditable.

2.4.2 Sedex:

Sedex (<https://www.sedex.com/>) is a global platform used by suppliers of all sizes, including small farms, processing facilities, service providers, and smallholders, and buyers to manage and share information about labor standards, health and safety, environmental practices, and business ethics. It allows businesses to store data in a determined format and share it with multiple business partners in a standardized way. Sedex allows suppliers to store their data once and share it with multiple buyers, reducing duplication and improving transparency. For each factory, farm or facility risk rating, audit results and open corrective actions can be accessed. The system monitors labor standards, protects workers by addressing risks like child labor, forced labor, excessive working hours, underpayment, discrimination, and lack of worker representation. The platform also safeguards workplaces through monitoring of safety procedures, protective equipment, emergency readiness, and occupational health, reduces environmental harm by managing waste, emissions, pollutants, chemical handling, and compliance with environmental permits, and promotes business integrity by tackling corruption, unfair practices, lack of transparency, and weak grievance mechanisms.

Key benefits claimed include fewer audits and less disruption, less administrative work, better visibility of risks, and stronger buyer trust. Sedex helps suppliers answer compliance questions and share evidence with multiple buyers, streamlining operations and reducing costs. Joining Sedex typically involves sellers creating a Sedex account, completing a self-assessment, uploading relevant documents, sharing information with buyers, and deciding, with buyers, if and when an audit is needed.

The platform presents owner, location, product category, and initial risk flags in a single dashboard. Users can access built-in risk screening and targeted questionnaires to focus on the highest-risk sites. The platform allows variables such as labour, health and safety, environment and business ethics to be scored consistently across businesses and can be used to create actions from findings, assign an owner and due date to required actions, request proof of implementation, and track status to closure. It can also provide targeted training linked to identified issues, offering modules on topics such as working hours, health and safety and grievance mechanisms.

Although detail regarding what information must be supplied to satisfy audit criteria and audit criteria themselves are not readily available, the Sedex system would appear to provide a platform for growers and grower-packers to enter their data, maintain integrity of that data, and provide auditability with appropriate data governance standards.

3. Discussion

The general structure underpinning the on-farm and post-farm certification processes presented herein is HACCP analysis, development of a food safety and quality plan, documentation of the plan, documentation of procedures, processes, policies into an operations manual, ongoing review and update of all aspects of the operation against the operations manual, and audit against the Operations Manual. Where new versions of standards are issued businesses are required to update all Food Safety Program documentation and collection of records to meet the requirements of the new version. Vegetable grower compliance with FSANZ and the alternative purchaser quality assurance schemes should provide a framework to identify and address points of vulnerability in production and processing chains for the introduction of antimicrobial-resistant (AMR) plant or human pathogens, minimising risks to the community. FSANZ and the purchaser quality assurance schemes should be regularly reviewed for adequacy as more information becomes available regarding AMR risk in Australian production and processing chains.

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Glossary:

appropriate enforcement agency means an enforcement agency prescribed by the regulations under the Act for the purposes of enforcement of the Act or similar purposes.

authorised officer, in relation to a jurisdiction, means a person authorised or appointed under an application Act or other legislation of the relevant *jurisdiction for the purposes of enforcement of a provision of the relevant application Act, or for purposes that include that purpose.

authorised officer means a person authorised or appointed under the Act or other legislation for the purposes of enforcement of the Act, or similar purposes, such as an 'authorised officer', 'environmental health officer' or 'inspector'.

contaminant means any biological or chemical agent, foreign matter, or other substances that may compromise food safety or suitability.

contamination means the introduction or occurrence of a contaminant in food.

equipment means a machine, instrument, apparatus, utensil or appliance, other than a single-use item, used or intended to be used in or in connection with food handling and includes any equipment used or intended to be used to clean food premises or equipment.

food business means –

(a) a business, enterprise or activity (other than primary food production)

that involves one or both of following:

(i) the handling of food intended for sale; or

(ii) the sale of food: regardless of whether the business, enterprise or activity concerned is of

a commercial, charitable or community nature or whether it involves the handling or sale of food on one occasion only; or

(b) a cell culturing food business; or

(c) a cell line supplier.

food handler means a person who directly engages in the handling of food, or who handles surfaces likely to come into contact with food, for a food business.

food handling operation means any activity involving the handling of food.

food premises means any premises including land, vehicles, parts of structures, tents, stalls and other temporary structures, boats, pontoons and any other place declared by the relevant authority to be premises under the Food Act kept or used for the handling of food for sale, regardless of whether those premises are owned by the proprietor, including premises used principally as a private dwelling, but does not mean food vending machines or vehicles used only to transport food.

A food safety management statement is a statement which – (a) has been approved or recognised by the authority; and (b) is subject to ongoing verification activities by the business or person; and (c) if required by the authority, is also subject to ongoing verification activities by the relevant authority; and (d) sets out how the obligations imposed by the Code are to be, or are being, complied with. Businesses with existing approved food safety arrangements (for example, HACCP-based food safety programs, Standard 3.2.1 of this Code, DAFF approved arrangements) should be considered to meet the

outcomes of a food safety management statement. However, the relevant authority is required to verify that the existing food safety arrangement meets the requirements of the Code.

handling of food includes the making, manufacturing, producing, collecting, extracting, processing, storing, transporting, delivering, preparing, treating, preserving, packing, cooking, thawing, serving or displaying of food.

hazard means a biological, chemical or physical agent in, or condition of, food that has the potential to cause an adverse health effect in humans.

primary food production means the growing, cultivation, picking, harvesting, collection or catching of food, and includes the following – (a) the transportation or delivery of food on, from or between the premises on which it was grown, cultivated, picked, harvested, collected or caught; (b) the packing, treating (for example, washing) or storing of food on the premises on which it was grown, cultivated, picked, harvested, collected or caught; and (c) any other food production activity that is regulated by or under an Act prescribed by the regulations for the purposes of this definition. Primary food production does not include – (d) any process involving the substantial transformation of food (for example, manufacturing or canning), regardless of whether the process is carried out on the premises in which the food was grown, cultivated, picked, harvested, collected or caught; or (e) the sale or service of food directly to the public; or (f) any other food production activity prescribed by the regulations under the Act for the purposes of this definition.

ready-to-eat food means a food that: (a) is ordinarily consumed in the same state as that in which it is sold; and (b) will not be subject to a *listericidal process before consumption; and (c) is not one of the following: (i) shelf stable foods; (ii) whole raw fruits; (iii) whole raw vegetables (iv) nuts in the shell; (v) live bivalve molluscs.

supplier, in relation to food, includes the packer, manufacturer, vendor or importer of the food.

Appendix 2C

Deliverable 2.3: Economic and Trade Data for Selected Levy Vegetables (Bagged Leafy Salad Vegetables, Carrots and Cucumbers)

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VegeNotes #3 (submitted to AusVEG in March for publication; however, the decision was made not to publish this VegeNote). *Economic and Trade Analysis of Selected Levy Vegetable Crops: Bagged Leafy Salads, Carrots, and Cucumbers. Contacts: Jessica Muller (AusVEG) and Rosalie Daniel (AusVEG).*

1. Introduction

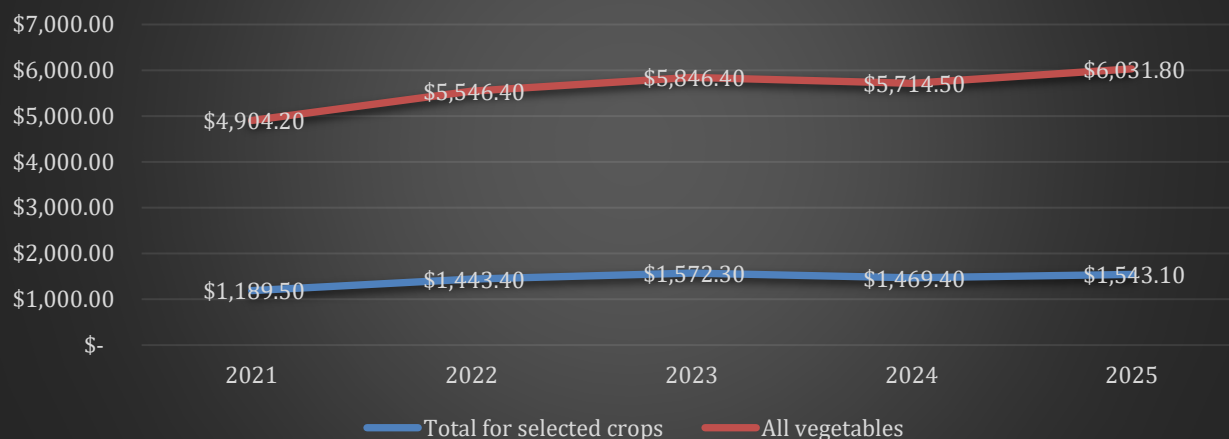
The Australian vegetable-growing sector supplies most of the fresh vegetables consumed in Australia, provides inputs for processed vegetable products, and contributes to export income. The sector produces 34 levied products (Hort Innovation, 2026). For the year ending June 2025 the total farm gate value of production of levy vegetables in Australia was \$A6.03 billion, up from \$A5.70 billion in 2023/24 (Hort Innovation 2026). Levy vegetables are those commodities which have a grower-funded levy applied to their production by the Australian government and include a wide range of vegetables, onions, and potatoes as reported in the Australian Horticulture Statistics Handbook; farm gate value (referred to as Value of Production) is derived from the modelled Wholesale price less 'known logistical, marketing and wholesale costs' (Hort Innovation 2026). Data quoted as pertaining to a year refer to the year ending June 30 of that year. Data presented herein unless stated otherwise are sourced from that publication and are stated in \$A.

The category 'bagged leafy salad vegetables' includes, but is not limited to, washed and bagged cabbage, spinach, rocket, and kale, leafy Asian vegetables, leafy salad vegetables, and head lettuce; it does not include baby broccoli or cauliflower florets. Because 'bagged leafy salad vegetables' are not reported as a specific category the sum of the values reported for cabbage, spinach, rocket, and kale, leafy Asian vegetables, leafy salad vegetables, and head lettuce is taken as a proxy for this category of levy vegetable products.

The change in value of levy vegetable production in Australia compared to the selected crops (bagged leafy salad vegetables, carrots, and cucumbers) from 2021-2025 is shown in Figure 1, with total production value increasing from \$4.90 billion in 2020/21 to \$6.03 billion in 2024/25 while the total value of production for bagged leafy salad vegetables, carrots, and cucumbers increased from \$1.19 billion to \$1.54 billion.

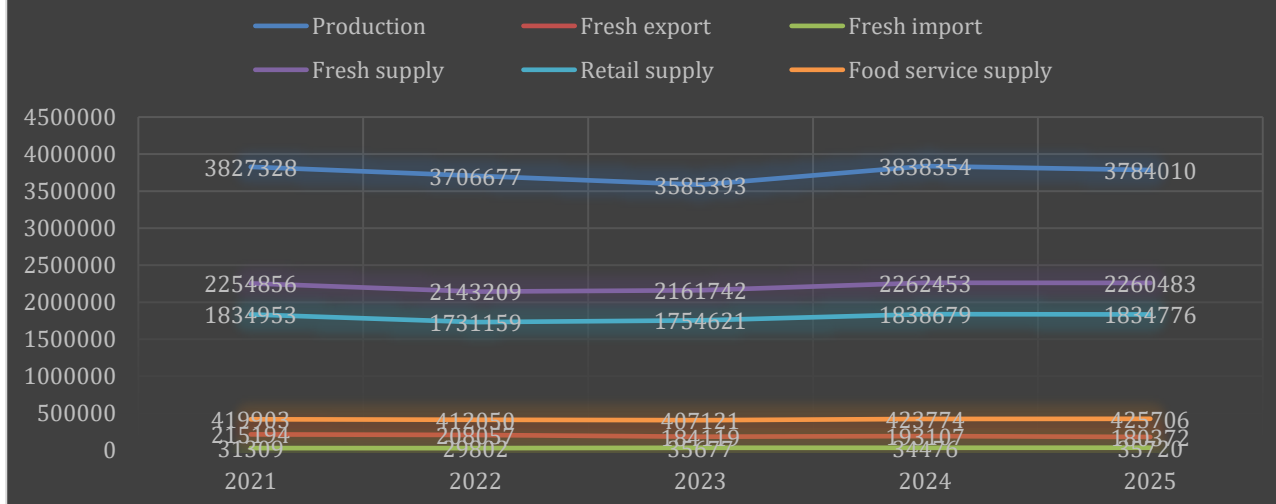
Of the 3.78 million tonnes of levy vegetables produced in Australia in 2024/25 180.4kt (5%) went to fresh export, 1.38 million tonnes (36%) went to processing, and 2.23 million tonnes went to fresh supply. Imports of fresh vegetables totalled 35.7kt, of which 79% (28.2kt) went to fresh supply and 21% (7.5kt) went to processing. Of the 2.26 million tonnes of fresh vegetable supply available in 2024/25 (2.23 million tonnes of local production and 28.2kt fresh imports) 81% went to the retail market and 19% went to the food service market. The retail market represents the volume of vegetables purchased by households through retail distribution outlets; the food service market comprises volumes of vegetables which go to food service outlets such as providores and restaurants.

Figure 1. 5-Year history of value of production for selected crops vs all levy vegetables (\$ million)



The share of total levy vegetable production going to the various end destination markets (export, retail, food service) has remained relatively constant over the last 5 years, with only minor year-on-year fluctuations; the total annual import volumes have averaged around 33kt over the same period (Fig 2).

Figure 2. 5-Year history of total levy vegetable production and end market (t)



As can be seen from Figure 3 and Figure 4, the total volume and value of levy vegetables available as fresh supply closely tracks the volume and value taken up by the retail market, with the food service sector remaining relatively constant. The last 2 years have seen a 6% year-on-year lift in the value of fresh produce going to the retail market despite the volume falling by 1% year-on-year. The wholesale value is modelled using wholesale pricing information collected from several sources by Freshlogic on behalf of Hort Innovation (Hort Innovation 2026).

Figure 3. 5-Year history of fresh vegetable supply volumes and end-market (t)

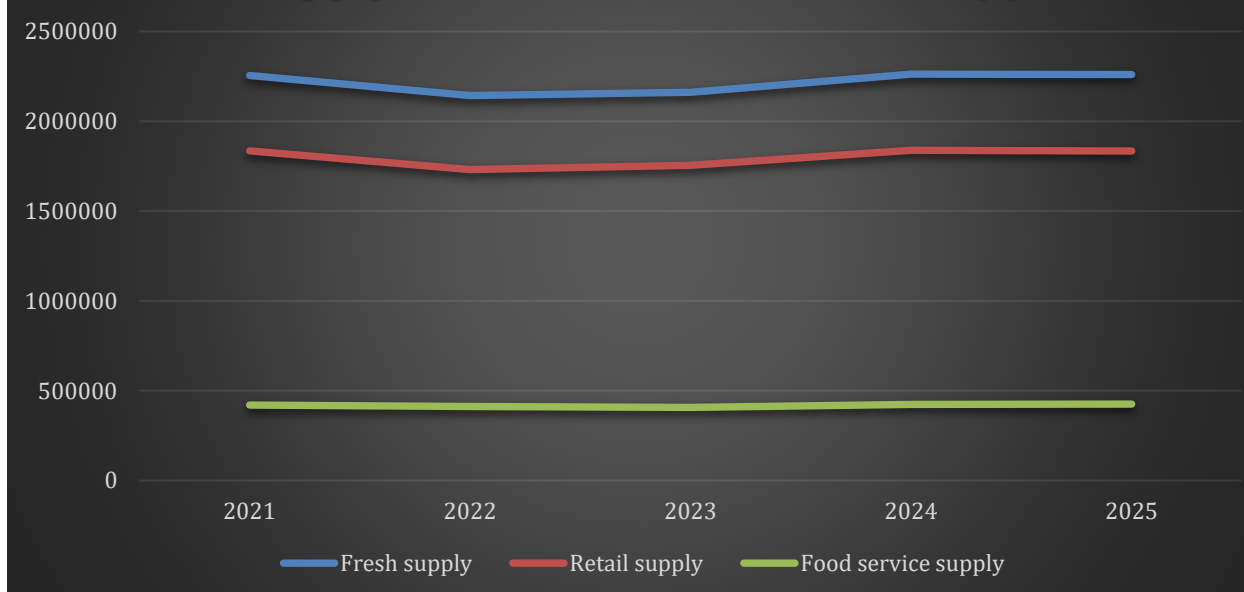
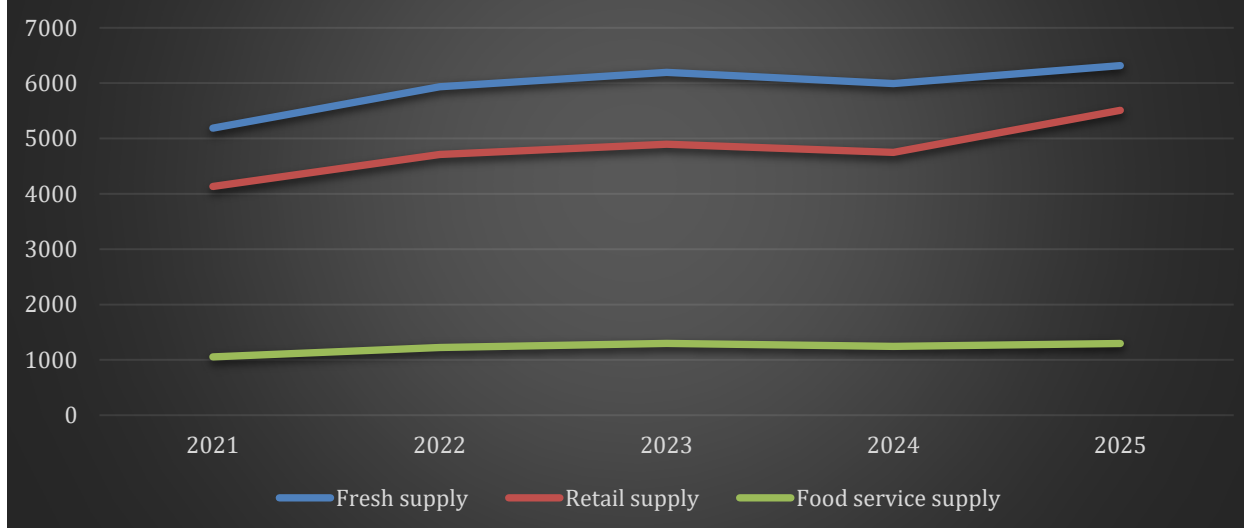


Figure 4. 5-Year history of total value of fresh production and end market destination (\$ million)



2. Data for selected vegetables (bagged leafy salad vegetables, carrots, and cucurbits)

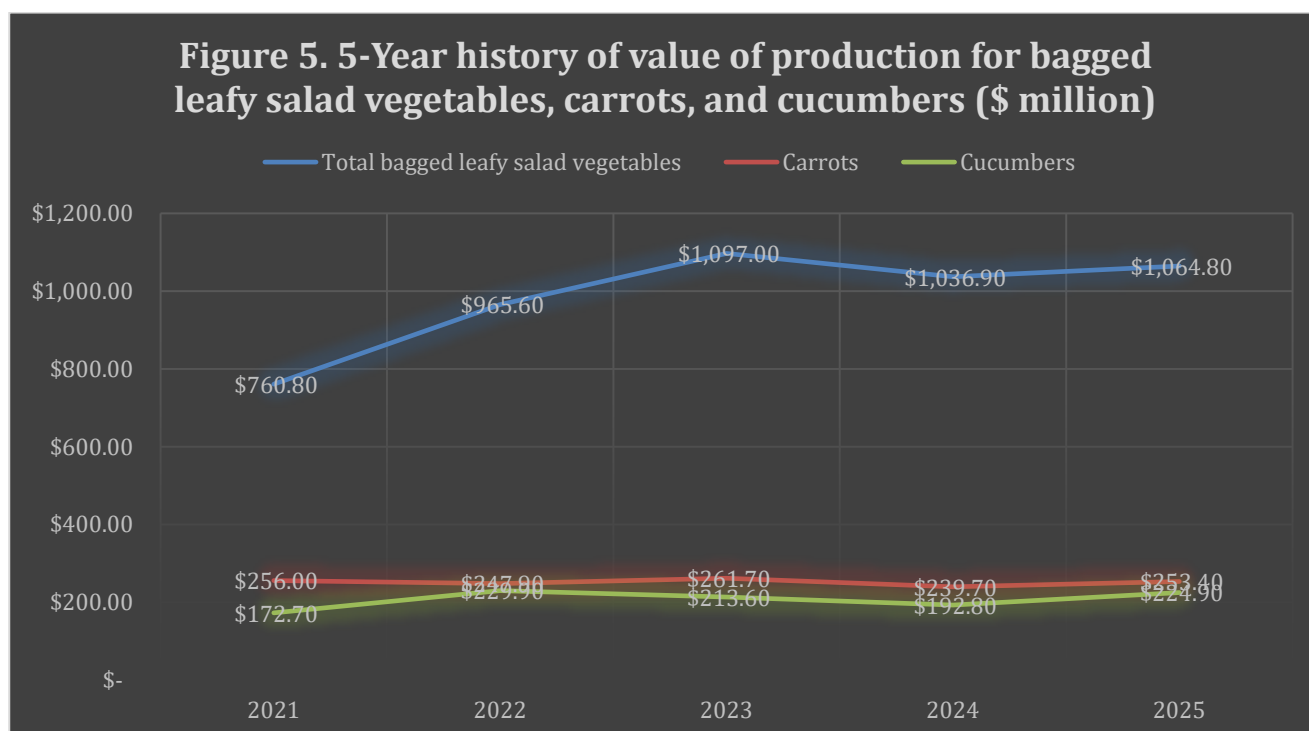
Production volumes and values for 2023/24 and 2024/25 for the selected crops (bagged leafy salad vegetables, carrots, and cucurbits) compared to the total levy vegetable industry are shown in Table 1. The selected crops represent 26.5% of the total value of levy vegetables produced in Australia in 2024/25.

Table 1. Production volumes and values for 2023/24 and 2024/25 for bagged leafy salad vegetables, carrots, and cucurbits

Commodity/ commodity group	Production volume (t)		Production value (\$ million)	
	2023/24	2024/25	2023/24	2024/25
Cabbage	62,617	63,776	\$55.0	\$55.7

English spinach/ silverbeet/ kale	6,642	6,737	\$22.4	\$24.6
Leafy Asian vegetables	30,076	27,604	\$82.4	\$79.1
Leafy salad vegetables	78,329	82,133	\$688.3	\$685.3
Head lettuce	162,418	160,382	\$243.8	\$275.8
Total bagged leafy salad vegetables	340,082	340,632	\$1,091.9	\$1,120.5
Carrots	298,821	304,038	\$239.7	\$253.4
Cucumbers	106,268	113,815	\$192.8	\$224.9
Total for the selected crops	745,171	758,485	\$1,524.40	\$1,598.80
Total for all levy vegetables	3,838,354	3,784,010	\$5,714.5	\$6,031.8
Contribution of selected crops to total levy vegetable industry	19.46%	20.05%	26.68%	26.51%

Figure 5 shows the development in sales of each of the 3 selected categories over the 5 years from 2020/21 to 2024/25. The production value of carrots and cucumbers have remained relatively steady over the 5 years whereas the bagged leafy salad vegetables category saw a 45.6% increase from a combined value of \$794.5 million in 2020/21 to \$1156.7 million in 2023/24, with a levelling off thereafter.



This increase was partly driven by an increase in the volume of leafy salad vegetables produced from 74,571t in 2020/21 to 75,720t in 2023/24 (Table 2), but primarily by an increase in value of this commodity from \$6,638/t in 2020/21 to \$9,727/t in 2023/24 (Figure 6).

Table 2. Production volume and value for bagged leafy salad vegetables 2021-23

Commodity/ commodity group	Fresh production volume (t)			Fresh production value (\$ Million)		
	2021	2022	2023	2021	2022	2023
Year	2021	2022	2023	2021	2022	2023

Cabbage		59,635	65,306	62,848	33.7	49.8	59.7
English spinach/ silverbeet/ kale		6,925	6,716	6,674	22.2	23.5	25.5
Leafy Asian vegetables		30,547	29,547	29,092	71.7	86.2	91.2
Leafy salad vegetables		74,571	78,495	75,720	495.0	589.2	736.5
Head lettuce		139,023	134,726	145,394	171.9	266.7	243.8

Figure 6. Farm gate value for selected commodities (\$/t) for 2021-23

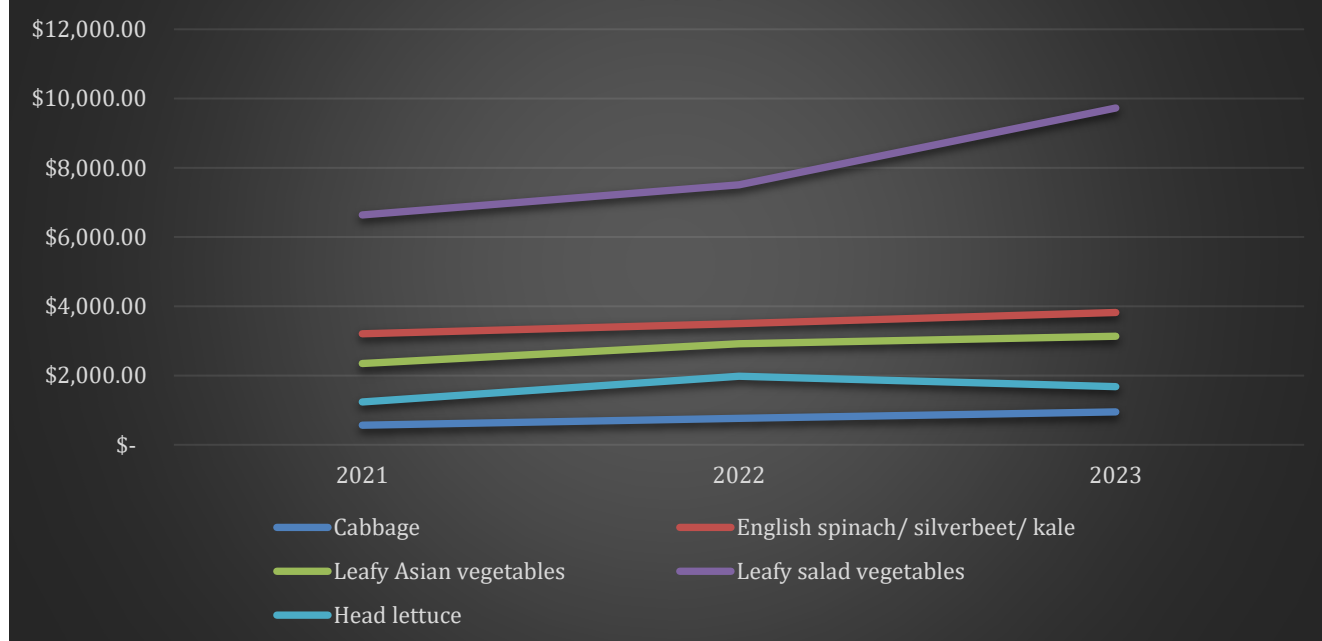


Table 3 shows the volume, value, and proportion of production which goes to the fresh export market for each of the components of the bagged leafy salad vegetable, carrot, and cucumber categories. Exports of the selected crops represent 5.55% of the total value of production for the group and 37.1% of the total value of all fresh levy vegetable exports in 2024/25.

Table 3. Commodity-wise contributions to fresh levy vegetable exports in 2024/25 for selected vegetable commodities

Commodity/ commodity group	Production volume (t)	Fresh export volume (t)	Percentage of exports to total production	Production value (\$ million)	Fresh export value (\$ million)	Percentage of exports to total value
Cabbage	62,617	467	0.75%	\$55.7	\$2.0	3.59%
English spinach/ silverbeet/ kale	6,642	506	7.62%	\$24.6	\$4.1	16.67%
Leafy Asian vegetables	30,076	0	0.00%	\$79.1	\$0.0	0.00%

Leafy salad vegetables	78,329	535	0.68%	\$685.3	\$4.7	0.69%
Head lettuce	162,418	176	0.11%	\$275.8	\$1.0	0.36%
Total bagged leafy salad vegetables	340,082	1,684	0.50%	\$1,120.5	\$13.8	1.23%
Carrots	298,821	86,414	28.92%	\$253.4	\$74.3	29.32%
Cucumbers	106,268	69	0.06%	\$224.9	\$0.6	0.27%
Total for the selected crops	745,171	88,167	11.83%	\$1,598.80	\$88.70	5.55%
Total for all levy vegetables	3,838,354	180,372	4.70%	\$6,031.8	\$239.1	3.96%

2.1 Bagged leafy salad vegetables

This segment of the Australian vegetable production industry is difficult to quantify and analyse due to its complexity. The category includes individual components such as single bag products containing e.g., baby cos lettuce, mizuna, tatsoi, chard, rocket, or baby spinach, and combination leafy salad mixes containing blends of e.g., cos, iceberg lettuce, Romaine lettuce, pea tendrils, tatsoi, mizuna, or mesclun leaves, salad kits with and without dressings and other inclusions such as broccoli or cauliflower florets, prepared fresh vegetables, and stir-fry vegetables which are grown, prepared, packed, and sold by companies such as Hussey & Co (<https://husseyco.com.au/>), OneHarvest (<https://www.oneharvest.com.au/about-us/>), and Koala Farms (<https://www.koalafarms.com.au/>) and many others. For the purposes of CRC-SAAFE Project 012 (Risk assessment of antimicrobial resistance in the vegetable industry) the category ‘bagged leafy salad vegetables’ has been defined as including, but not limited to, washed and bagged cabbage, spinach, rocket, and kale, leafy Asian vegetables, leafy salad vegetables, and head lettuce; it does not include baby broccoli or cauliflower florets. The category ‘bagged leafy salad vegetables’ is not reported as a specific category in the Australian Horticulture Statistics Handbook 2024/25 hence the sum of the values reported for cabbage, spinach, rocket, and kale, leafy Asian vegetables, leafy salad vegetables, and head lettuce have been taken as a proxy for this category, accepting that not all cabbage and head lettuce production goes into bagged leafy salad vegetable mixes.

Figure 7 shows the 5-year history to 2025 for the value of production of the total bagged leafy salad vegetable category using the above definition and the individual component categories. The total production (farm gate) value of bagged leafy salad vegetables for the 2024/25 year was \$1,120.5 million, an increase of 2.6% on the previous year. Leafy salad vegetables with a production value of \$685.3 million in 2024/25 represented 61.2% of the overall production value for the bagged leafy salad vegetable segment, followed by head lettuce (\$275.8 million; 24.6%).

Figure 7. 5-Year history of value of production for bagged leafy greens (\$ million)

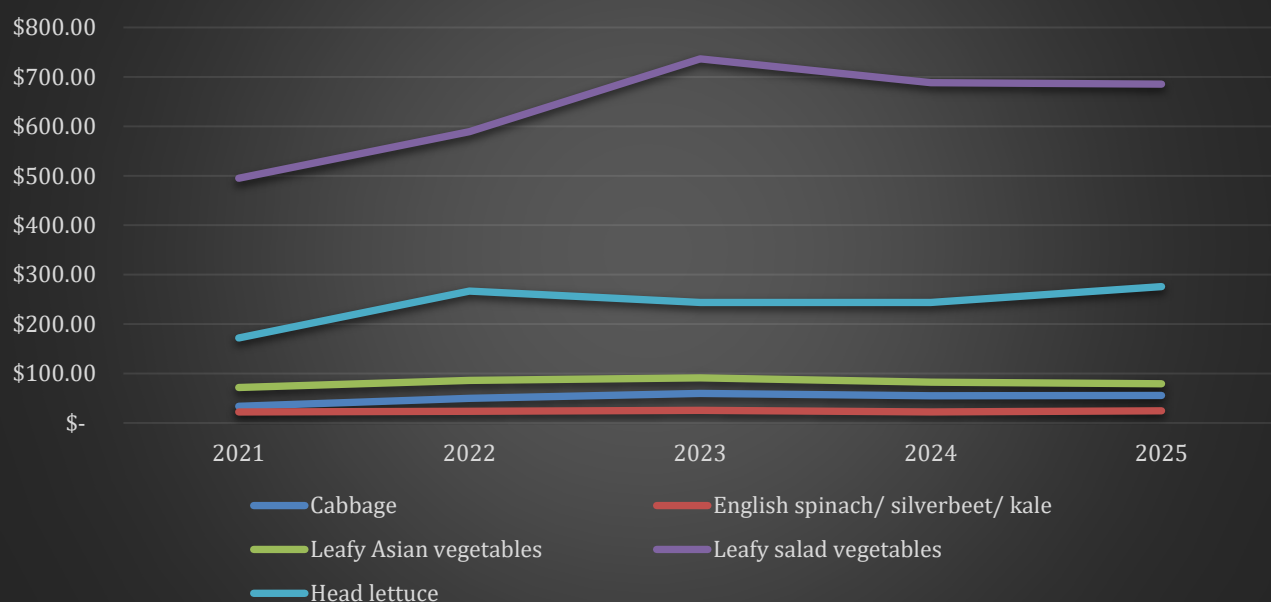


Table 4 shows the value chain for each commodity group within the category ‘bagged leafy salad vegetables’. Exports and imports for each of the commodity groups are relatively small compared to farm gate production value. The proportion of fresh supply value going to each of retail supply and food service supply varies between the commodity groups, averaging approximately 70% to retail and 30% to feed service across the category. Approximately 82% of the wholesale value of cabbage supply, 63% of the wholesale value of English spinach, silverbeet and kale supply, 88% of the wholesale value of leafy Asian vegetables supply, 69% of the wholesale value of leafy salad vegetables supply, and 85% of the wholesale value of head lettuce supply goes to the retail market. Conversely, the figures for wholesale value going to the food service sector for these commodities is approximately 18%, 37%, 12%, 31%, and 15% respectively.

Table 4. Value chain for bagged leafy salad vegetables, 2024/25

Commodity/ commodity group	Production farm gate value (\$ million)	Fresh value million)	export (\$	Fresh value million)	import (\$	Fresh supply (wholesale value; \$ millions)	
						Retail supply	Food service supply
Cabbage	\$55.7	\$2.0		\$0.0		\$51.2 (81.9%)	\$11.3 (18.1%)
English spinach/ silverbeet/ kale	\$24.6	\$4.1		<\$0.1		\$15.5 (62.8%)	\$9.2 (37.3%)
Leafy Asian vegetables	\$79.1	\$0.0		\$0.0		\$81.7 (87.8%)	\$11.4 (12.3%)
Leafy salad vegetables	\$685.3	\$4.7		\$0.0		\$551.2 (68.8%)	\$250.3 (31.2%)
Head lettuce	\$257.8	\$1.0		\$0.1		\$275.6 (85.2%)	\$48.0 (14.8%)
Total bagged leafy salad vegetables	\$1,102.50	\$11.80		\$0.10		\$975.20 (69.3%)	\$432.80 (30.7%)

Table 5 shows the percentage of the commodities grown in each state and the contribution by state to the export market, with production and exports concentrated largely in Qld, NSW, and Victoria.

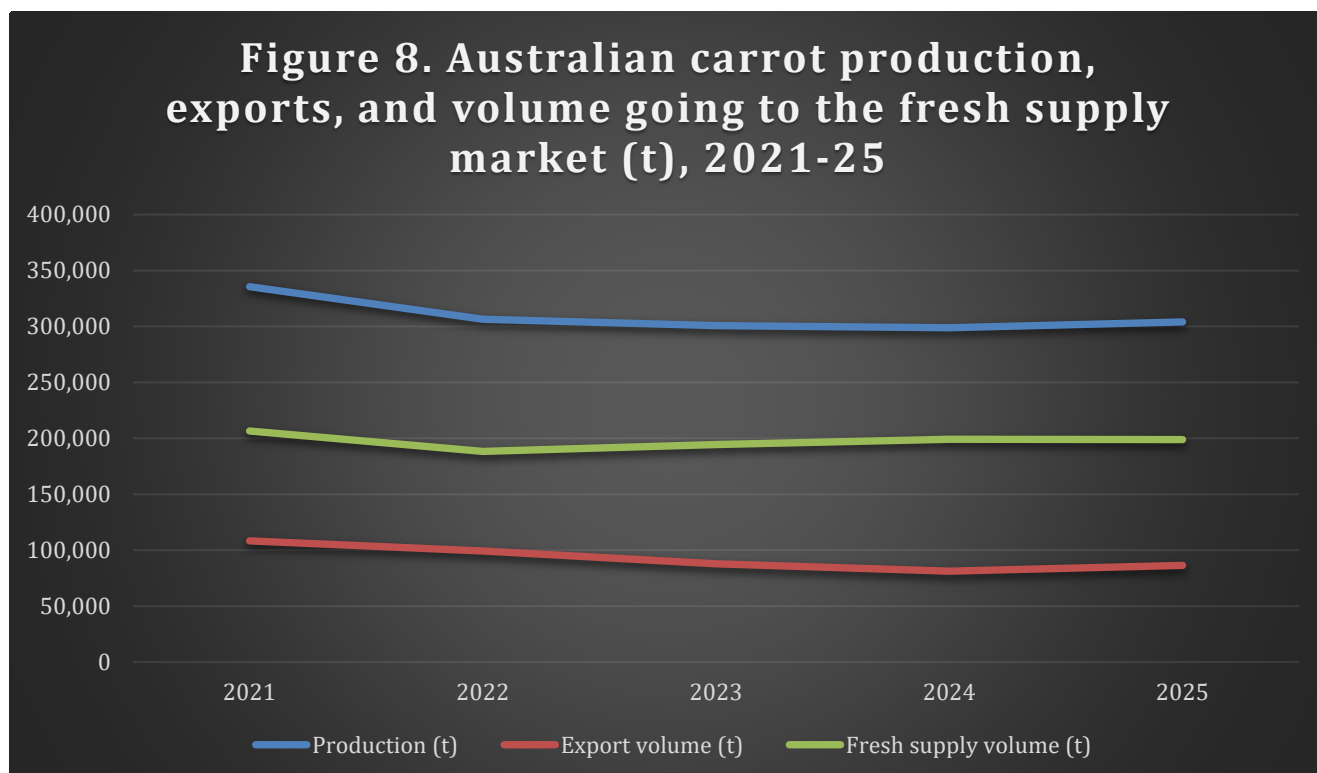
Table 5. State-wise contribution to production and exports for bagged leafy salad vegetables, 2025

Commodity/ group	commodity	Qld	NSW	Vic	Tas	SA	WA
Cabbage	Production	31.5%	26.0%	30.4%	0.5%	2.9%	8.8%
	Exports	31.0%	8.1%	45.0%	0.0%	5.4%	10.5%
English spinach/ silverbeet/ kale	Production	31.5%	12.7%	45.1%	4.1%	1.4%	5.3%
	Exports	1.0%	1.2%	69.2%	0.0%	1.3%	27.3%
Leafy Asian vegetables	Production	27.9%	42.7%	23.9%	<0.1%	0.2%	3.2%
	Exports	No exports made					
Leafy salad vegetables	Production	27.7%	7.4%	44.7%	9.6%	7.4%	3.2%
	Exports	20.1%	7.0%	69.2%	0.0%	1.9%	1.9%

2.2 Carrots

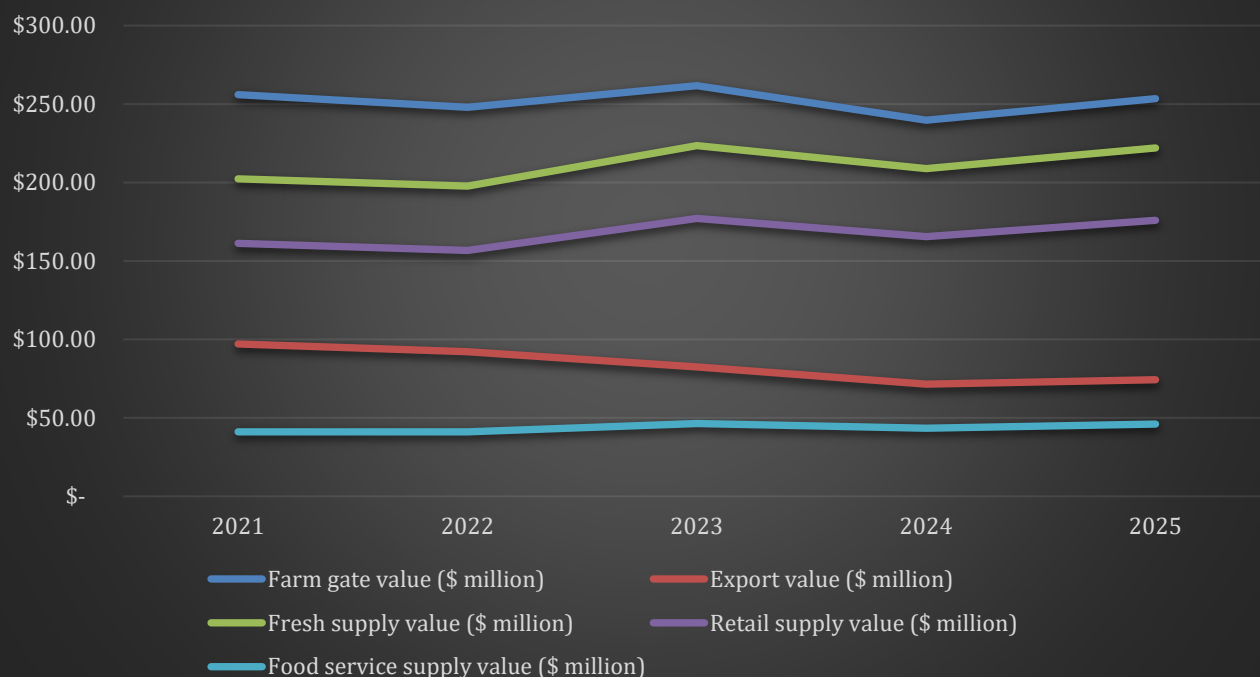
Carrot production in Australia is concentrated in the hands of a number of large producers such as Harvest Moon (<https://www.harvestmoon.com.au/>), Kalfresh (<https://www.kalfresh.com.au/>), Lamattina (<https://globalfarms.com/supplier/rocky-lamattina-and-sons/home>), Moffatts (<https://www.moffattcarrots.com.au/>), Premium Fresh (<https://www.premiumfresh.com.au/>), Sumich (<https://www.sumich.com/>), and Zerella (<https://zerellafresh.com.au/carrots>).

Carrot production has been relatively stable over the last 5 years with annual production ranging from a high of 335.5kt in 2021 to a low of 298.8kt in 2024; since 2022 production levels have been stable, averaging 302.5kt (Figure 8). Some 28% of the volume produced (Figure 8) and 30% of the farm gate value (Figure 9) goes to the export market.



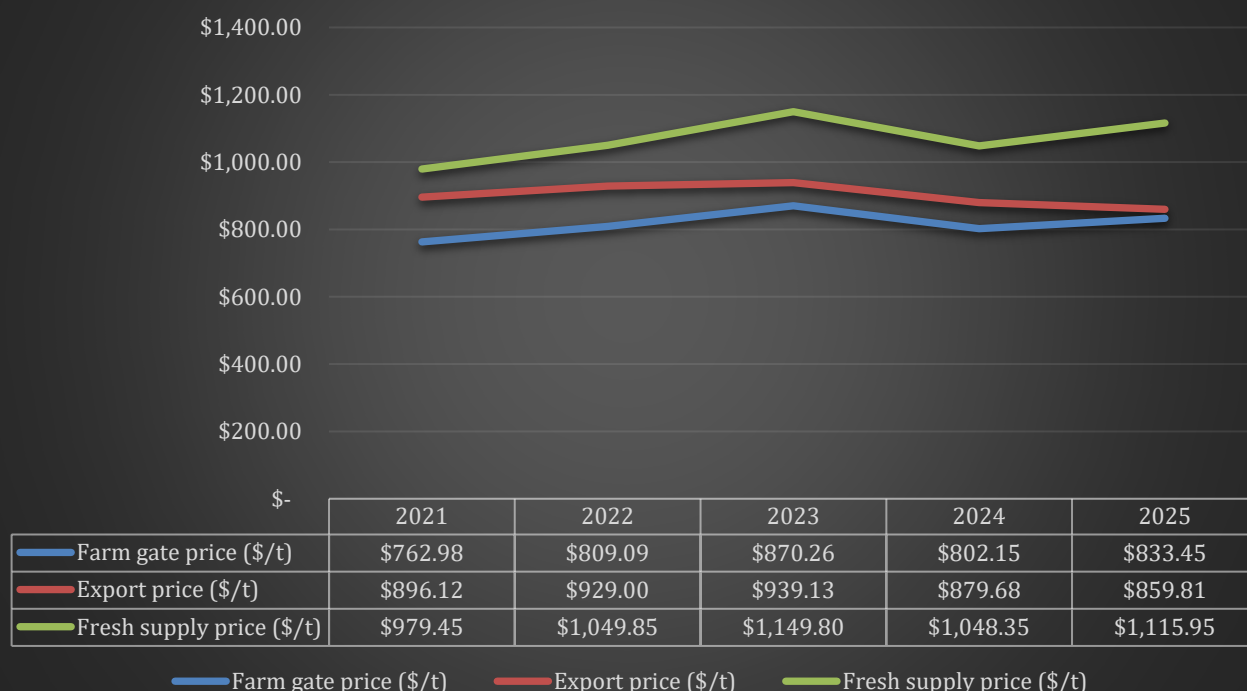
The farm gate value of carrot production in Australia has averaged \$251.7 million from 2021-2025 with the export value falling steadily from a high of \$97.1 million in 2021 to \$74.3 million in 2025 (Figure 9). In 2025 the retail market accounted for 79% of the fresh supply market for carrots and the food services supply market accounted for 20%. The value of the retail market for carrots in Australia tracks the farm gate price and has ranged from a high of \$177.1 million in 2023 to a low of \$156.7 million in 2022, with an average value of \$167.3 million; the value of the food service supply market has ranged from a high of \$46.4 million in 2023 to a low of \$41.1 million in 2021 and 2022, with an average value of \$43.6 million (Figure 9).

Figure 9. Value of Australian carrot production, exports, fresh supply market, retail market, and food service market (\$ million), 2021-25



The wholesale price per tonne for carrots in the retail market tracks the farm gate price closely (Figure 10) but this may be an artefact of the model used to calculate farm gate prices from surveyed wholesale prices rather than collecting information on both variables independently. The 5-year average farm gate price is \$815.59/t compared to the fresh supply wholesale price of \$1,068.68/t, implying a wholesale margin of \$253.09/t (23.68%) across the 5 years.

Figure 10. Farm gate, export, and fresh supply price (\$/t) for Australian carrots, 2021-25



Based on figures for 2025 (Table 6) Western Australia is the largest carrot producing state by volume, accounting for 38.6% of production and 92.6% of exports. Victoria, Tasmania and South Australia each produce similar volumes of carrots at 17.5%, 16.4%, and 15.3% respectively; Queensland produces 10.3% of the crop. Queensland and Tasmania each contribute 3% of production to exports and Victoria contributes 1%.

Table 6. State-wise contribution to production and exports volumes for carrots, 2025

	Qld	NSW	Vic	Tas	SA	WA
Production	10.3%	1.9%	17.5%	16.4%	15.3%	38.6%
Exports	3.0%	0.0%	1.0%	3.0%	0.3%	92.6%

The main export markets for Australian carrots are in the Middle East and Southeast Asia (Table 7). The UAE accounted for 34% of carrots exported from Australia in 2025, followed by Saudi Arabia (17%), Malaysia (14%), Singapore (12%), and Qatar (8%). The 3 year average export figures suggest that this export trade is well established.

Table 7. Carrot exports (t) by country of destination, 2023-25

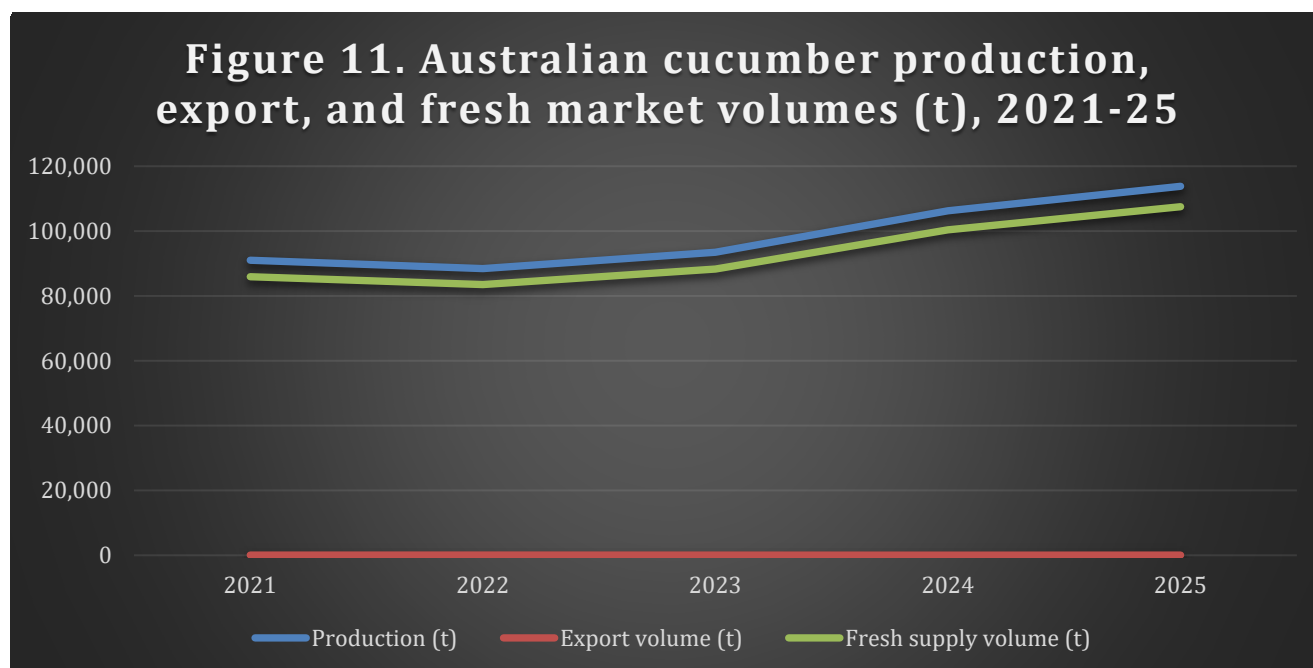
Country destination	of 2023	2024	2025	3-year average
UAE	29,950 (34%)	25,888 (32%)	29,255 (34%)	28,364 (33%)
Saudi Arabia	13,371 (15%)	13,995 (17%)	14,905 (17%)	14,090 (17%)
Malaysia	13,447 (15%)	12,494 (15%)	12,101 (14%)	12,681 (15%)
Singapore	10,934 (12%)	9,900 (12%)	9,602 (12%)	10,145 (12%)
Qatar	6,925 (8%)	4,745 (6%)	6,694 (8%)	6,121 (7%)
Others	13,221 (15%)	14,259 (18%)	13,857 (16%)	13,779 (16%)

Total	87,847	81,280	86,414	85,180
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2.3 Cucumbers

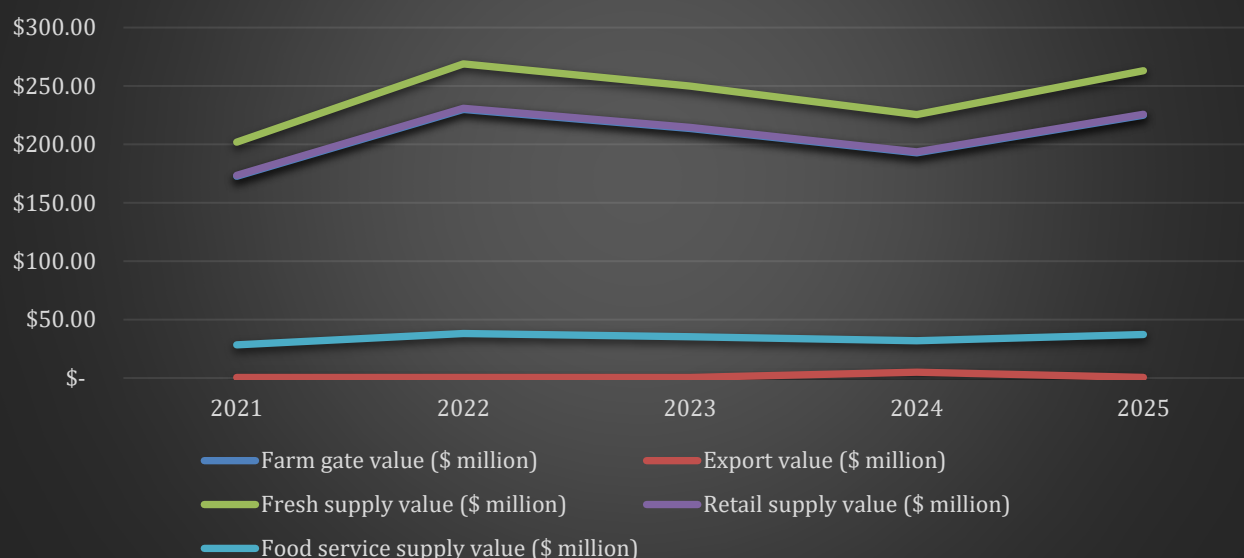
Cucumber production in Australia is characterised by a diversity of production systems (plastic tunnels, glasshouses, and open-field cultivation), varieties (Lebanese, continental, and baby ‘snacking’), locations, and scale.

Cucumber production has been steadily increasing over the last 4 years in Australia with annual production ranging from a low of 88.4kt in 2022 to a high of 113.8kt in 2025 (Figure 11). A very small volume of production (69t, equivalent to 0.06% of total production in 2025) goes to export markets. As can be seen from Figure 11, this trend has been consistent across the last 5 years.



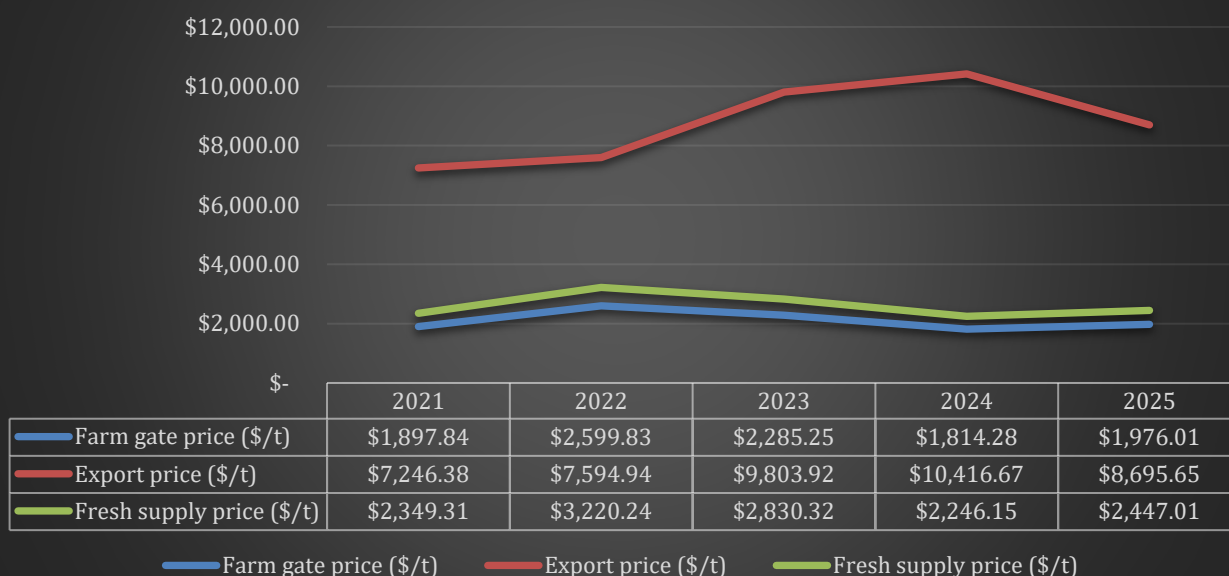
The farm gate value of cucumber production in Australia has averaged \$206.8 million from 2021-2025 (Figure 12). In 2025 the retail market accounted for 86% of the fresh supply market for cucumbers and the food services supply market accounted for 14%. The value of the retail market for cucumbers in Australia tracks the farm gate value and has ranged from a low of \$173.5 million in 2021 to a high of \$230.9 million in 2022, with an average value of \$207.7 million; the value of the food service supply market for cucumbers has ranged from a low of \$28.4 million in 2021 to a high of \$38.1 million in 2022, with an average value of \$34.2 million (Figure 12).

Figure 12. Value of Australian cucumber production, exports, fresh supply, retail supply, and food service market (\$ million), 2021-25



The 5-year average farm gate price for cucumbers is \$2,114.64/t compared to the 5-year average fresh supply wholesale price of \$2,618.61/t, implying a wholesale margin of \$503.97/t (19.25%) across the 5 years (Figure 13).

Figure 13. Farm gate, export, and fresh supply price (\$/t) for Australian cucumbers, 2021-25



Based on figures for 2025 (Table 8) South Australia and Queensland are the two largest cucumber producing states by volume, accounting for 34.1% and 31.0% of production respectively. Victoria is the largest state for exports of cucumbers (61.4%), followed by Queensland (32.4%).

Table 8. State-wise contribution to production and exports for cucumbers, 2025

Qld	NSW	Vic	Tas	SA	WA
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Production	31.0%	10.2%	12.8%	2.0%	34.1%	8.4%
Exports	32.4%	4.6%	61.4%	00	1.2%	0.0

The main export markets for Australian cucumbers are Hong Kong and Singapore (Table 9). Hong Kong accounted for 46% of cucumbers exported from Australia in 2025, followed by Singapore (16%), New Zealand (15%), Nauru (9%), and Brunei Darussalam (3%). The 3-year average export figures suggest that this export trade is small and not increasing.

Table 9. Carrot exports (t) by country of destination, 2023-25

Country of destination	2023	2024	2025	3-year average
Hong Kong	37 (73%)	27 (56%)	32 (46%)	32 (57%)
Singapore	6 (12%)	15 (31%)	16 (23%)	12 (21%)
New Zealand	0 (0%)	<1 (<2%)	10 (15%)	3 (5%)
Nauru	1 (2%)	1 (2%)	6 (9%)	3 (5%)
Brunei Darussalam	<1 (<2%)	<1 (<2%)	2 (3%)	1 (2%)
Others	6 (12%)	3 (6%)	3 (4%)	4 (7%)
Total	51	48	69	56

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Appendix 2D

Deliverable 2.4: Exploring the Potential for Antimicrobial Resistance in Ready-to-Eat Vegetables: A Farmer-Level Scoping Study

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Abstract

In vegetable production systems AMR risks can be linked to antibiotic use in animal production enterprises or in-crop use of antibiotics, irrigation water, soils, composts, and pesticides, and in post-harvest processing and packing. Inputs such as fungicides, herbicides, metals, and disinfectants can act as co-selection agents for AMR. To gain a better understanding of these risks in Australian ready-to-eat vegetable production systems a preliminary scoping study was conducted at the grower level. The survey sought to identify potential points of entry for AMR pathogens into vegetable production systems, to identify certification schemes which could mitigate the introduction of AMR pathogens into the system, and to understand grower estimates of the potential economic impact of AMR on the industry. Data collection was via a survey which was administered face-to-face to 13 vegetable producers from southeast Queensland to Victoria and Tasmania. It is recognized that the respondent cohort is small compared to the estimated 4,000+ vegetable growers in Australia. However, the study identified that vegetable production systems are diverse and complex, ranging from single operator protected cucumber production to open field production of a range of crops and that vulnerabilities exist in the use of composts, the supply of seeds and seedlings, and in post-harvest processing and packing enterprises. The study recommends that these areas of the production chain be investigated to further qualify their potential AMR risks. The study also recommends that consideration be given to conduct a base-line survey for prevalence of AMR pathogens at the retail level of the vegetable production industry.

1. Introduction

Local production is the major contributor to total vegetable consumption in Australia and also supplies a small, established export market. The industry produced 3.78 million tonnes (Mt) of vegetables with a farm gate value of \$A6.03 billion in 2024-25, of which 2.26Mt went to the fresh supply market (1.83Mt to retail outlets; 0.43Mt to food services), 0.18Mt went to export markets, and 1.38Mt went to processing. Bagged leafy salad vegetables, carrots, and cucumbers represent 26.5% of the total value of levy vegetables produced in Australia in 2024/25 (Hort Innovation 2026). Consumption of ready-to-eat bagged leafy salad vegetables is increasing in Australia and the range of products available is widening, from simple pre-packed bags of baby spinach or rocket to more complex mixtures such as Asian-style salad bowls which offer a combination of salad mix (cabbage, carrots, corn kernels, mizuna), noodles, and soy and sesame dressing, or honey mustard salad kits which combine salad mix (carrot, cabbage, wombok, mizuna, and celery) with honey mustard dressing and croutons. The potential for these ready-to-eat bagged products as vectors of antimicrobial-resistant (AMR) pathogens is recognized of snacking varieties of cucumbers and carrots. The opportunity for transmission of AMR with these commodities is higher than with processed or cooked vegetables because they are generally eaten raw. To identify points in production systems where AMR might be introduced it is necessary to understand the relevant production chains, compliance systems which operate in the production environment, and farmer perceptions of the risks and potential costs posed by AMR. Leafy greens have been repeatedly associated with foodborne disease transmission (e.g., FDA 2021a, FDA 2021b). In the US in 2024 an outbreak of *Salmonella* attributed to cucumbers from two Florida farms resulted in 551 cases of illness and 155 hospitalizations across 34 states (FDA 2024). In 2025 a second *Salmonella* outbreak attributed to cucumbers originating from one of the farms implicated in the 2024 outbreak resulted in a 21-state recall, 69 cases of illness, and 22 hospitalizations (FDA 2025). In Western Australia in 2022 19 cases of *Salmonella* infections linked to consumption of baby cucumbers resulted in 3 hospitalizations (FSN, 2023). In March 2025 a major pre-emptive Australia-wide recall of a wide range of bagged leafy green products was undertaken following the detection of Shiga-toxin producing *E. coli* (STEC) in two spinach products (Food Research Lab 2025). In Australia between 2001 and 2017 there were 92 confirmed or suspected cases of foodborne disease outbreaks associated with fresh produce, resulting in 3,422 reported illnesses, 446 hospitalizations, and 4 deaths (Rothwell *et al.*, 2024). Of the disease outbreaks attributed to single-ingredient fresh produce in this study, 1 was attributed to shredded iceberg lettuce (*Salmonella*; 36 illnesses; 6 hospitalizations), 1 to cucumbers

(*Salmonella*; 6 illnesses; 1 hospitalization), and 1 to bagged salad products (*Salmonella*; 311 illnesses; 24 hospitalizations). Recognizing the risk for leafy vegetables to vector human pathogens Food Standards Australia New Zealand introduced Standard 4.2.8 - Primary Production and Processing Standard for Leafy Vegetables in February 2025 with the aim of 'reducing the presence of hazards on leafy vegetables, keeping vegetables safe for consumers to eat raw' (FSANZ 2025). Leafy vegetables are defined under the Standard as fresh vegetables of a leafy nature where the leaf is consumed raw including, but not limited to all lettuces, spinach, kale, Asian leafy greens, leafy herbs, spring onions/scallions, silverbeet/chard, cabbage, and microgreens. The Standard specifically excludes broccoli, broccolini, cauliflower, asparagus, artichoke, root and tuber vegetables, bulb vegetables, brussel sprouts, kohlrabi, cucumber, peppers, eggplant, rhubarb, squash, celery and leek. The Standard applies to all primary producers who grow and/or harvest leafy vegetables and primary processors of leafy vegetables (businesses that wash, trim, sort, sanitize, store, combine or pack leafy vegetables, or transport leafy vegetables between pack houses). The Standard requires subject primary producers and primary processors to have an approved food safety management statement showing how risks are managed, demonstrating traceability of products, showing how inputs (including seeds, seedlings, soil, fertilizer and water) are managed so they do not make leafy vegetables unsafe to eat, and demonstrating good personal hygiene and health practices of people, premises, and equipment used. The Standard also prohibits primary producers and primary processors from selling or supplying leafy vegetables for human consumption if they ought reasonably know or suspect that the leafy vegetables are unacceptable. Antimicrobial resistance (AMR) occurs when disease-causing microorganisms (including bacteria, viruses, fungi and parasites) are no longer effectively controlled by antimicrobial agents such as antibiotics, antivirals, antifungals and antiparasitics used to kill them, or to prevent or treat disease. In agriculture AMR can be related to the use of antibiotics in animal production systems such as intensive poultry or piggery operations. In these production systems use of antibiotics can produce resistant pathogens which can be introduced to cropping systems through contaminated manures, composts, or irrigation water. AMR pathogens can then be passed via contaminated vegetable products to consumers, resulting in product recalls and leading potentially to illness, hospitalizations, and deaths. Similarly, the use of fungicides or bactericides in crop production can lead to the development of resistance in the target pathogen or in human pathogens, limiting treatment options and increasing treatment costs.

2. Aim

The aim of this preliminary scoping study was to gain a basic understanding of vegetable production chains in order to identify potential points of entry for AMR pathogens into the system, to identify certification schemes which could mitigate the introduction of AMR pathogens into the system and which vegetable growers must comply with, and to gather grower estimates of the potential economic impact of AMR on the industry.

3. Materials and methods

Rationale and recruitment

The original study design proposed 2 focus groups each involving 5-6 producers in 2 regions of significant vegetable production on the Australian east coast (1 in SE Queensland; 1 in the Melbourne metropolitan/ west Gippsland area), locations which serve two of Australia's largest population centres (Brisbane and Melbourne). Consultations with AUSVEG, the prescribed peak industry body representing the Australian vegetable, potato, and onion industries (<https://ausveg.com.au/about-ausveg/>) indicated that focus groups would be unlikely to attract sufficient participants due to the heavy work schedules of target growers. It was subsequently decided to conduct individual informal discussions accompanied by, where interviewees verbally agreed, a brief anonymized survey of production processes employed, individuals' perspectives on AMR and pesticide resistance management, and estimates of the potential economic impact of AMR. The survey was developed and validated internally and was modified following three initial interviews by adding a question regarding growers' use of beneficial insects and IPM in their crop management practices. Recruitment was elicited through an introductory email followed by a further email request 7-14 days after the initial email. Twenty-seven requests resulted in 13 face-to-face discussions and surveys being conducted from October 2025 to February 2026. All interactions were conducted by the same person who introduced the rationale for the study and the concept of AMR as it pertains to vegetable production before offering the opportunity to participate in the survey. Thirteen growers participated in the interview-survey format.

Respondent profiles

Three respondents were from the Melbourne-East Gippsland region, 1 from Werribee-Werribee South, 1 from Bacchus Marsh, 1 from northern Tasmania, 1 from the Sydney basin region, 4 from Coffs Harbour/ Woolgoolga, and 2 from southeast

Queensland (Fig. 1). Individual respondents were either owner/ operators or senior staff involved in the businesses. Eight of 13 respondents grew their crops in open field production systems and 5 employed protected cropping methods (all in poly tunnels). All open-field production respondents could be classified as large-scale commercial vegetable producers. One protected cropping respondent could be classified as a medium-scale producer, and the 4 protected cropping cucumber growers could be classified as medium-scale producers. Several of the respondents grew their crops across multiple sites. None of the respondents sell their produce at the farm gate level, and all sell at least part of their production to wholesale markets (5 sell to wholesalers only). Eight of 13 respondents sell to multiple markets (wholesale, retail, processing), 6 supply export markets, 5 supply retail markets, and 6 supply processors.

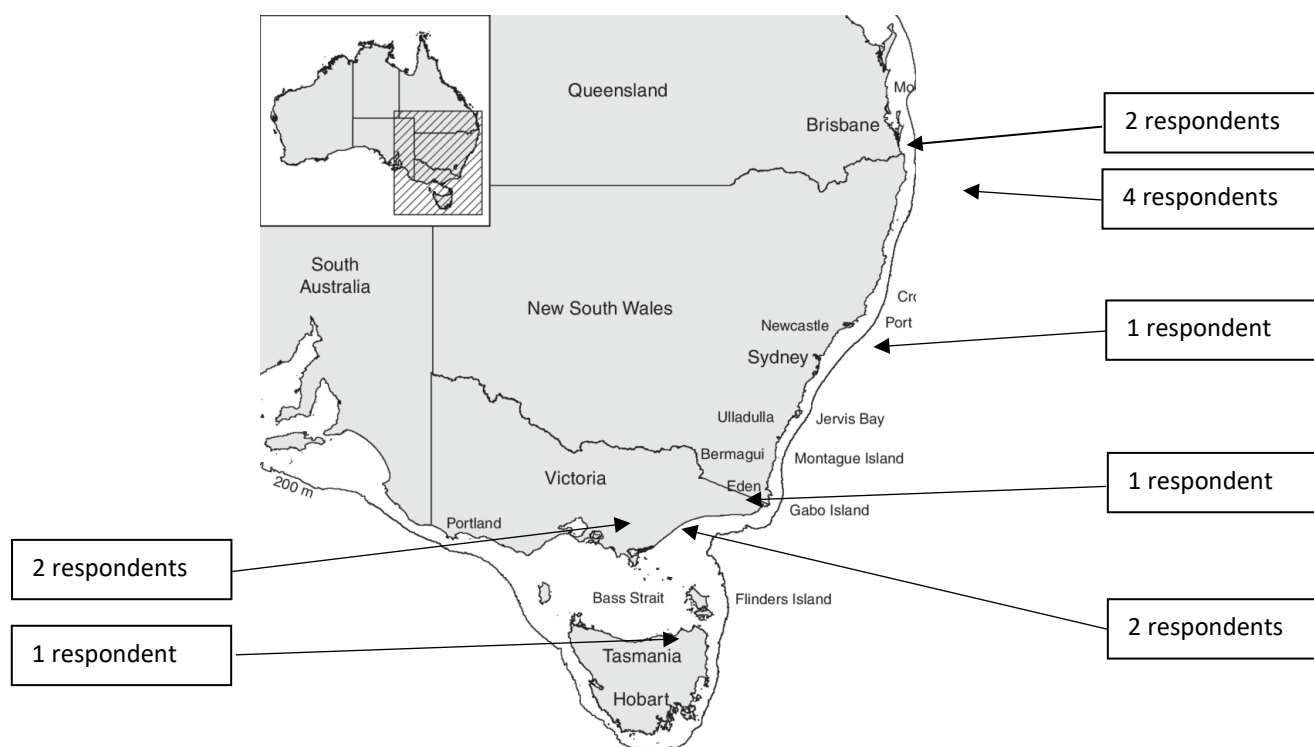


Figure 1. Locations of respondents (map source: <https://www.researchgate.net/publication/255731616/figure/fig2/AS:667833314844691@1536235278844/Map-of-south-east-Australia-showing-locations-and-upper-slope-sampling-areas-dark-line.png>)

Cropping systems employed

The enterprise mix between the open field cropping respondents included baby leafy greens, brassicas, carrots, corn, green beans, head lettuce, leeks, and onions. The cropping mix between the 5 protected cropping respondents included Armenian cucumbers, basil, bitter melon, blueberries and blackberries, cucumbers, green beans, okra, and pak choy.

None of the respondents grew either carrots or cucumbers in rotation with leafy greens or lettuce. Two respondents grew leeks and baby leaf vegetables or baby cos. The two producers of baby leafy greens and salad mixes also grow head lettuce. The carrot producers grow several carrot varieties and a range of other vegetables, including brassicas, corn, and green beans but do not grow leafy green vegetables or lettuce. All respondents harvest into field bins, including bulk bins for transport to processing or cooling facilities, off-site consolidators or processors, or wholesale markets. Six of 13 respondents bag their own produce, 1 respondent washes, dries, packs, and pre-packs their own produce. One respondent sends bulk product off-site to a separate processing facility. One carrot grower sells to a third party for juicing and disposes of 'off-specification' product to cattle producers for feed; one carrot grower cuts and grates their own product.

4. Results

Some respondents were not able answer all questions.

Production environment

The environment surrounding each individual growing site varied significantly. Respondents in Bacchus Marsh, Coffs Harbour, the Sydney basin, Tasmania, Werribee-Werribee South, and west Gippsland were located on the outskirts of major population centers hence were closer to residential properties whereas the east Gippsland producer and the southeast Queensland producers were more remote. All respondents reported other vegetable growing enterprises within 1km. Seven of 13 respondents reported cattle-based enterprises (grazing and dairy; no feedlots) located within 1km of their farm. Four of 13 respondents reported poultry production enterprises within 1km, 8 stated that there were none, and 1 was not sure. One respondent reported a piggery within 1km, 1 reported that there was an orchard within 1km, and 1 reported that there was a very small vineyard within 1km. Nine of 13 respondents reported that there were residential buildings or industrial facilities within 1km, including hobby farms. No cotton growing was conducted within 1km of any of the vegetable producing sites however, 1 respondent reported strawberry cropping within 1km of their production area and, in the Coffs Harbour area all of the respondents were within 1km of small berry farms, particularly blueberries. One respondent reported a fertilizer storage and blending facility was located within 1km of their farm.

Production inputs and field practices

Eight respondents stated that they buy seeds sourced from overseas, 3 stated that they did not buy seed internationally, and 2 stated that they use transplants. Of the 2 respondents using transplants, 1 grew their own seedlings and 1 bought seedlings from a specialist producer. All respondents stated that they buy seed from local suppliers. This question could have been worded more clearly as most local seed suppliers are subsidiaries of international seed companies (Fig 2.), hence there was some cross-over in responses between buying from international companies and Australian companies. Of the 13 respondents who purchase seed, all use multiple suppliers whereas the 2 who purchase transplants nominated only 1 source each. Where respondents were willing to name their seed suppliers (10 respondents) sources included the main companies involved in this market: Bejo, Enza Zaden, Fairbanks, HM Clause, Lefroy Valley, Nunhems, Rijk Zwaan, Seminis, and SPS. The seedling suppliers nominated were Ace Seedlings, Berwick Speedy Seedlings, and Leppington Speedy Seedlings.

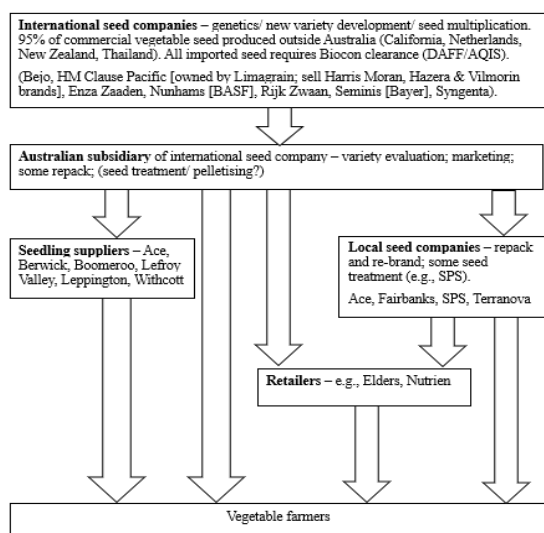


Figure 2. Structure of the Australian vegetable seeds market

None of the 13 respondents required any certification from seed or seedling suppliers regarding disease-free or pesticide residues status or had any testing done on purchased products. Rather, they relied on statements on seed labels, implied warranties, and trust gained through long-term relationships with suppliers. Nine respondents stated that they do not require seed be treated with any specific products; 1 respondent required that carrot seed be treated with thiram and metalaxyl; 1 carrot grower stated they sometimes require their seed be treated. Two respondents stated that they took whatever was supplied by the seed company. One lettuce grower required seed be primed and coated to make seeding easier. None of the respondents required seed be irradiated or fumigated. The respondent who grows their own transplants

uses peat moss as a growing substrate and irrigates with potable water. The 5 respondents growing under protected cropping systems all use cocopeat slabs as growing media; 1 uses municipal mains water for irrigation, 3 irrigate from dams, and 1 uses municipal re-cycled water. None of the respondents use biosolids or fresh animal manure on their crops. Four of 13 respondents (4 of 8 open-field producers; 0 protected cropping growers) use commercial compost (1 uses composted poultry manure; 1 uses a product manufactured from several waste streams in Gippsland, including the dairy industry, 1 uses compacted, sterilized, and extruded product, and 1 uses commercial compost from an unspecified source). None of the respondents use degradable or non-degradable mulches; 1 respondent uses cover crops as mulch in their production system.

Irrigation

Some respondents use water from more than one source; 9 respondents use dam water for irrigation, 5 use bore water, and 2 use municipal water. Two of the protected cropping cucumber growers use chlorine-based water treatments. One protected cropping producer uses a hydroponic system for some crops and drip irrigation for other crops. The 4 protected cropping cucumber growers use drip irrigation and the 8 open-field growers use sprinkler irrigation systems including fixed sprinklers, centre pivot, and travelling irrigation systems. All respondents indicated that crops are irrigated as required and depending on the growing system employed.

Fertilisers, herbicides, and soil amendments

Eight of 8 open field producers apply gypsum, 6 apply lime, and 3 apply dolomite. None of the protected cropping producers use soil ameliorants as these are not relevant to protected cropping systems. Seven of 8 respondents growing in open-field situations use solid NPK-based fertilizers, 1 applies calcium nitrate, and 1 applies ammonium sulphate. Two of the 8 use NPK+micronutrient blends, and 2 of the 8 use foliar fertilizers. The hydroponic and protected cropping growers apply nutrients via fertigation through the irrigation system. None of the protected cropping farmers used herbicides in-crop. Herbicides commonly used by open field producers include asulam sodium, s-metolachlor, dimethenamid-p, pendimethalin, glyphosate, paraquat+diquat, propachlor, and pronamide. Six of the 13 respondents (4 open-field growers and 2 protected cropping growers) apply a range of biostimulants including amino acid combinations (2 open field growers; 1 protected cropping grower) and *B.subtilis* (2 protected cropping growers and 1 open field grower).

Field operations

Six respondents (4 open field; 2 protected cropping) employ their own field staff, 5 utilise a combination of casual employees or contractor-supplied staff and their own employees, and 2 protected cropping growers utilise contractors. Two open field croppers use contract employees supplied through the PALM (Pacific Australia Labour Mobility) scheme. Eight of 13 respondents employ local staff for harvesting operations, some of whom are of Cambodian, Thai, or Vietnamese background, and some are backpackers. One respondent identified that they employ backpackers from countries including Korea, Japan, Taiwan, Indonesia, Timor Leste, Laos, and Myanmar. All open field growers have equipment cleaning protocols in place. Seven respondents clean down their equipment using sanitizers; an additional 4 respondents use water. Of the 8 open field croppers, 6 use at least 1 specific product (1 uses alcohol spray, 2 did not specify what products were used; 2 use products based on a combination of quaternary ammonium compounds, benzalkonium chloride, and ethanol; 1 producer used hydrogen peroxide; 1 used peracetic acid); 3 open field producers and 1 protected cropping grower use water for washing equipment. Of the 4 respondents using contract staff (2 open field croppers and 2 protected croppers) only 1 inspected contractor equipment. Three of 13 respondents wash harvested produce in the field, but not for all products. Twelve of 13 respondents have harvest bin cleaning protocols in place. The respondent who does not have protocols in place packs directly from cocopeat slabs into plastic sleeves and then into cartons for shipping to the wholesale market. Packing shed processes varied with the commodity under consideration and with the scale of the enterprise. The 3 carrot producers followed similar procedures whereby the carrots were mechanically harvested in the field and transported to the packing shed where they were washed, polished, graded, and hydrocooled prior to further processing and packing. Two of the open field croppers sent produce off-site in bulk bins for packing, 1 washed and packed on-site, and 1 sent bulk product direct to the food service market. The 5 protected cropping growers sent product in bulk bins or boxes to the wholesale market.

Worker hygiene and biosecurity

Eight respondents provide hygiene training to their staff, 4 respondents did not provide specific hygiene training for staff, and 1 respondent was a sole owner/ operator. Ten of 13 respondents have biosecurity measures in place, ranging from

display of relevant signage (5 respondents), surveillance cameras (1 respondent), mandatory vehicle washdown with water (2 respondents), ban on equipment transfer between properties (1 respondent), and use of a sanitizer on equipment (1 respondent). One respondent of 13 utilized dam water in their hygiene practices; this water was sometimes treated with chlorine. One respondent of 13 utilized bore water in their hygiene practices, 7 respondents of 13 utilized municipal water, and 1 respondent uses river water treated with bromochlorodimethyl hydantoin in their hygiene practices. No respondents use on-site recycled water in their hygiene practices, and no respondents use municipal recycled water in their hygiene practices. Three respondents dispose of wastewater into a septic tank system, 1 recycles into a sump, 1 uses drains to feed wastewater into local channels, 1 uses a liquid waste contractor, and 1 recycles this wastewater into a dam, the water from which is then used to irrigate crops. Three of the protected cropping cucumber growers pump waste onto grassed areas on their properties. Ten of 13 respondents communicate and enforce hygiene protocols through their induction processes and/ or day-to-day management practices. One respondent communicates their requirements through implementation of HARPS protocols, 1 has no formal communication and enforcement regime, and 1 of the protected cropping cucumber growers is a single person owner/operator. Three respondents employed separate field and harvest crews, the 3 carrot growers all harvested mechanically; 6 respondents did not have separate field and harvest crews; 1 respondent was the sole owner/ operator of their enterprise. Six respondents reported that they utilize the same staff in the field and in the packing shed, 1 open field grower and the 4 protected cropping cucumber growers did not use a packing shed but dispatched bulk product, and 2 used different crews in the field and packing shed. Seven of 13 respondents have packing hygiene protocols in place; 1 has no formal protocols in place. Seven of 13 respondents use soap, water, and personal protective equipment in their packing hygiene processes. Seven of 13 respondents package product and have product washing and cleaning protocols in place and conduct QA testing; 6 respondents do not package their produce. Of the 7 who package product, 1 uses dam water in the process, 3 use bore water, 2 use municipal water, and 1 uses water which is recycled on-site. None of the 13 respondents apply fungicides, waxes, or preservatives to their produce post-harvest.

Pest and disease control programs

All respondents applied fungicides to their crops. Seven of 13 respondents used programmed fungicide spray applications; 2 of these respondents adjusted their programs during the crop cycle depending on needs. Seven of 13 respondents applied pesticides as required. One respondent applied pesticides on a regular schedule for 1 crop and sprayed another crop on an 'as needs' basis. Fungicides and insecticides nominated by respondents as being used on their crops are shown in Table 1.

Table 1. Fungicides and insecticides reported as being used in vegetable production and their classification by mode of action:

Fungicides	Insecticides
Group M1 (inorganic - electrophiles) - tribasic copper-based sprays, including tribasic copper sulphate	Group 1B - (organophosphate) - trichlorfon Group 2B - (phenylpyrazole) - fipronil
Group M3 (dithiocarbamates and relatives) - metiram, propineb	Group 3A - (synthetic pyrethroid) - alphacypermethrin
Group 4 (phenylamides) - metalaxyl	Group 4C - (sulfoximine) - sulfoxaflor
Group 11 (quinone outside inhibitors; strobilurin) - azoxystrobin	Group 5 - (spinosyns) - spinetoram
Group 21 (quinone inside inhibitors) - cyazofamid	Group 9D - (pyropenes) - afidopyropen
Group BM02 - bacterial <i>Bacillus</i> spp. - QST713 strain of <i>Bacillus amyloliquefaciens</i> (also known as <i>Bacillus subtilis</i>); <i>Streptomyces lydicus</i>.	Group 11A - (<i>Bacillus thuringiensis</i> and their insecticidal proteins) - <i>Bacillus thuringiensis</i>
Group 49 (oxysterol binding protein homologue inhibition) - oxathiapiprolin	Group 23 - (tetramic acid group) - Spirotetramat
Coformulations of different modes of action: azoxystrobin+difenconazole, flupicolide+propamocarb, and pydiflumetofen+difenconazole	Group 28 - (anthranilic diamide) - chlorantraniprole

Nine of 12 respondents use tribasic copper-based sprays (including tribasic copper sulphate) against bacterial diseases. 1 respondent uses a product based on *Streptomyces lydicus* for controlling bacterial diseases; 1 respondent was not able to

answer this question. The respondent growing their own transplants uses fluopicolide+propamocarb, metalaxyl, metiram, propineb, azoxystrobin, pydiflumetofen+difenconazole, and oxathiapiprolin. The hydroponic grower uses copper sprays for control of bacterial and fungal diseases and cyazofamid for control of Oomycete pathogens; the 4 protected-cropping cucumber growers use a range of fungicides and insecticides, all of which are recommended by the NSW Local Land Services (2025a, 2025b). All respondents use insecticides on their crops and all 13 respondents maintain electronic (9/13) or paper-based (4) spray diaries. Twelve of 13 respondents reported crop damage due to vertebrate pests, including crows (1/13), ducks (6/13), waterfowl (1/13), cockatoos (1/13), foxes (1/13), rabbits (3/13), kangaroos (1/13), mice (1/13), rats (3/13), deer (1/13), and pigs (1/13). One respondent reported that vertebrate pests were not a significant problem.

Certification

Ten of 13 respondents are Freshcare accredited, 4 are GlobalGAP compliant, 5 are Fair Farms accredited, 9 are HARPS accredited (Harmonised Australian Retailer Produce Scheme), 7 are AusVeg members, 2 are SQP accredited (Supplier Qualification Program), 1 is GRASP accredited (an add-on module to GlobalGAP), 2 are Sedex accredited, 1 is LEAF accredited (Laboratory Efficiency Assessment Framework), 2 have HACCP certification, and 3 are accredited by importing countries or AQIS. Twelve of the 13 respondents supply QA documentation to their buyers, including spray diaries and documentation required under the various compliance programs which they subscribe to, including HARPS, Freshcare, GlobalGAP, and HACCP.

Waste management processes

Nine of 13 respondents dispose of any excess pesticide by spraying it out on the crop, minimising waste for disposal; 2 use a contract collection service; 1 uses an evaporation pit to dispose of pesticide waste. Disinfectant waste is disposed of through a septic system (1 respondent), draining to a sump (1), to municipal drainage (1), to an unspecified drainage system (1), and to contract collection services (2). Ten respondents use the DrumMuster program to dispose of used pesticide containers, 1 uses a private contract collection service, and 1 respondent was not able to answer this question. Wastewater disposal methods depend on the business scale and complexity, as well as location and availability of alternatives: 2 of 13 respondents run wastewater to drains, 1 drains to an evaporation pit, 1 drains to a septic system, 2 recirculate through dams to irrigate crops, 4 pump to grassed areas, 1 uses waste water for the first product wash, and 1 uses the ChemClean contract waste collection service.

Grower perspectives on AMR and estimates of the potential economic impact of AMR

When asked to describe their knowledge of resistance management practices in vegetable production all 13 respondents stated that they understand how herbicide, fungicide, and insecticide resistance management practices work. When asked if they implement resistance management strategies in their vegetable production systems 9 of 13 respondents agreed with the statement: 'Always - resistance management strategies form the basis of all our spray programs and management practices', 4 respondents agreed with the statement: 'Sometimes - we generally follow resistance management strategies but not if it means we might end up with a disease, pest, or weed problem'. No respondents agreed with the statement: 'Not at all - we don't worry about resistance management because the chemical companies always come up with new products if resistance becomes a problem'. Of 10 respondents who were asked 'With regard to the use of insect/mite predators or 'biological control agents' in your crop production process, do you 1. Regularly introduce pest predators to your crops; 2. Promote the presence of pest predators by using 'soft' chemicals; 3. Promote the presence of pest predators by not using insecticides in the process; 4. Not worry about pest predators', 8 responded that they promote the presence of pest predators by using 'soft' chemicals, 1 respondent stated that they regularly introduce pest predators to relevant crops, and 1 protected cucumber cropping respondent stated that they don't worry about pest predators. One of 13 respondents previous first-hand experience of a product recall in the vegetable sector. Respondents were asked: How much do you think an average product recall might cost a vegetable producer in direct costs (removing product from the market, product disposal/destruction, investigating, and fixing the problem). Response options were: Don't know (6 respondents), <\$1million (4), \$1-2million (1), \$2-5million (2), or >\$5million (0). Eleven of 13 respondents had no first-hand experience with fungicide resistance in vegetable production, 1 respondent was not sure, offering that resistance is hard to confirm definitively, and 1 respondent did not answer this question. Twelve respondents were asked: How much do you think an outbreak of resistant disease might cost a vegetable producer. Responses were: Don't know (5 respondents), <\$1million (3), \$1-2million (2), \$2-5million (2), or >\$5million (0). There were only 12 responses to this question as it was added to the survey after the first interview. Two individuals who replied 'Don't know' qualified their responses by saying that the cost depends on the circumstances such as crop involved and area affected. Participants were then asked a series of questions regarding the potential impact of AMR on various levels of the vegetable production industry; responses are presented in

Table 2.

Table 2. Participant responses to questions regarding the potential impact of AMR on the Australian vegetable production industry.

Response options and number of respondents	Question: How would you rate the following statement?		
	AMR has the potential to significantly impact your business financially.	AMR has the potential to significantly impact the national vegetable market financially.	AMR has the potential to significantly impact the export market for Australian vegetables financially.
Strongly agree	9	9	12
Somewhat agree	4	3	0
Neither agree nor disagree	0	1	1
Somewhat disagree	0	0	0
Strongly disagree	0	0	0

5. Discussion

This scoping study seeks to identify points where AMR might be introduced into Australian production systems for leafy green vegetables, carrots, and cucumbers through elucidation of relevant production chains. The study also seeks to identify key compliance systems governing vegetable production which may mitigate the risks identified. Farmer perceptions of the risks and potential costs posed by AMR are also explored. It should be noted that the following discussion is based on a small sample of vegetable growers across a limited number of production areas in eastern Australia. Potential points of entry for AMR into Australian production systems identified in this study include via seeds and seedlings, composts and cocopeat-type substrates, and packing facilities. The study identified that production chains for ready-to-eat vegetables vary with the commodity being grown, the scope of the enterprise, and the established practices of individual growers. Leafy green salad varieties may be purchased by growers as seedlings for transplanting, raised from seed by growers for transplanting, or direct-seeded. Carrots are direct-seeded into open fields using internationally produced seed, and protected cropping cucumbers are direct seeded into cocopeat slabs or blocks, also using internationally produced seed. Farmers who grow from seed purchase from multiple seed suppliers; growers who purchase transplants purchase from a single supplier. When seeds are purchased by growers or seedling suppliers the product label states what fungicide product(s) have been applied to the seed but there is generally no history available regarding what fungicide or bactericide products may have been applied to the crop from which the seed was harvested. Similarly, when growers purchase seedlings for transplanting there is no information available regarding fungicide or bactericide products which may have been applied to the plants by the seedling producer. This lack of information has the potential to undermine the framework on which the internationally accepted fungicide resistance management strategy is predicated: if a grower does not know the history of fungicide applications to the seed or seedlings, they cannot determine the appropriate product to apply to disease outbreaks in their crop in order to comply with the resistance management strategy. In field cropping systems, manures have been shown to vector AMR pathogens (Thanner, Drissner & Walsh 2016). The results of the current survey indicate that the use of composts is common in open-field vegetable production across the survey region. However, the term 'composting' encompasses several different processes the effects of which on the survival of pathogenic bacteria and horizontal or vertical transfer of AMR are not known (Tang *et al.*, 2023). An important extension of the current project would be to understand what composting systems are used in the market and what quality assurance schemes operate to govern the compost industry. No organic farmers were surveyed in this project but it is important to understand whether they use manures, biosolids, or composts in their production systems, and what quality assurance or certification schemes might be in place to mitigate the risks of generating or transmitting AMR pathogens through organic production systems. In protected cropping systems the use of cocopeat and related growing media is common. These materials typically originate in India, Indonesia, and Sri Lanka and are imported directly into Australia or via Europe where additional processing occurs. Manufacturers claim that the product is naturally free from pathogens, weed seeds, and harmful chemicals. The potential for composts and cocopeat substrates to vector AMR organisms under Australian conditions is not known but provides a possible point of entry for AMR pathogens. Additionally, it is important to understand the production process for cocopeat products imported into Australia for the vegetable production industry and what certification or quality assurance schemes exist for these products. The environmental conditions under which vegetables are grown in the areas surveyed vary widely although all the production sites were close to other vegetable production enterprises such that spray and dust drift across property boundaries is a real risk. In open field cultivation in southeast Queensland and eastern

Gippsland production sites are remote from residential dwellings and more likely to be close to animal production enterprises such as beef cattle grazing and dairy farms. Open field production in west Gippsland, Werribee, and Bacchus Marsh is close to residential and industrial buildings and is under continual pressure due to urban spread from Melbourne. Protected cropping production of vegetables in the Coffs Harbour/ Woolgoolga area and the Sydney basin regions are also close to new residential subdivisions and are impacted by major road and infrastructure developments occurring around them. Earth movement and dust created by these activities is relevant to the discussion regarding agricultural production and AMR development given that the Coffs Harbour/ Woolgoolga area has historically been a major banana producing area. *Aspergillus fumigatus*, the main causal agent of invasive aspergillosis, is a human lung pathogen commonly found in soil, organic debris, water, decaying vegetation and dust produced in renovation and/or building work (Spagnolo, 2025). The first-line treatment is azole fungicides. Azole resistance in *Aspergillus* spp. has increased significantly worldwide, possibly linked to increased environmental pressure caused by wider use of azole fungicides in agriculture (Bosetti & Neofytos, 2023; Chowdhary *et al.*, 2012, 2013; Stensvold, Jørgensen, & 2012). Azole-resistant *Aspergillus* strains have been associated with treatment failures and mortality rates as high as 90%, and effective alternative treatment regimens have not been widely tested (Bosetti & Neofytos, 2023). A recent Aspergillosis cluster in hospital patients in Sydney which resulted in 2 deaths has been linked to dust from an adjacent building site (NSW Government, 2026). Bananas in the Coffs Harbour/ Woolgoolga area have been sprayed regularly with the fungicide propiconazole and related azole products for the control of yellow sigatoka disease and other pathogens since the early 1980s, and these products are still used in local cucumber production. It may be of interest to assess the prevalence of azole-resistant *A.fumigatus* in this region in the future. All growers subscribe to various certification schemes which encompass food safety, food quality, and compliance with ethical and social norms and can be classified as either government regulations (e.g., FSANZ), on-farm and off-farm food safety and quality certifications (e.g., BRCGS, Freshcare, Global GAP, SQF), retailer-driven post-farm certifications (e.g., HARPS), and on-farm and post-farm ethical and social certifications such as Fair Farms and Sedex (AUSVEG 2025). These compliance programs require that businesses seeking certification develop operational procedures and protocols related to their businesses and that these are regularly reviewed in the pursuit of continuous improvement. The certification schemes are based on the widely accepted HACCP framework and require that businesses maintain adequate detailed records of various aspects of daily operations and that they submit themselves to regular scheduled internal and external audits and unannounced external audits to maintain compliance. HACCP addresses three categories of hazards: biological threats (e.g., bacteria and viruses), chemical dangers (e.g., pesticides or cleaning agents), and physical hazards (e.g., glass fragments or metal contaminants) and focuses on identifying and controlling hazards at specific points during the production process using planned interventions to prevent, eliminate, or reduce identified risks to acceptable levels. Survey results suggest that grower compliance with the various schemes is widespread, providing a level of confidence in the integrity of vegetable production chains with regard to mitigating the risks around the possible introduction, generation, and transmission of AMR pathogens through the production process. Water source(s) used across individual enterprises vary depending on enterprise scale, location, and availability. In some situations, close to large cities, A-class recycled water or potable water is used. In more remote areas water is pumped direct from rivers or established irrigation schemes. In some situations, bore water is used in the production chain; some growers utilise multiple sources of water for their operations. Treatment regimes for irrigation water or water used in post-harvest processes vary, as do disposal methods. Any potential risks associated with water use through the production chain should be identified and addressed through the various grower quality assurance certification schemes. Survey results suggest that there is a high level of understanding of and compliance with fungicide, insecticide, and herbicide resistance management and integrated pest management strategies among vegetable producers. This finding is perhaps not unexpected given the significant efforts which the agrochemicals industry has gone to over the past 40-45 years to develop, refine, and communicate these strategies to maximise the longevity of their products in the market. The success of this program could be evaluated as a potential template for any stewardship program envisaged in the future for communicating AMR risk mitigation strategies through vegetable production chains. Responses show that the amount of post-harvest processing carried out by individual farmers varies widely with the commodities produced and the scale of the enterprise. At one end of the scale a smaller producer of poly tunnel cucumbers sends product to a local consolidator who bulks product from several growers for sale in the Brisbane wholesale market. At the other end of the scale several larger leafy greens producers and carrot producers have their own packing, processing, and bagging facilities either close to their production site(s) or at a remote location where they wash, blend, and bag different proprietary blends for sale to the large retail chains. One respondent sends product to a third party for bagging. None of the respondents apply post-harvest treatments such as fungicides or waxes to their products. The post-harvest vegetable processing and packing sector in Australia is very diverse as an inspection of packaged or bagged vegetables on any supermarket shelf will attest to. Product can be designated as 'grown and packed by' the nominated producer (e.g., Corrigan Farms; Gazzola Farms), 'grown and packed for' a specific producer, suggesting that farmers are contract growing for the nominated producer who has the product packed by a third party (e.g., Harvest Moon; Riviera Farms), 'grown by', suggesting that the product is grown by the nominated producer but packed by a third party (e.g., Koala Farms produce sold under the Coles brand), or 'packed by' suggesting that the nominated packer purchases product

from a number of producers to sell under their own brand (e.g., North East Equity; Wanniasa Wheeler). An example of how complex and integrated the processing and packing industry can be is OneHarvest, a national business which includes a vegetable-growing farm and four processing facilities (Brisbane, Bairnsdale, Sydney, Perth) producing over 145 different products which are supplied to supermarkets and green grocers nationally (<https://www.oneharvest.com.au/>). Contract growers supplement OneHarvest's own production and their product range spans the gamut of leafy salads, salad kits and bowls with dressings and inclusions, prepared fresh vegetables and stir-fries, deli salads, and fresh-cooked vegetables. The recall of multiple brands of spinach and mixed salad products in early 2025 in Australia (Food Research Lab, 2025) exemplifies the complexity and inherent AMR risks of the processing and packing industry. This recall followed a 2022 recall of baby spinach-based products from a single source which was packed under the Coles, Woolworths, Riviera Fresh, and Fresh Salad Co brands. The products were contaminated by seeds from *Datura stramonium* and caused at least 42 people to seek medical attention (<https://www.foodstandards.gov.au/food-recalls/FoodIncidents/recall-baby-spinach-products>). The 2025 multi-state store-based recall followed the detection of Shiga toxin producing *E.coli* in two pre-packaged spinach products purchased from separate Queensland supermarkets as part of a proactive public health surveillance program. The recall was expanded to cover 40 pre-packaged spinach, mixed salad, and stir-fry blend products from all major Australian retailers. The contamination was tentatively ascribed to post-harvest practices during the production process between harvesting, washing, and packing operations. These two incidents suggest that multiple growers can supply facilities which consolidate, process, and pack produce for multiple brands. This construct allows small amounts of contaminated product to be mixed with otherwise uncontaminated product, providing a mechanism to amplify any contamination, including AMR pathogens, significantly increasing the potential for harm to consumers. The breadth of different post-harvest processing and packing practices argues for the need to gain a better understanding of the structure of this market in order to be able to quantify the AMR-related risks in this segment of the production chain. Responses to questions regarding the potential financial impact of AMR on individual, national, and export vegetable production suggest that, once AMR and its relevance to the industry is explained, growers recognize the detection of AMR in vegetable production systems could have significant impacts at the different market levels. The lack of first-hand experience of product recalls among respondents (only 1 respondent had direct experience) meant that only 7 respondents were able to estimate what they thought average recall costs might be. These estimates ranged from <\$1million (4 respondents), to \$1-2million (1 respondent), and \$2-\$5million (2 respondents). Responses to the question regarding estimating the cost of fungicide resistance to a vegetable producer returned a similar response pattern (Don't know=5 respondents; <\$1million=3; \$1-\$2million=2; \$2-\$5million=2; >\$5million=0). While the actual cost of a product recall will depend on factors such as the product involved, the volume of product involved, and the depth of the recall through the market chain (wholesale, retail, consumer) estimates suggest a cost of around \$10million. Similarly, the cost of an occurrence of fungicide resistance will depend on several factors related to the specific circumstances making quantification of an average cost difficult. Informal discussions with a range of vegetable producers during the survey process but which do not form a part of the survey itself suggest that AMR is not 'top-of-mind' with industry participants.

6. Avenues for further investigation:

Survey responses identified a number of potential points of vulnerability in the vegetable production chain for the introduction or generation of AMR pathogens which suggest several areas for future research. The first area for investigation is the potential for introduction of AMR through composts (open field cropping) and cocopeat-type substrates (protected cropping). It is important for the industry to have a detailed understanding of the processes involved in composting in Australia and in cocopeat processing which could mitigate or amplify the risks. This includes the processes involved in producing these materials and the quality assurance/ certification schemes which seek to minimize the AMR risks associated with the end products. Biosolids and manures present an AMR risk to vegetable producers. This survey did not involve organic vegetable producers, a cohort which could potentially use these materials or composts in their production processes. It is important that organic production chains and the ARM risks associated with them are understood. The seed and seedling production industries also present an AMR risk to the Australian vegetable production industry because growers who purchase seeds or seedlings do not know what products have been applied in the seed/ seedling production process, prejudicing their fungicide resistance management decision making. Additionally, seed which is produced in other countries and potentially processed and packed in a third country can be vectors for AMR plant pathogens, further placing local resistance management strategies at risk. It is important to understand what systems are in place with international seed producing companies to manage these risks. The survey identified that processing and packing of vegetable products is very diverse and quite complex. Recent product recalls suggest that this sector presents a risk for AMR transmission and amplification which needs to be quantified. Products and processes employed in the sector need to be understood in terms of their AMR risks, and quality assurance/ certification schemes applicable to the sector need to be identified and assessed. Finally, the prevalence of AMR pathogens in vegetable produce in Australia is not known. In 2026 FSANZ published the results of a 2022-23 nationwide survey of AMR among bacteria isolated from

Australian raw retail beef, chicken and pork meat samples (Food Standards Australia New Zealand, 2026). The study provides a comprehensive national snapshot of AMR in foodborne and commensal bacteria among raw retail beef, chicken and pork meat and relates the results back to an earlier survey conducted in 2007. Such comprehensive data are not available for the Australian vegetable industry but, if available, would establish a baseline against which future data could be reviewed. A study of this type is considered a fundamental part of a second phase of Project 012 – Risk assessment of antimicrobial resistance in the Australian vegetable industry.

7. Shortcomings of the present study:

The study was conceptualized to provide a basic understanding of the key processes in different vegetable production systems in order to identify areas where AMR pathogens could be introduced into or generated within the production process, to identify certification schemes operating in the industry which could militate against the introduction of AMR pathogens into the system, and to gather grower estimates of the potential economic impact of AMR on the industry. These aims have been achieved, however due to the broad nature of the remit, the survey instrument was quite long (31 primary questions, some with multiple response option); future survey instruments should consist of fewer questions. Additionally, the number of respondents was small compared to the estimated 4,000+ vegetable producers in Australia, particularly the number of respondents by enterprise type (open-field vs protected cropping) and was not amenable to statistical analysis. However, several points of vulnerability regarding the introduction of AMR into vegetable production chains were identified and deserve further investigation. Future studies should seek to increase the number of respondents. This desired outcome is complicated by the fact that it is difficult to engage vegetable growers on issues regarding AMR which are not top-of-mind for time-poor vegetable growers who are focused on more immediate concerns such as the cost of inputs such as fertilizer and fuel, and maintaining their margins in a concentrated market for their produce.

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Appendix 2E

Deliverable 2.5: Grower Engagement and Knowledge Dissemination Activities

To effectively disseminate information on antimicrobial resistance (AMR) and chemical-resistant pathogen issues to vegetable growers, the project committed to delivering a series of regional extension activities through the national VegNET network and to presenting at the Hort Connections Conference. During this reporting period, Dr Mark Drew undertook several extension activities, including participation in the VicVID Field Days in Tyabb, Victoria (7–8 May 2026), attendance at the associated Elders Networking Event (7 May 2026), and delivery of a grower information evening in Woolgoolga, New South Wales (20 May 2026).

VicVID Field Days (Tyabb, Victoria)

VicVID 2026 was held over two days at Taranto Farms in Gippsland and was organised by AUSVEG, VegNET Victoria, and Stuart Grigg Ag-Hort Consulting. The event featured more than 70 partners and exhibitors and provided Victorian vegetable growers with updates on seed genetics, crop protection, and agricultural machinery innovations.

Adelaide University had intended to present project findings on AMR, chemical-resistant pathogens, and the outcomes of the national grower survey conducted during 2025–2026. However, by the time discussions commenced with the organisers, all formal presentation opportunities had been allocated.

Despite this, Dr Mark Drew attended the event and maximised the opportunity to engage directly with growers and industry stakeholders. He held numerous informal one-on-one discussions with vegetable producers, agricultural input suppliers, and seed companies, and attended technical presentations to better understand current production challenges. These discussions focused primarily on industry perceptions of AMR and fungicide resistance and provided valuable insight into current knowledge and attitudes within the sector.

Woolgoolga Grower Information Evening (New South Wales)

On 20 May 2026, Dr Mark Drew delivered a grower information session in Woolgoolga in collaboration with AgNova Technologies Pty Ltd, a manufacturer and supplier of crop protection products, and the Ace Ohlsson Woolgoolga branch, a major distributor of fertilisers, agrochemicals, and horticultural inputs to protected-cropping growers.

The event was attended by 27 protected-cropping cucumber producers, several of whom also produce berries, including blueberries, raspberries, and blackberries.

Dr Drew presented a 20-minute overview covering:

- the risks of AMR in vegetable production;
- key findings from the national grower survey; and
- potential future research directions aimed at reducing AMR risks in ready-to-eat vegetable production.

The presentation generated productive discussion among participants and was complemented by a presentation from AgNova on responsible fungicide stewardship in protected cropping systems. Informal discussions continued during the networking dinner, providing further opportunities for knowledge exchange.

Key Outcomes

Engagement across both events highlighted that antimicrobial resistance is currently not a primary concern for most vegetable growers, whose immediate priorities remain production efficiency, business viability, and profitability in a challenging economic environment.

In contrast, growers and agricultural input suppliers demonstrated a strong awareness of fungicide resistance and the importance of implementing established resistance management strategies and following industry best-practice recommendations for fungicide use.

These findings indicate that there is a clear opportunity to develop targeted communication and extension activities to increase awareness of AMR and its potential implications for vegetable production. Future engagement should focus on communicating the relevance of AMR to growers while building on the industry's existing understanding of fungicide resistance management.

Appendix 2F

VegeNotes #2 (submitted to AusVEG in March for publication in the Spring 2026 follow-up edition of the magazine): *Antimicrobial Resistance in Ready-to-Eat Vegetables: What We Know, What We Don't, and What We Can Do*. Contacts: Jessica Muller (AusVEG) and Rosalie Daniel (AusVEG). The article will be published by AUSVEG in December 2026.

Background

A recent national Food Standards Australia New Zealand (FSANZ) survey provides the most comprehensive snapshot to date of antimicrobial resistance (AMR) in the Australian food supply, analysing more than 4 000 raw retail beef, pork and chicken samples from across all states and territories. The findings show that overall resistance to antibiotics of high importance to human health remains low and multidrug resistance is uncommon, offering reassurance that, under current production and handling practices, the risk of AMR transmission through these foods is low when safe food practices are followed.

However, in broader literature and risk assessments, data on AMR in horticultural products such as fresh vegetables remains extremely limited in Australia and worldwide, and these categories have historically received far less surveillance attention compared with animal-derived foods. Consequently, while fresh produce is not currently a major focus in national AMR reporting, its potential role in environmental transmission pathways via soil, water, manure or human handling suggests it should not be overlooked in future.

Like other food products, ready-to-eat (RTE) vegetables, such as bagged leafy salads, are a potential pathway for exposure to AMR. Because these products are often eaten raw, any bacteria carrying AMR present on the produce can reach consumers directly. From the paddock to the processing facility and retail shelves, vegetables pass through multiple steps involving exposure to microbes which could potentially contaminate them.

In vegetable production systems, AMR risks are not only directly linked to antibiotic use. Other sources can also play a role, including irrigation or recycled water, soils, organic fertilisers and composts, and processing environments. In addition, some chemicals commonly used in farming and food processing, such as fungicides, herbicides, and disinfectants—may unintentionally favour the survival of resistant bacteria. This process, known as co-selection, means that resistance can persist even where antibiotics are not used.

Despite these potential pathways, most monitoring and risk assessment efforts have historically focused on meat production and human health settings. Current food safety frameworks are largely designed to detect traditional foodborne pathogens that cause immediate illness, rather than AMR genes and the ways they can spread or increase during processing and handling.

To better understand these risks in vegetable supply chains, we conducted a scoping review of scientific and industry literature published between 2000 and 2025. The aim was to identify how AMR risks are currently assessed in ready-to-eat vegetable systems, including risks linked to chemical co-selection, and to highlight the key knowledge gaps that currently limit practical risk prioritisation and decision-making for the vegetable industry.



AMR and pathogen presence in vegetable systems

Levels of AMR found on vegetables vary widely depending on farming practices, water quality, and local regulations. Studies from regions where untreated wastewater is used for irrigation, or where untreated raw manure is commonly applied, have reported much higher levels of resistant bacteria on vegetables, sometimes between 60% and 90% of samples. In contrast, studies from more tightly regulated production systems generally report lower levels, although direct Australian baseline data for vegetables remain limited.

Fresh-cut and ready-to-eat salad products often show higher bacterial levels than whole vegetables. This is likely because these products go through additional washing, cutting, and handling steps, which can create more opportunities for microbes to spread or increase if controls are not well managed.

A recent global analysis (Nkhebenyane et al., 2024) found that about 12% of vegetable samples contained bacteria producing extended-spectrum beta-lactamases (ESBLs), enzymes that make bacteria resistant to important antibiotics. The study also suggested that this level may be increasing over time, rising from about 9% in 2018–2019 to nearly 16% in 2022–2024.

Overall, these findings reinforce the value of practical controls: clean water, well-managed soil amendments, effective hygiene, and stringent post-harvest handling systems.

How antimicrobial resistance can spread in vegetable systems

Research shows that AMR can spread between bacteria naturally in the environment. Bacteria can share resistance traits with each other, allowing resistance to persist in soils, water, and on plant surfaces. Certain chemicals commonly used in agriculture and food processing can unintentionally support this process. Products such as fungicides, herbicides, metals, and disinfectants and even micro- or nano-plastics can place stress on bacteria and favour strains that carry resistance traits. In some cases, the same genetic elements that carry antibiotic resistance can also carry resistance to metals or disinfectants. This means resistance can continue to spread even where antibiotics are not used. For growers, this highlights the importance of good water management, careful use of soil amendments, and balanced chemical use as part of broader food safety and environmental management practices.

Mixed farming landscapes can create pathways for microbes to move between animals, water, soil and crops, particularly through manure, runoff or floodwater. This does not mean vegetables are a major AMR source, but it does support a One Health approach to managing water, soil amendments and hygiene across the whole farm environment.



Current regulations and industry standards

Most current food safety regulations focus on general hygiene indicators, such as *E. coli* levels in irrigation water or *Listeria species* in processing environments. These indicators are useful for managing traditional food safety risks but do not specifically measure antimicrobial resistance. Monitoring of AMR in vegetable production systems is still limited worldwide. In many cases, buyer requirements and export standards are evolving faster than formal regulations, particularly for ready-to-eat products and international supply chains. Although there is currently no formal requirement to assess AMR within the vegetable production environment, a suite of preventative controls is embedded across the industry. These controls are implemented through both voluntary quality assurance programs and mandatory food safety standards, such as Primary Production and Processing Standards requirements. Together, they promote safer production practices by addressing key risk factors associated with contamination and microbial spread.

These frameworks incorporate elements such as hygiene and sanitation protocols on input use, and the responsible use of agricultural inputs. Collectively, these measures help limit the introduction, persistence, and transmission of microorganisms, including those that may carry AMR traits. By reducing overall microbial load and preventing contamination events, the standards indirectly mitigate the risk of AMR dissemination through fresh produce.

How AMR risks are currently assessed

Most research assessing AMR risks uses quantitative risk assessment methods similar to those used for traditional foodborne pathogens. However, many studies stop at identifying hazards and possible exposure pathways.

Fully estimating health risks is difficult because there is still limited information about:

- how many resistant microbes are needed to cause colonisation in humans (i.e. what is the threshold?)
- how resistance in microbial population affects treatment outcomes
- how risks should be measured consistently across studies.

As a result, current assessments often focus on well-known bacteria such as *E. coli*, *Salmonella*, and *Listeria*. New approaches are emerging to better understand chemical pressures and the movement of resistance genes, but these methods are not yet widely standardised for routine industry use.

Key gaps in current risk assessment for vegetable systems

Existing food safety systems are effective at managing general hygiene and acute foodborne pathogens, but they are less developed for managing AMR risks.

Key gaps include:

- limited links between monitoring results and clear action thresholds
- insufficient consideration of post-harvest steps, where bacteria can spread or increase
- limited integration of chemical pressures and gene movement into risk models.

Many studies still focus on simply detecting resistant bacteria without providing guidance on what actions should follow. Differences in sampling methods and reporting also make it difficult to compare results across farms, regions, and seasons.

Potential benefits of including AMR considerations in existing practices

Adding targeted AMR awareness to existing food safety and quality programs could help strengthen vegetable supply chains without requiring major changes to current systems.



Before harvest, monitoring and management can help:

- identify higher-risk irrigation water sources
- support better decisions on water reuse, treatment, and timing of applications

- improve management of manures and organic amendments.

After harvest, improvements can have a strong impact because washing, cutting, and packaging are points where bacteria can spread quickly in ready-to-eat supply chains.

Looking at hygiene and chemical programs through an AMR lens may also help reduce conditions that favour resistant bacteria. Targeted monitoring can provide better visibility of trends than traditional indicator testing alone.

Overall, these steps can help:

- strengthen confidence for buyers and export markets
- support future regulatory expectations
- focus resources on the points in the supply chain where interventions are most effective.

Conclusions

AMR is not a reason for growers to panic, and it does not mean Australian vegetables are unsafe. The practical message is simpler: the same systems that reduce microbial contamination today also help protect the tools growers may need tomorrow.

Other sectors are already moving in this direction. In human health, Australia now tracks antimicrobial use and resistance through national AURA surveillance. The latest report found 23.2 million antimicrobial prescriptions were supplied in 2024 and reports of critical antimicrobial resistance increased by 25.2% from 2023 to 2024. In the animal sector, Australia has a dedicated Animal Sector AMR Action Plan running from 2023 to 2028. In food, FSANZ's recent raw retail meat survey tested 4,151 samples and now provides a national benchmark for future monitoring.

Vegetables do not yet have the same level of AMR baseline data. That matters because published crop examples show that important tools can lose effectiveness when resistance or tolerance becomes established. Streptomycin resistance in plant pathogens was detected within five to ten years of its commercial use, and a Queensland vegetable study found copper-tolerant bacterial spot strains in capsicum increased after 12 copper sprays and dominated a field population after 21 sprays.

For vegetable businesses, the immediate priority is prevention, not extra complexity. Good irrigation water management, careful use of manures and composts, strong hygiene during harvest and processing, effective sanitation, and avoiding over-reliance on any single input all help reduce microbial pressure. Over time, targeted AMR monitoring could also help the industry show buyers, regulators and consumers that Australian vegetables are produced under strong, evidence-based systems.

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Deliverable 3

Appendix 3A

Risk Assessment Framework and Model Development

Risk Profile and Problem Formulation

The starting point for this assessment was development of a risk profile, a structured description of the situation, the commodity involved, the pathways by which exposure or harm could occur, and the distribution of possible risks among different segments of the affected population. The risk profile was generated to identify data gaps, recommend additional data collection warranted via grower and wholesaler surveys, and establish the scope and structure of the semi-quantitative assessment (FAO/WHO, 2003). This assessment was scoped as explicitly screening-level from the outset. In certain cases, such as this, the risk characterization can be a screening exercise, providing only a sense of whether the risk might be judged high, medium, or low rather than a full quantitative estimation of risk probability (FAO/WHO, 2003). This framing is appropriate here for three reasons: the data available for parameterization are predominantly from international literature and expert elicitation rather than Australian-specific empirical measurement; the pathogens of concern (ESBL-producing *E. coli* and the target plant pathogens) do not have established dose-response relationships suitable for full QMRA; and the primary decision need - where should risk management investment be directed? - is better served by a credible risk ranking than by a precise point estimate of harm probability. A bounding analysis approach is embedded in the results presentation: results are assessed against reference thresholds (FSANZ microbiological criteria for total *E. coli*; precautionary ESBL fraction benchmarks from the international literature) to indicate whether the system is well below, at, or well above the level of concern. If the model indicates that outcomes are well below the relevant benchmark even under conservative parameterization, no further data on those parameters is immediately necessary. If outcomes are at or above the benchmark, investment in improved data or conducting a value for information analysis justified (FAO/WHO, 2003).

Hazard Identification and Characterization

*Human health pathway - ESBL-producing *E. coli**

The hazard of interest for the human health pathway is extended-spectrum beta-lactamase (ESBL)-producing *E. coli* present on fresh produce at the point of consumption. ESBL genes inactivate a broad range of beta-lactam antibiotics — including third-generation cephalosporins, which the WHO classifies as critically important antimicrobials for human medicine (Category I; WHO AGISAR, 2019). ESBL genes are predominantly located on mobile genetic elements (plasmids), enabling horizontal transfer between *E. coli* strains and to other Enterobacteriaceae. This means that even a small number of ESBL-carrying *E. coli* reaching the consumer has the potential to transfer resistance genes to a much larger recipient population, a dynamic not captured in a standard dose-response framework. It is this gene transfer risk, alongside a direct pathogenic dose-response relationship, that motivates the use of a resistance fraction threshold as the primary risk indicator for this pathway. This assessment uses total *E. coli* as the indicator organism, tracking both absolute concentration and ESBL

resistance fraction through the supply chain. Total *E. coli* does not have a defined dose-response relationship in the context of ESBL gene transfer; the hazard identification is therefore prospective in character, identifying a potential mechanism of harm rather than quantifying a known dose-response curve. The approach is consistent with the definition of a prospective risk assessment: one that applies to potential hazards for which the adverse human health effects are not yet fully established (FAO/WHO, 2003).

Plant health pathway: Agrochemical resistance

The hazard of interest for the plant health pathway is the development and accumulation of resistance in plant pathogen populations to the agrochemicals used for disease management. Unlike the human health pathway, the 'exposure' here is the crops' exposure to a resistant pathogen — and the adverse outcome is not harm to a human host but the loss of chemical efficacy resulting in disease. The risk characterization therefore takes a different form, rather than estimating the probability of human infection or illness, it estimates whether the resistance fraction in the pathogen population at the time of treatment is at a level likely to compromise treatment efficacy.

Three pathogen–chemical combinations are assessed, each with a distinct resistance mechanism:

- **Bacterial phyllosphere complex/copper (leafy greens):** resistance mediated by plasmid-borne *cop/czc* gene clusters conferring tolerance to copper ions. The plasmid-mediated mechanism enables horizontal gene transfer (HGT) between strains and species, allowing resistance to spread independent of direct selection by agrichemical use. Classified as medium-to-high resistance risk, the multi-site activity of copper (reducing the probability of complete resistance through a single mutation) is counterbalanced by the HGT-capable mobility of resistance determinants and co-selection from other chemical stressors.
- ***Pseudoperonospora cubensis*/strobilurin QoI fungicides (cucumbers):** resistance mediated by a single G143A point mutation in the mitochondrial cytochrome *b* gene. This is a qualitative resistance mechanism: a single nucleotide change confers near-complete insensitivity to the entire FRAC Group 11 class. The mutation appears to impose minimal fitness cost in field conditions, enabling resistant genotypes to persist in soil spore banks across seasons. FRAC Group 11 carries a high resistance risk designation.
- ***Pythium* spp./*Phytophthora* spp./phenylamide fungicides (carrots):** resistance is polygenic (quantitative), developing gradually through accumulation of multiple tolerance alleles across selection cycles. Intermediate resistance phenotypes are common and meaningful, partial resistance allows some residual treatment effect at low resistance frequencies, unlike the qualitative strobilurin mechanism. FRAC Group 4 carries a high resistance risk designation.

The characterization of resistance mechanisms is important for interpreting model outputs. For qualitative resistance (complete or major-gene resistance i.e. strobilurin), there is a clear threshold below which treatment is likely to be effective and above which it is not, and the transition is abrupt. For quantitative resistance (partial, polygenic, or minor-gene resistance, i.e. phenylamide), the relationship between resistance fraction and treatment efficacy is more gradual, with a wider uncertainty band around the threshold. For copper/HGT, the threshold concept is further complicated by the ability of resistance to spread independently of selection.

Conceptual Models

Explicit conceptual models were developed for each risk pathway before quantitative parameterization. The conceptual model depicts the movement of the hazardous agent from source to host, describes the relationships among assessment endpoints, identifies the data required at each stage, and makes explicit the assumptions embedded in the model structure (FAO/WHO, 2003). The human health conceptual model identifies two structurally independent risk dimensions that must be tracked separately through the supply chain:

1. Total *E. coli* concentration (CFU/g or CFU/unit): the absolute number of *E. coli* cells on the produce surface, which determines the dose per serving after home preparation. This dimension is driven primarily by contamination events (irrigation, soil contact, handling) and growth during temperature-permissive holding periods, moderated by die-off and washing.
2. ESBL-resistant fraction: the proportion of total *E. coli* that carries ESBL resistance determinants, which determines the AMR relevance of any given contamination level. This dimension is driven primarily by the resistance characteristics of *E. coli* entering the system at pre-production, and is largely conserved through the supply chain, it does not increase due to growth but may increase slightly due to processing-stage co-selection (e.g. sanitizer exposure).

These two dimensions potentially require separate management strategies. Interventions that reduce concentration (harvest timing, post-harvest cooling, washing) do not necessarily reduce the ESBL fraction, and vice versa. This structural

independence is explicit in the model and is a key finding in itself. The plant health conceptual model tracks pathogen population dynamics from pre-season inoculum through infection, chemical treatment, and resistance selection. The key structural feature is the feedback loop: the resistance fraction in the post-treatment population directly determines the starting resistance fraction for the next season, creating a ratchet dynamic under repeated chemical application in the presence of resistant inoculum.

Model Structure and Implementation

Modelling Approach

Each model was implemented as a modular deterministic-stochastic hybrid: the model structure of each model (the relationships between variables) is fixed by the conceptual model, but the inputs are stochastic, sampled from assigned probability distributions where possible across 10,000 Monte Carlo iterations per scenario. This approach is commonly described as a 'probabilistic' or 'Monte Carlo' exposure assessment approach, it explicitly propagates uncertainty and variability through the supply chain, producing distributions of outputs rather than single-point estimates (FAO/WHO, 2003). This model deliberately errs toward simplicity and transparency: each supply chain stage is represented by a relatively small number of parameters with explicit biological interpretations, and the mathematical relationships used are drawn from established predictive microbiology and epidemiology literature rather than developed specifically for this assessment.

Mathematical structure: human health model

The human health model tracks three quantities through each supply chain stage:

- Batch prevalence (Prev): the probability that a batch or lot of produce contains at least one contaminated unit, modelled as a function of the contamination concentration and the batch size.
- Conditional concentration (C_cond): the concentration of total *E. coli* on positive (contaminated) units ($\log_{10}$ CFU/g), driven by the source concentration and a series of stage-by-stage growth and die-off factors.
- Resistance fraction (Frac_res): the proportion of total *E. coli* that carries ESBL resistance genes, carried through the supply chain as a weighted function of source resistance fractions and any selective pressure applied at processing.

Growth and die-off at each stage are modelled using established predictive microbiology relationships: temperature-dependent growth via the Ratkowsky square-root model, and published pre-harvest and post-harvest (cold-chain) die-off rates for *E. coli* on leafy produce. A maximum population density cap prevents concentration from exceeding a biologically realistic ceiling. Exact parameter values and formulas are in the parameter workbook.

Mathematical structure: plant health model

The plant health model tracks pathogen population dynamics through four sequential stages:

- Pre-production: seed-borne and nursery-borne inoculum entering the production system, after seed storage die-off and seed treatment efficacy.
- Production: field inoculum concentration from all sources (seed, irrigation water, soil), infection dynamics under environmental conditions, and the pre-treatment resistance fraction as a weighted function of inoculum sources.
- Treatment: chemical application with differential efficacy on susceptible and resistant subpopulations, plus HGT-driven gain in resistant cells (copper scenario only).
- Post-treatment: resistance fraction in next-season inoculum calculated from surviving resistant population, adjusted for inoculum persistence, fitness cost, and between-season die-off.

Disease incidence is modelled from inoculum concentration, a colonization rate constant, and environmental infection modifiers (leaf wetness, temperature). Pre-treatment disease incidence reflects the baseline disease burden entering the treatment decision; post-treatment disease incidence reflects the net effect of treatment on the total pathogen population (susceptible and resistant combined). These are not equivalent to the efficacy of treatment on susceptible individuals alone. Full formulas for treatment efficacy, HGT parameterization, and between-season persistence are in the parameter workbook.

Die-off parameterization

Die-off parameters were added across all six models to represent the natural decline in viable organisms between key

supply chain events; specific rates and sources are documented in the parameter workbook.

Key Assumptions

All models involve assumptions and the following documents the most consequential assumptions in each model, the direction of their influence on outcomes, and the rationale for their adoption. Assumptions that are systematically conservative (tending to overestimate risk) are noted as such; assumptions whose direction is uncertain are flagged.

Assumptions common to all six models

- **Independence of contamination events across supply chain stages:** the model treats contamination at each stage as probabilistically independent of other stages. In practice, a highly contaminated irrigation water source may simultaneously affect field contamination, soil load, and subsequent processing water quality. This underestimates correlation between pathways. Direction: uncertain, likely understates risk in high-contamination scenarios.
- **Static parameter values within each scenario:** parameters are sampled once per iteration and held constant throughout the supply chain calculation. Seasonal variation, within-batch heterogeneity, and real-time weather variation are not explicitly modelled. Direction: uncertain; captures between-scenario variability but not within-season dynamics.
- **Representative single scenario per crop:** each crop is represented by a single production scenario informed by the grower surveys. High-risk outlier farms (e.g. those using heavily contaminated water sources or with very high soil resistance burdens) and low-risk farms (clean water, certified seed, proactive rotation compliance) are not separately characterized. The model output represents a distribution across scenarios centered on the representative case. Direction: neutral.

Assumptions specific to the human health models

- **Equal die-off rates for resistant and susceptible organisms:** the *E. coli* models assume that resistant and susceptible strains decline at equal rates during pre-harvest and post-harvest die-off periods. If resistant ESBL-carrying strains have greater environmental persistence than susceptible strains, as suggested by some evidence on plasmid-bearing bacteria in agricultural environments, this assumption would understate the increase in ESBL fraction over time. Direction: conservative (understates resistance enrichment).
- **Pre-production resistance fraction as the primary AMR input:** the resistance fraction of *E. coli* entering the system via seed, nursery, and early irrigation is the dominant driver of the resistance fraction at consumption. The model assumes that this fraction reflects the environmental *E. coli* AMR burden in the inputs, that is, that resistance in the inputs is representative of the ESBL prevalence in the relevant source populations (seed microbiome, nursery water, irrigation water). If the source populations have higher or lower ESBL prevalence than parameterized, the model output will shift accordingly. This is the highest-priority uncertainty in all three human health models.
- **Within-season selection is captured through four co-selection multipliers applied at production:** S_{soil} , S_{water} , S_{fert} , and S_{agrochem} , for soil, irrigation water, organic amendment, and agrochemical residues respectively applied to $\text{Frac}_{\text{res_mix}}$ to produce $\text{Frac}_{\text{res_field}}$. Each is right-skewed, with a mode near 1.0 and an upper tail reflecting the maximum plausible co-selection effect reported in the literature.

The limitation here is parameterization, not structure: Australian co-selection data for horticultural conditions are sparse, so these four distributions draw mainly on international studies from different production contexts. Sensitivity analysis captures their influence, their importance relative to $\text{Frac}_{\text{res_preprod}}$ indicates how much within-season selection matters as a secondary driver of resistance fraction at consumption.

- **MPD cap as a concentration ceiling:** the maximum population density cap prevents concentration from exceeding a biologically determined ceiling. For cucumbers, the median concentration at consumption (11,600 CFU/g) approaches the MPD ceiling under ambient retail temperature conditions. In these scenarios, the P90 concentration is effectively the MPD value rather than a model-derived estimate. This should be interpreted as 'concentration would be near-maximal under these conditions' rather than as a precise quantitative estimate.
- **Dose per serving calculated from post-processing concentration:** the dose per serving is calculated as $C_{\text{pproc}} \times \text{serving size} \times (1 - \text{washing reduction})$. This does not account for the possibility that some proportion of *E. coli* on produce surfaces may be internalized into plant tissue (particularly via natural openings or stomata) and thus not accessible to surface washing. This assumption may understate the dose per serving for crops with natural surface openings (carrot stem scars; leafy green stomata). Direction: understates dose per serving.

Assumptions specific to the plant health models

- **Binary treatment application:** each iteration either applies treatment (with probability P_{treat}) or does not. In

reality, the number of applications, timing, and tank mix composition all vary. The model captures application number ($N_{\text{applications}}$) but not timing variability within the season. Direction: neutral.

- **Inoculum concentration as a proxy for disease risk:** the model estimates the concentration of viable pathogen propagules in the field environment and tracks the resistance fraction within that population. It does not model epidemic spread within a crop in full epidemiological detail. Pre-treatment disease incidence is estimated from inoculum concentration, infection probability, and environmental modifiers. A screening-level approximation rather than a mechanistic epidemic model. Direction: likely understates disease incidence under favorable epidemic conditions.
- **Equal persistence of resistant and susceptible oospores between seasons:** the between-season die-off term applies equally to resistant and susceptible *Pythium* oospores. If resistant strains have differential persistence (possible given the energetic costs of some resistance alleles), this assumption may under- or overstate the resistance fraction entering the following season. Direction: uncertain.
- **HGT modelled as a fixed per-application rate (copper scenario only):** HGT of copper resistance plasmids is parameterized as $R_{\text{HGT}} \times C_{\text{sus}} \times N_{\text{applications}}$, where R_{HGT} is a fixed transfer rate per susceptible cell per application. In reality, HGT rates are highly variable and influenced by bacterial density, plasmid compatibility, and environmental conditions. The fixed-rate assumption introduces substantial structural model uncertainty for this scenario specifically. Direction: uncertain; could either under- or overstate resistance spread depending on actual field HGT rates.
- **No immigration of susceptible inoculum from outside the modelled system:** the model does not include the possibility that susceptible pathogen propagules may enter the field from outside the modelled supply chain (e.g. from neighboring properties, wind dispersal from unmanaged reservoirs). If this occurs, it would reduce the resistance fraction below what the model predicts. Direction: overstates resistance fraction relative to reality if external susceptible inoculum sources are significant.

Exposure Assessment

Sources, pathways, and routes of exposure — human health

The source of *E. coli* contamination in these supply chains is predominantly environmental (irrigation water, soil, and human handling) rather than a single point source. The assessment follows the FAO/WHO (2003) framework for structuring exposure assessment: first characterizing the sources that supply organisms to the supply chain; second, identifying the pathways by which organisms reach the produce surface; third, characterizing the conditions under which organisms grow or decline at each stage; and fourth, estimating the exposure (dose per serving) at the point of consumption.

Table 5 Sources identified and parameterized for each crop

Source	Leafy greens	Cucumbers	Carrots	Primary pathway
Irrigation water	High importance (overhead)	Low (drip irrigation)	Moderate (overhead)	Direct deposit on edible surface (LG); soil/root contact (CAR)
Soil	Moderate	Low	High (root crop)	Splash at harvest; mechanical soil inclusion
Seed/nursery	High (transplanted)	High (transplanted)	Moderate (direct-sown, seed only)	Pre-production resistance fraction; contamination at establishment
Worker handling	Low	Moderate (hand harvest)	Low (mechanical)	Hand-to-fruit transfer during picking
Processing water	Moderate	Moderate	Moderate	Post-harvest wash water recirculation
Retail cold chain	Moderate	High (ambient storage)	Moderate	Post-harvest <i>E. coli</i> growth on contaminated product

The key distinction between the three crops is the irrigation method and its interaction with the edible surface. For leafy greens, overhead irrigation places irrigation water in direct contact with the edible leaf surface at every application, this is the highest-risk contamination pathway for both total *E. coli* and ESBL-resistant *E. coli*. For cucumbers, drip irrigation substantially reduces aerial contamination of the fruit surface during the growing season, making nursery-sourced

contamination and post-harvest handling relatively more important. For carrots, the root crop is in continuous soil contact throughout the growing season, making soil the primary production-stage contamination source rather than irrigation water per se.

Consistent with guidance from FSANZ (2025): water that does not directly contact the edible part of the crop is considered lower risk; overhead irrigation systems that contact crops consumed uncooked represent the highest-risk irrigation configuration; and the withholding period between last irrigation and harvest is an important risk management parameter, as human pathogens generally decline on produce surfaces with time (FSANZ, 2025).

Sources, pathways, and routes of exposure: plant health

The source of plant pathogen inoculum in these supply chains is predominantly soil and seed, carried forward from previous seasons or introduced via planting material. The primary route of 'exposure' in the plant health context is the pathogen's contact with the host plant under conditions conducive to infection, moderated by the resistance fraction of the inoculum pool and the efficacy of chemical treatment. The exposure assessment for plant health therefore characterizes: the concentration and resistance fraction of inoculum entering the field; the environmental conditions governing infection probability; and the selective pressure applied by chemical treatment.

Risk Characterization

Risk characterization integrates the exposure assessment and hazard characterization to produce a statement of risk. For this semi-quantitative screening assessment, risk characterization takes the form of a comparison between modelled outputs (exposure concentrations, ESBL fractions, pathogen resistance fractions) and reference thresholds. The characterization is presented as: well below / at or approaching / well above the relevant threshold, with quantitative values reported as supporting evidence. This approach is consistent with a qualitative or semi-quantitative risk characterization that describes risk in terms of magnitude relative to a level of concern, without requiring a complete dose-response assessment (FAO/WHO, 2003).

Reference thresholds: human health

Two reference thresholds are used for the human health pathway:

FSANZ microbiological criteria for total *E. coli* (FSANZ, 2025): satisfactory (<100 CFU/g), borderline (100–1,000 CFU/g), and unsatisfactory (>1,000 CFU/g) for ready-to-eat vegetables. These are regulatory criteria applied at the point of sale. Their use in this assessment is as a directional benchmark for concentration at consumption, results falling in the satisfactory range indicate that, on a concentration basis, the supply chain is performing within accepted standards; results in the unsatisfactory range indicate a concentration-level concern independent of resistance fraction.

Precautionary ESBL fraction benchmark (20–30%): in the absence of a regulatory threshold for ESBL fraction on fresh produce, a precautionary benchmark of 20–30% ESBL-resistant fraction at consumption is used as the reference point. This range is derived from the international QMRA and epidemiological literature: EFSA (2021) identifies ESBL-producing *E. coli* on fresh produce as a pathway of public health concern; Overdevest et al. (2011) and Mughini-Gras et al. (2019) provide the evidentiary basis for a resistance fraction in this range as representing an elevated AMR transfer risk. This benchmark should be interpreted as indicative rather than definitive, it reflects expert and regulatory concern rather than a quantitatively derived safe level.

Reference thresholds: plant health

Reference thresholds for plant health are less well-defined in the literature than those for human health, there are no regulatory equivalents to the FSANZ criteria for plant pathogen resistance fractions. The thresholds used in this assessment are derived from the biology of each resistance mechanism and from resistance management literature, and should be treated as screening-level reference points rather than established scientific standards. The resistance frequency band and risk characterization in Table 3 are assigned using the median pre-treatment resistance fraction for each scenario; P90 values are reported alongside to indicate upper-tail risk but do not determine the categorical characterization.

- **Copper/bacterial phyllosphere complex:** a pre-treatment resistance fraction above approximately 20–30% is used as the reference point, informed by the relationship between copper tolerance and field control failures in *Xanthomonas* and *Pseudomonas* populations (Marco & Stall, 1983; Cooksey, 1990). Because resistance is HGT-capable, even lower frequencies can seed spread under selective pressure – this threshold carries the highest uncertainty of the three scenarios.
- **Strobilurin/*P. cubensis*:** a pre-treatment resistance fraction above approximately 10–15% is used as the reference, derived from FRAC Group 11 resistance management literature (Gisi et al., 2002). The G143A mutation is

- qualitative (a single gene switch) so control loss is abrupt once this frequency is reached.
- **Phenylamide/*Pythium-Phytophthora*:** a pre-treatment resistance fraction above approximately 20–25% is used as the reference, derived from FRAC Group 4 guidelines and sensitivity monitoring in the literature (Davidse et al., 1981). Resistance here is polygenic, so efficacy loss is more gradual, with partial control retained at intermediate frequencies.

Important caveat: The plant pathogen resistance fraction thresholds above are indicative screening-level benchmarks, not established regulatory or scientific standards. They reflect the current best available evidence but carry significant uncertainty, particularly for the copper and phenylamide scenarios where empirical threshold data are limited. Results described as 'at or approaching' or 'well above' these thresholds should be interpreted accordingly: as an indication that resistance is present at levels of concern, not as a definitive determination that treatment is ineffective.

Variability and uncertainty

Variability and uncertainty are distinct concepts in risk assessment but are difficult to fully separate in practice (FAO/WHO, 2003). Variability refers to genuine heterogeneity in the system being modelled — differences between farms, seasons, water sources, and production practices that exist in the real world. Uncertainty refers to incomplete knowledge about the true values of parameters or the correct structure of the model. In this assessment:

- **Parameter variability:** captured through the probability distributions assigned to each parameter where possible. The width of each distribution reflects the combined influence of true variability (e.g. real differences in soil resistance burden between farms) and parameter uncertainty (e.g. limited data on which to base the distribution). Where data are sparse, wider distributions (Triangular, Uniform) have been used; where empirical data support a tighter characterization, narrower distributions (PERT, truncated Normal) have been applied.
- **Structural model uncertainty:** the model structure makes simplifying assumptions about supply chain dynamics that may not fully represent reality. For example, the HGT parameterization for the copper scenario, the single-scenario representation per crop, and the sequential independence of contamination events. These structural uncertainties cannot be propagated through the Monte Carlo simulation in the same way as parameter variability and are acknowledged qualitatively in the limitations section.
- **Sensitivity analysis as an uncertainty diagnostic:** the Spearman correlation-based sensitivity analysis identifies which parameters most strongly influence each output. Parameters with high $|p|$ are both the most influential on outcomes and, typically, the parameters whose uncertainty most affects the reliability of the model's conclusions. The data collection priorities identified in the Recommendations section are directly derived from this analysis, addressing the uncertainty in high- $|p|$ parameters would have the greatest impact on improving confidence in the results.

Without explicit characterization of variability and uncertainty, it is possible that point estimates will substantially over- or under-estimate exposures. The Monte Carlo approach avoids this by presenting distributions of outcomes rather than single values where possible. However, the conclusions drawn from sensitivity analysis should be interpreted cautiously where multiple influential parameters are correlated in the real world, the independent sampling of parameters in the Monte Carlo simulation does not capture co-variation that may exist between, for example, *Frac_res_soil* and prior chemical use intensity on the same farm.

Model Validation and Future Iterations

Model validation (the evaluation of model outputs against independent empirical observations) is a critical step in building confidence in risk assessment results. At the time of this assessment, formal validation was not possible due to the absence of Australian-specific AMR surveillance data for fresh produce supply chains. The following describes what validation would involve and what is needed to enable it.

What validation would require

For the plant health pathway, validation would require longitudinal monitoring of resistance fraction in target pathogen populations across a representative sample of commercial production fields, paired with records of chemical use history and soil inoculum levels. This type of systematic resistance monitoring is not currently conducted for Australian vegetable production.

The most informative validation would compare model-predicted ESBL fraction and total *E. coli* concentration at consumption against measured values from a representative survey of retail produce across the three crop types. Such a survey does not currently exist in the Australian context. International retail surveys (primarily European and North American) have been used to parameterize the model, but their applicability to Australian conditions involves assumptions about the comparability of production systems, water quality, and supply chain management that cannot be verified

without domestic data.

Consistency check against available evidence

In the absence of formal validation data, a limited consistency check is possible. For the human health pathway, the ESBL-resistant fractions estimated for leafy greens (median 36.4%) and cucumbers (median 20.1%) are consistent with the range reported in European retail surveys (0–25% of *E. coli* isolates from fresh vegetables carrying ESBL genes; Overedges et al., 2011). For the plant health pathway, the high post-treatment resistance fractions estimated across all three scenarios (leafy greens copper (99.1%), cucumbers strobilurin (~100%), and carrots phenylamide (95.6%)) are directionally consistent with international reports of elevated resistance frequencies in bacterial and fungal pathogen populations with a history of exposure to these chemical classes (Marco & Stall, 1983; Gisi et al., 2002; Davidse et al., 1981). These checks provide directional support for the model outputs but do not constitute formal validation.

Future model iterations

The framework is designed to be iterative, outputs from this first iteration identify where data collection would most improve model confidence, and later iterations can be updated as Australian-specific data become available. Key enhancements recommended for future iterations:

- Incorporate Australian-specific ESBL prevalence data for irrigation water, soil, and seed lots as they become available, replacing the international-literature-based parameterization of `Frac_res_preprod`. This is the highest-priority model update.
- Incorporate baseline resistance monitoring data from Australian commercial production soils for each crop–pathogen combination. This would directly update the `Frac_res_soil` distributions, which are the dominant drivers in all three plant health models.
- Develop scenario variants to test the sensitivity of results to production system differences. For example, bore water versus surface water; organic versus conventional; glasshouse versus open field for cucumbers. These could be implemented within the existing model structure with targeted parameter changes.
- Extend the model to include a dose-response assessment once ESBL gene transfer risk relationships are better characterized in the literature, moving from a semi-quantitative risk characterization to a full QMRA for the highest-priority crop.
- Conduct formal value of information analysis to quantify the expected reduction in output uncertainty from collecting data on each high-influence parameter, enabling resource-efficient prioritization of future data collection investments.

Appendix 3B

Quantitative Results - Plant Health (Agrochemical Resistance)

Eighteen figures are provided: three per model (A: parameter sensitivity heatmap; B: overall risk pathway ranking; C: segmented pathway ranking by supply chain module).

Leafy greens — Plant health (Copper / bacterial phyllosphere)



Figure 1 Parameter sensitivity heatmap - leafy greens copper/bacterial plant health model. Spearman rank correlation coefficients (ρ) between each input parameter and each key model output across all 10,000 iterations. Top 15 parameters shown. Positive values indicate parameters that increase risk outputs when elevated; negative values indicate protective parameters. Parameters with near-zero variance (point estimates) are excluded.

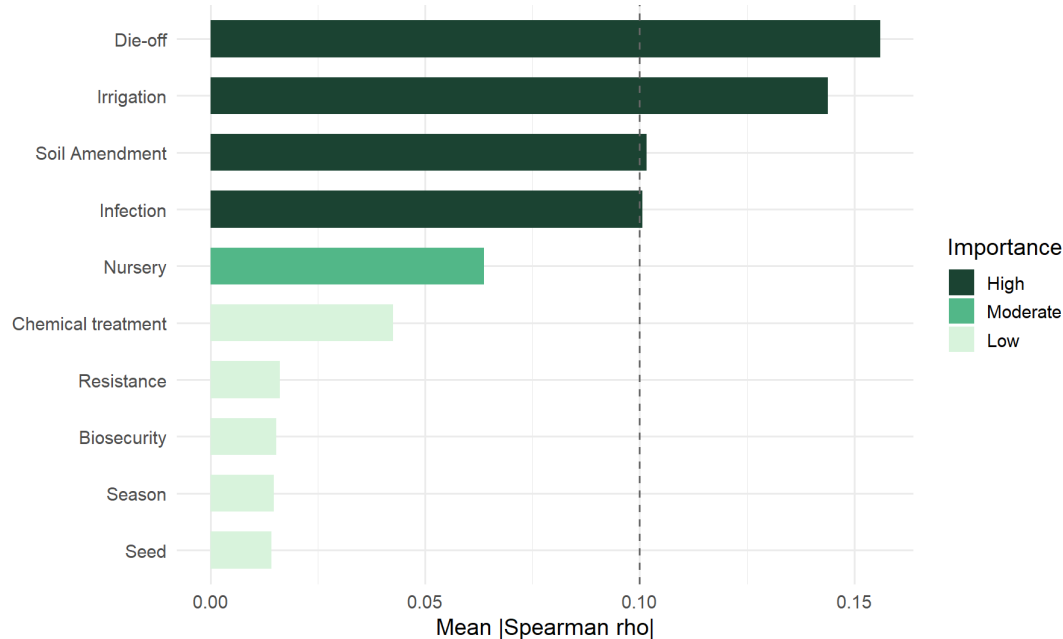


Figure 2. Overall risk pathway ranking - leafy greens copper/bacterial plant health model. Mean absolute Spearman rank correlation (mean $|p|$) across all key model outputs, aggregated by risk pathway. Dashed vertical line at mean $|p| = 0.10$ indicates the High importance threshold. Moderate: 0.05–0.10; Low: <0.05.

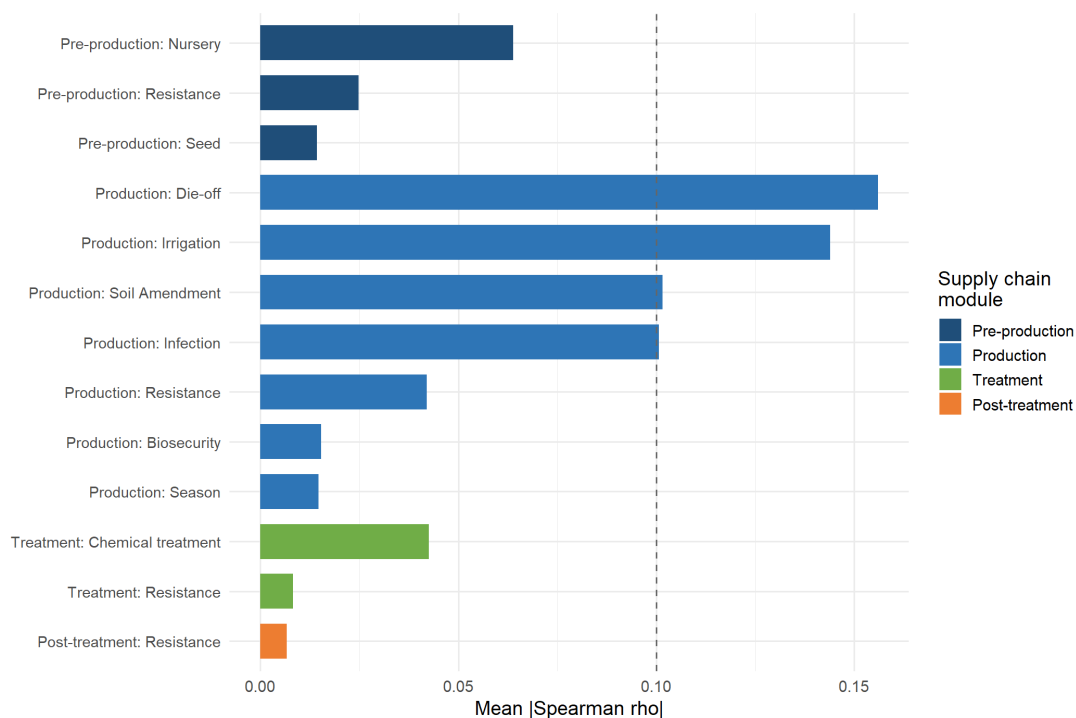


Figure 3. Risk pathway ranking by supply chain module - leafy greens copper/bacterial plant health model. Mean absolute Spearman rank correlation (mean $|p|$) for each pathway, disaggregated by supply chain module (pre-production, production, processing, post-processing). Allows identification of which stage within each pathway drives its overall ranking.

Cucumbers — Plant health (Strobilurin / *P. cubensis*)

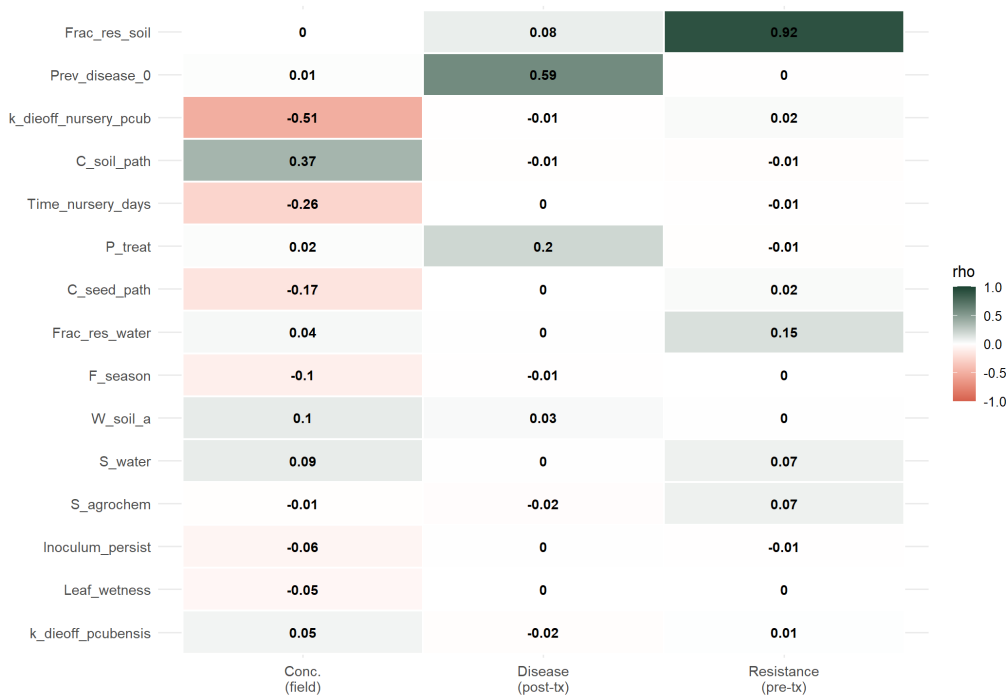


Figure 4. Parameter sensitivity heatmap - cucumbers strobilurin/*P. cubensis* plant health model. Spearman rank correlation coefficients (ρ) between each input parameter and each key model output across all 10,000 iterations. Top 15 parameters shown.

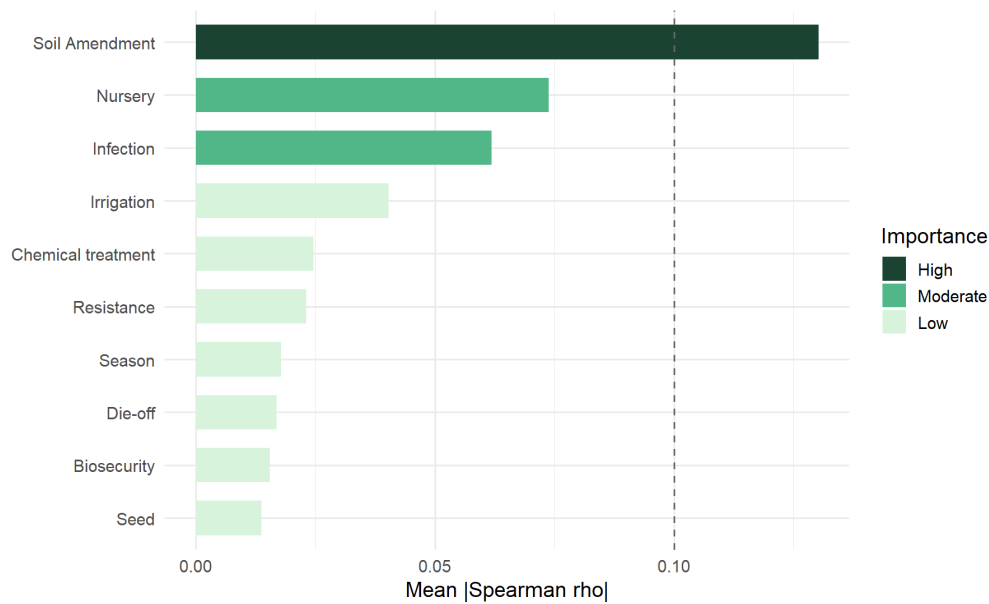


Figure 5. Overall risk pathway ranking - cucumbers strobilurin/*P. cubensis* plant health model. Mean absolute Spearman rank correlation (mean $| \rho |$) across all key model outputs, aggregated by risk pathway. Dashed vertical line at mean $| \rho | = 0.10$ indicates the High importance threshold.

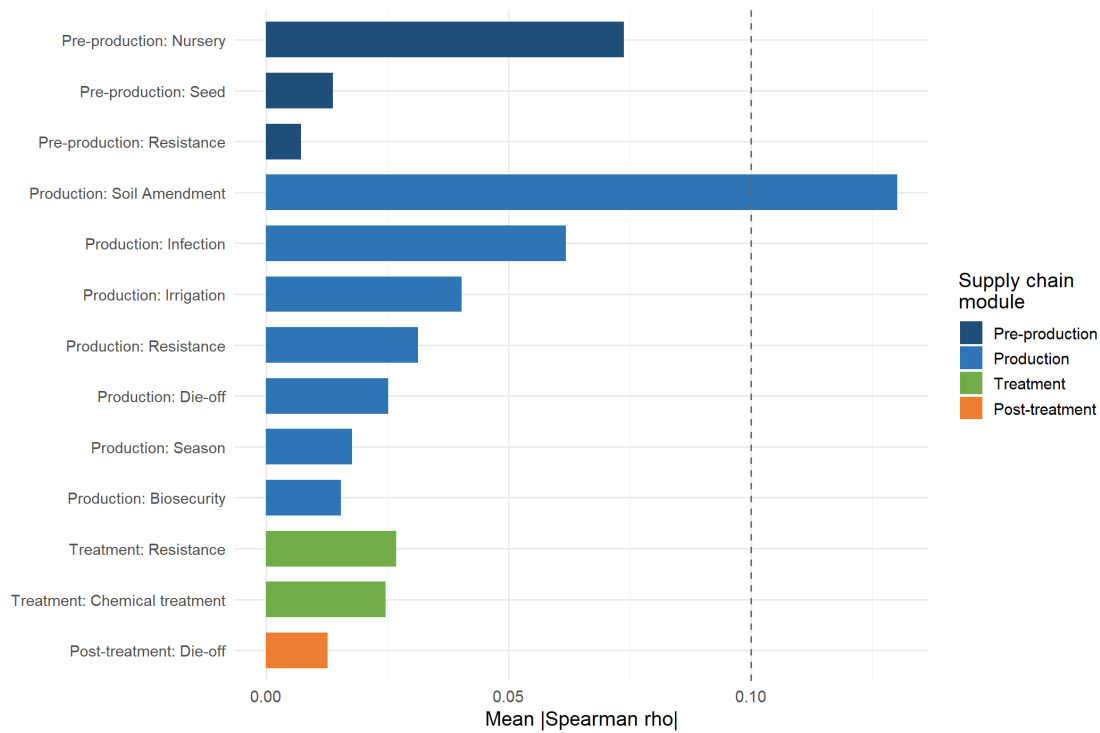


Figure 6. Risk pathway ranking by supply chain module - cucumbers strobilurin/*P. cubensis* plant health model. Mean absolute Spearman rank correlation (mean $|p|$) for each pathway, disaggregated by supply chain module.

Carrots — Plant health (Phenylamide / Pythium-Phytophthora)

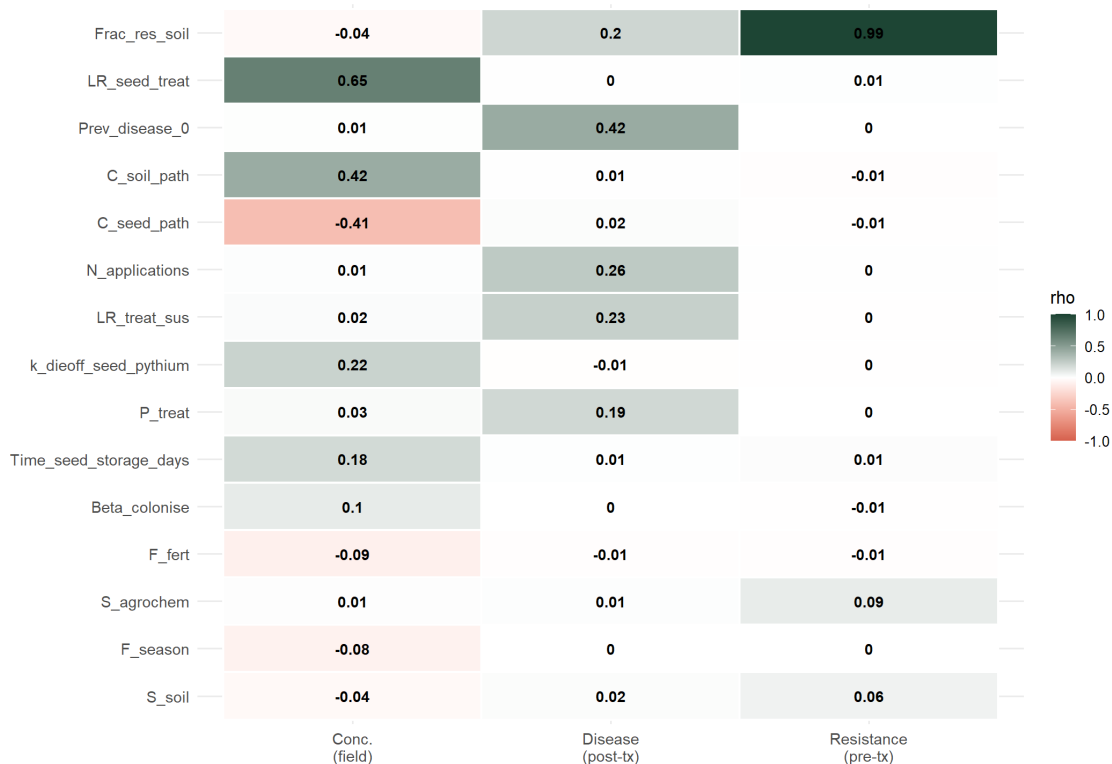


Figure 7. Parameter sensitivity heatmap - carrots phenylamide/Pythium-Phytophthora plant health model. Spearman rank correlation coefficients (ρ) between each input parameter and each key model output across all 10,000 iterations. Top 15 parameters shown.

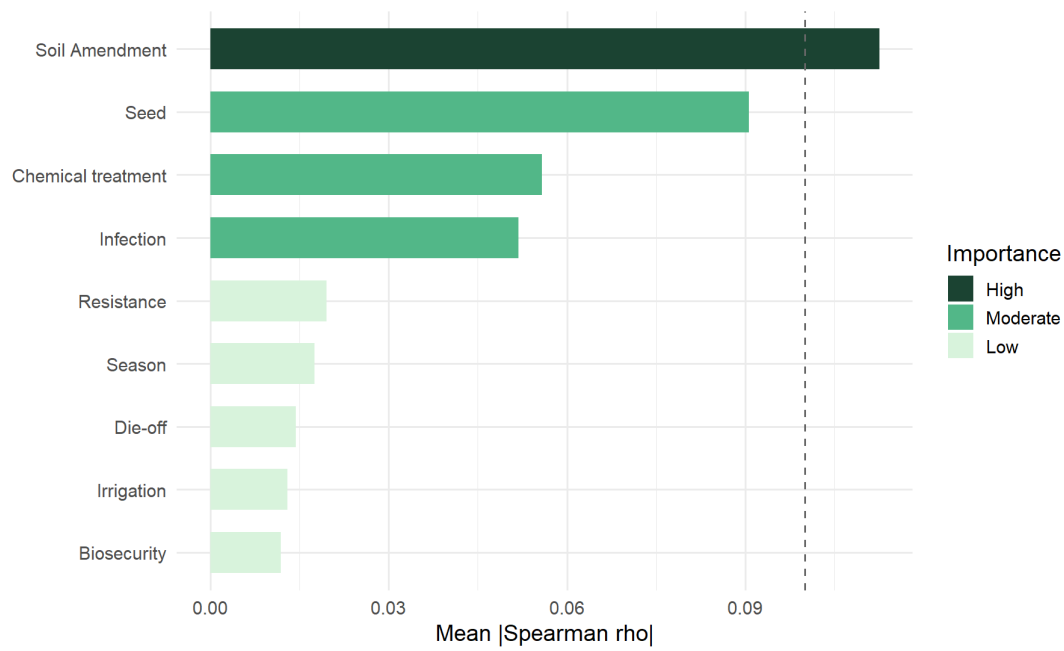


Figure 8. Overall risk pathway ranking - carrots phenylamide/Pythium-Phytophthora plant health model. Mean absolute Spearman rank correlation (mean $| \rho |$) across all key model outputs, aggregated by risk pathway. Dashed vertical line at mean $| \rho | = 0.10$ indicates the High importance threshold.

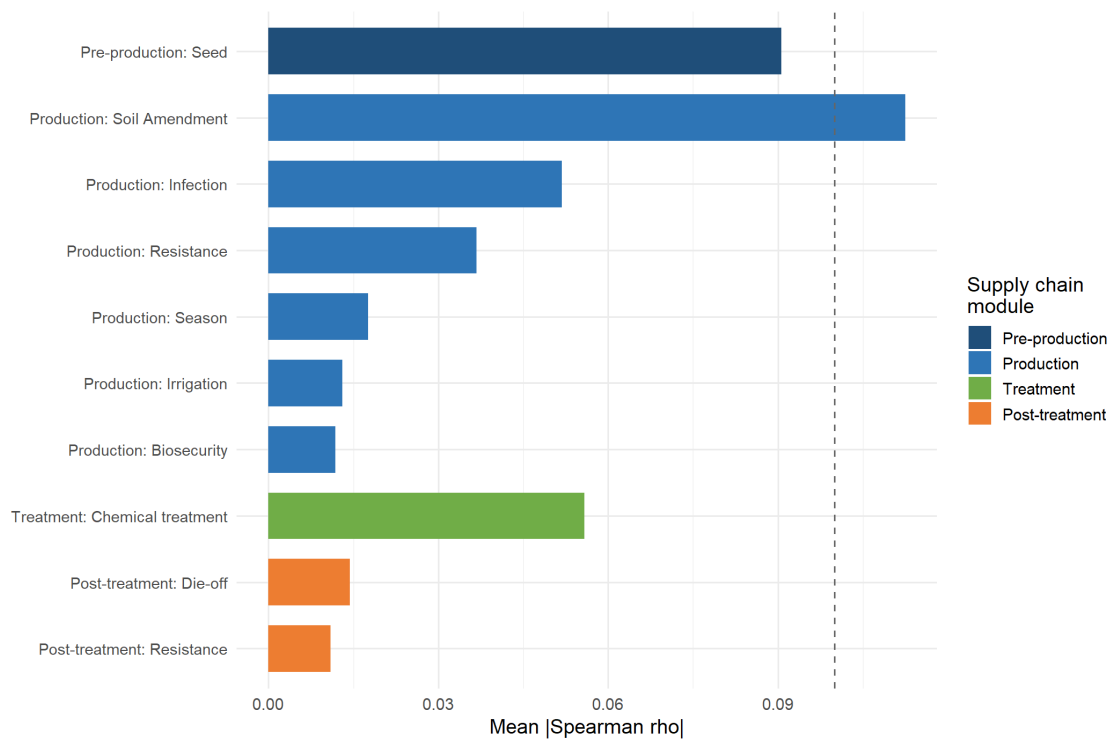


Figure 9. Risk pathway ranking by supply chain module - carrots phenylamide/Pythium-Phytophthora plant health model. Mean absolute Spearman rank correlation (mean $|p|$) for each pathway, disaggregated by supply chain module.

Appendix 3C

Quantitative Results - Human Health (*E. coli*/ESBL)

Leafy greens — Human health (*E. coli* / ESBL)

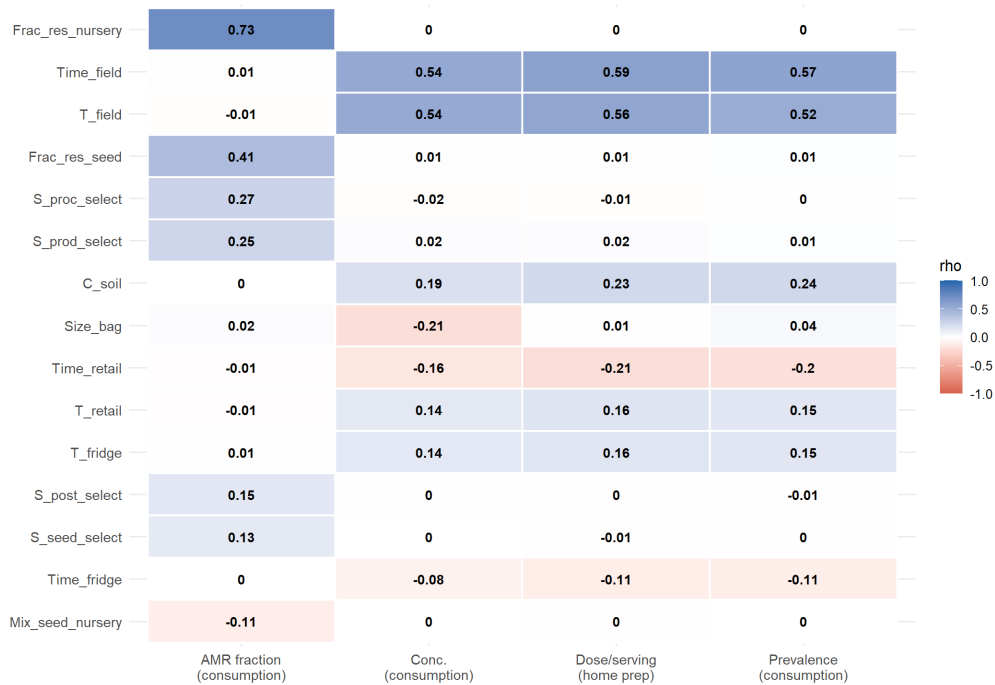


Figure 10. Parameter sensitivity heatmap - leafy greens *E. coli* ESBL human health model. Spearman rank correlation coefficients (ρ) between each input parameter and each key model output across all 10,000 iterations. Top 15 parameters shown.

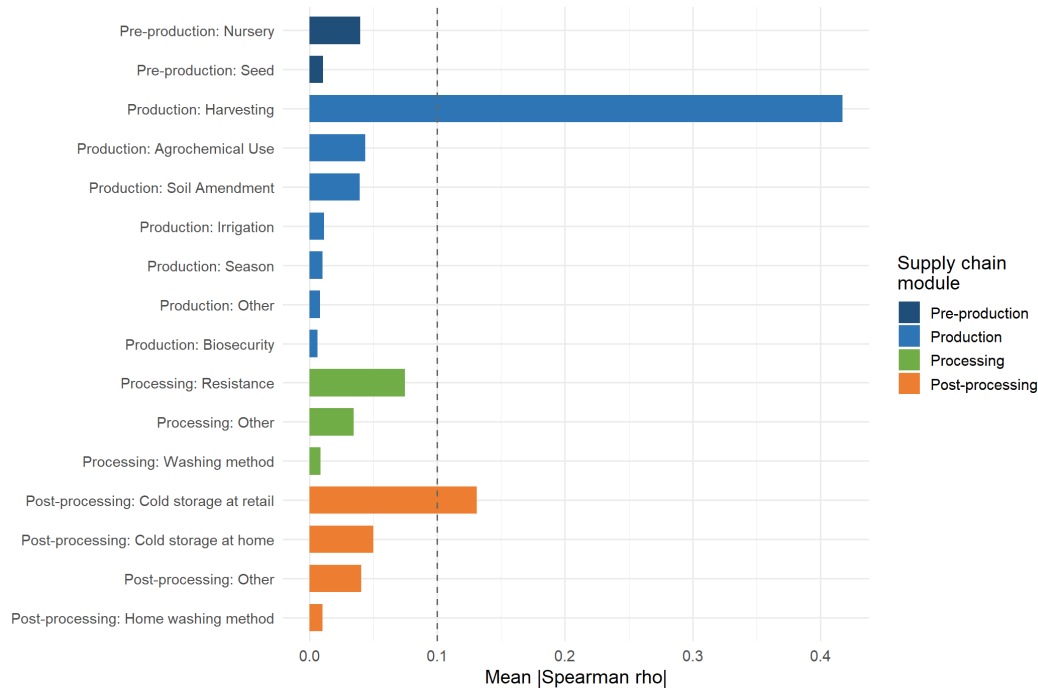


Figure 11. Overall risk pathway ranking - leafy greens *E. coli* ESBL human health model. Mean absolute Spearman rank correlation (mean $| \rho |$) across all key model outputs, aggregated by risk pathway. Dashed vertical line at mean $| \rho | = 0.10$ indicates the High importance threshold.

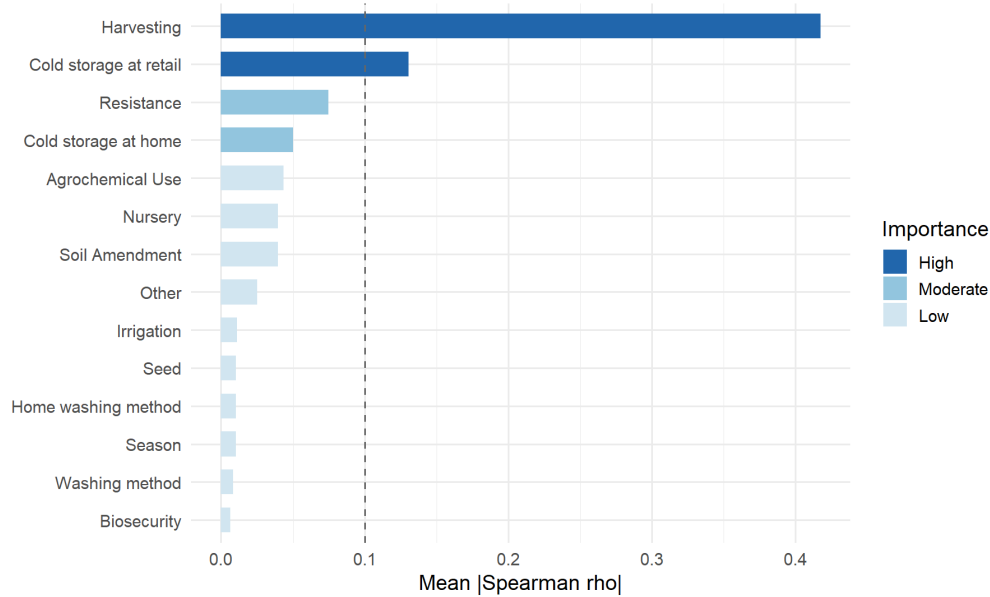


Figure 12. Risk pathway ranking by supply chain module - leafy greens *E. coli* ESBL human health model. Mean absolute Spearman rank correlation (mean $|\rho|$) for each pathway, disaggregated by supply chain module.

Cucumbers — Human health (*E. coli* / ESBL)

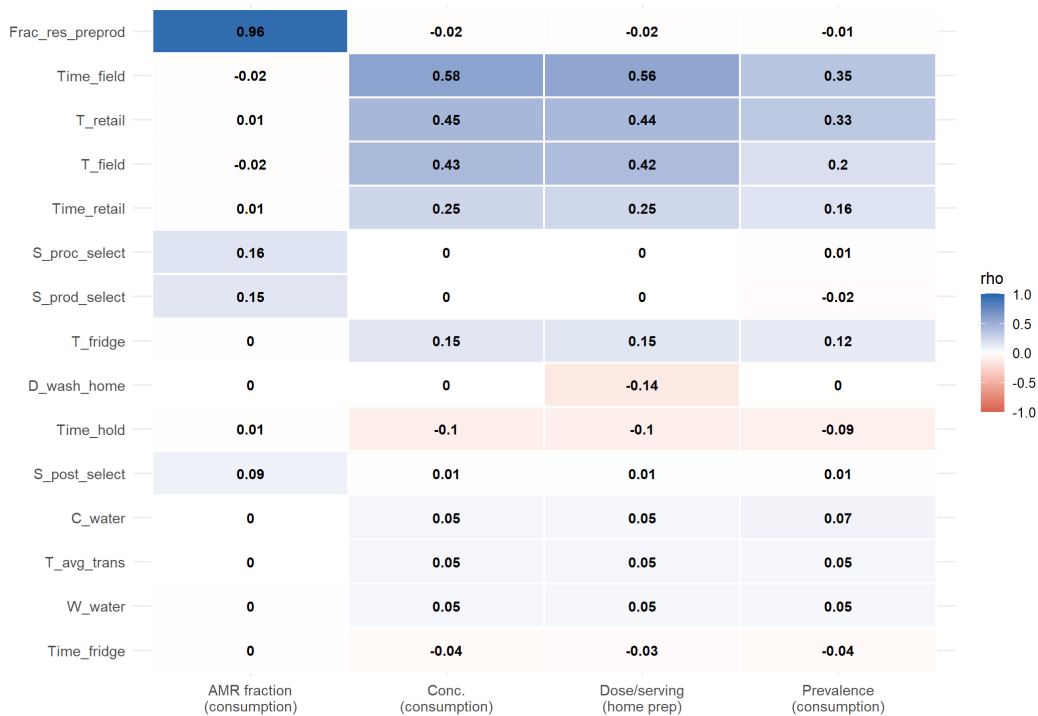


Figure 13. Parameter sensitivity heatmap - cucumbers *E. coli* ESBL human health model. Spearman rank correlation coefficients (ρ) between each input parameter and each key model output across all 10,000 iterations. Top 15 parameters shown.

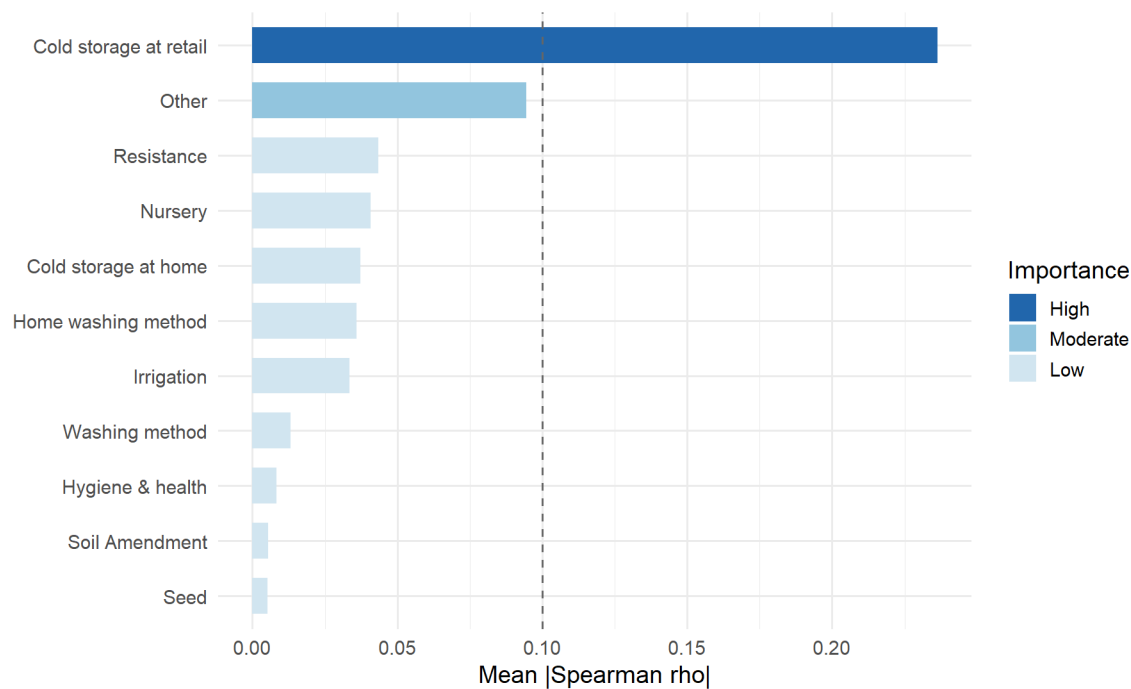


Figure 14. Overall risk pathway ranking - cucumbers *E. coli* ESBL human health model. Mean absolute Spearman rank correlation (mean $|p|$) across all key model outputs, aggregated by risk pathway. Dashed vertical line at mean $|p| = 0.10$ indicates the High importance threshold.

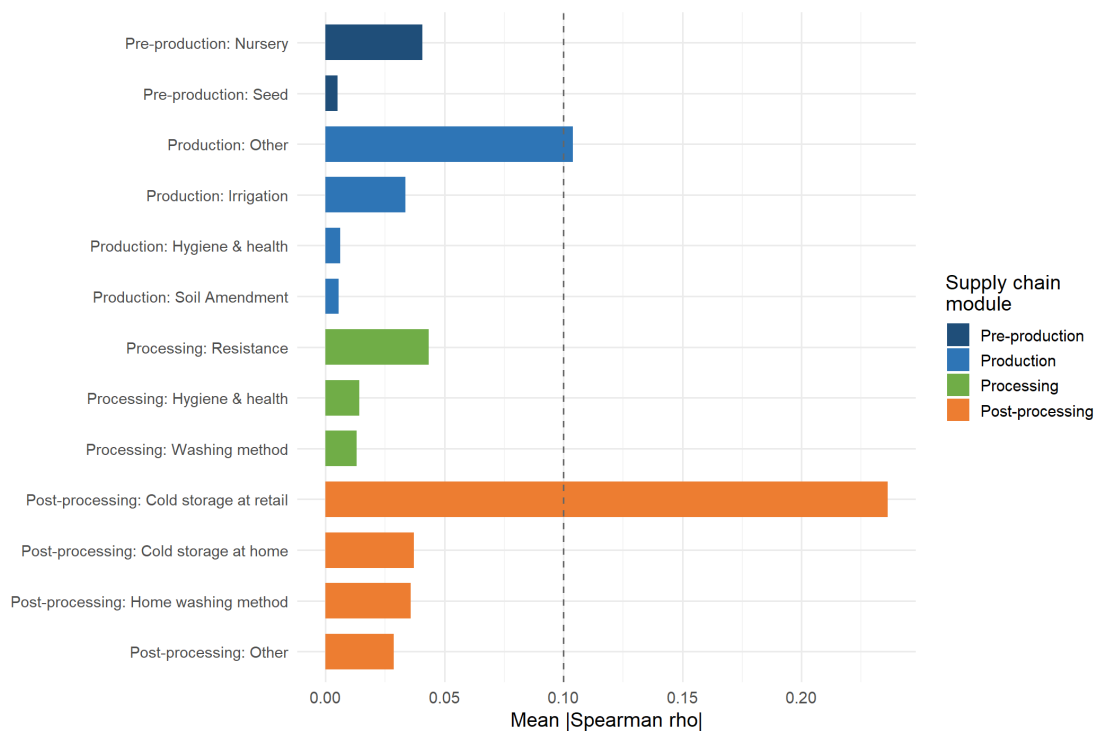


Figure 15. Risk pathway ranking by supply chain module - cucumbers *E. coli* ESBL human health model. Mean absolute Spearman rank correlation (mean $|p|$) for each pathway, disaggregated by supply chain module.

Carrots — Human health (*E. coli* / ESBL)

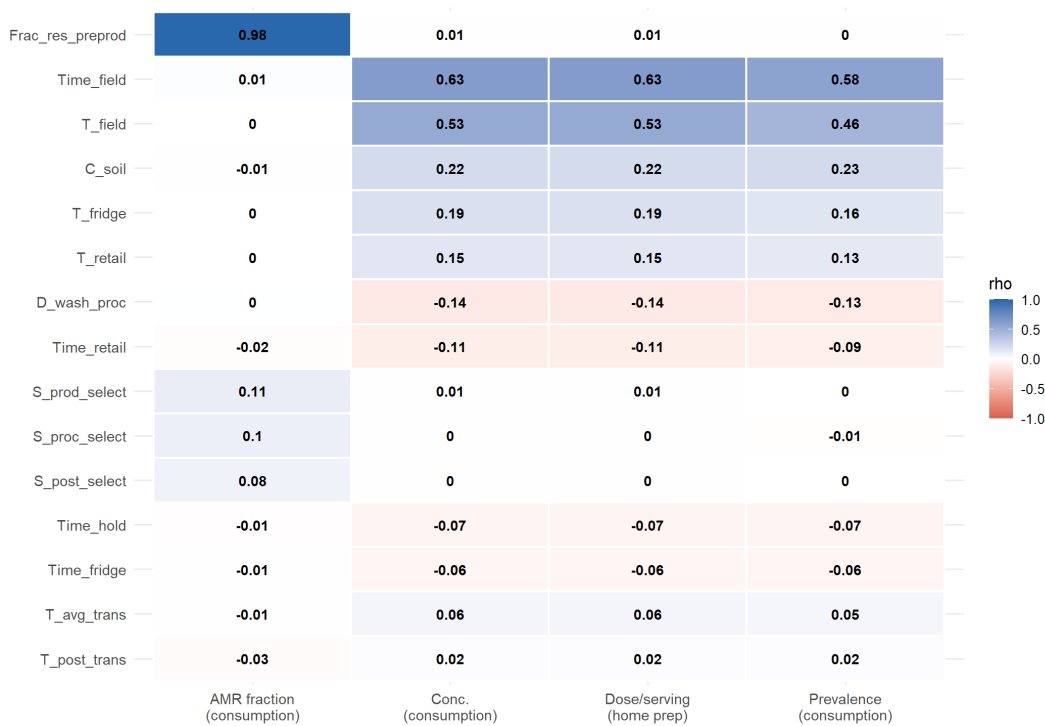


Figure 16. Parameter sensitivity heatmap - carrots *E. coli* ESBL human health model. Spearman rank correlation coefficients (ρ) between each input parameter and each key model output across all 10,000 iterations. Top 15 parameters shown.

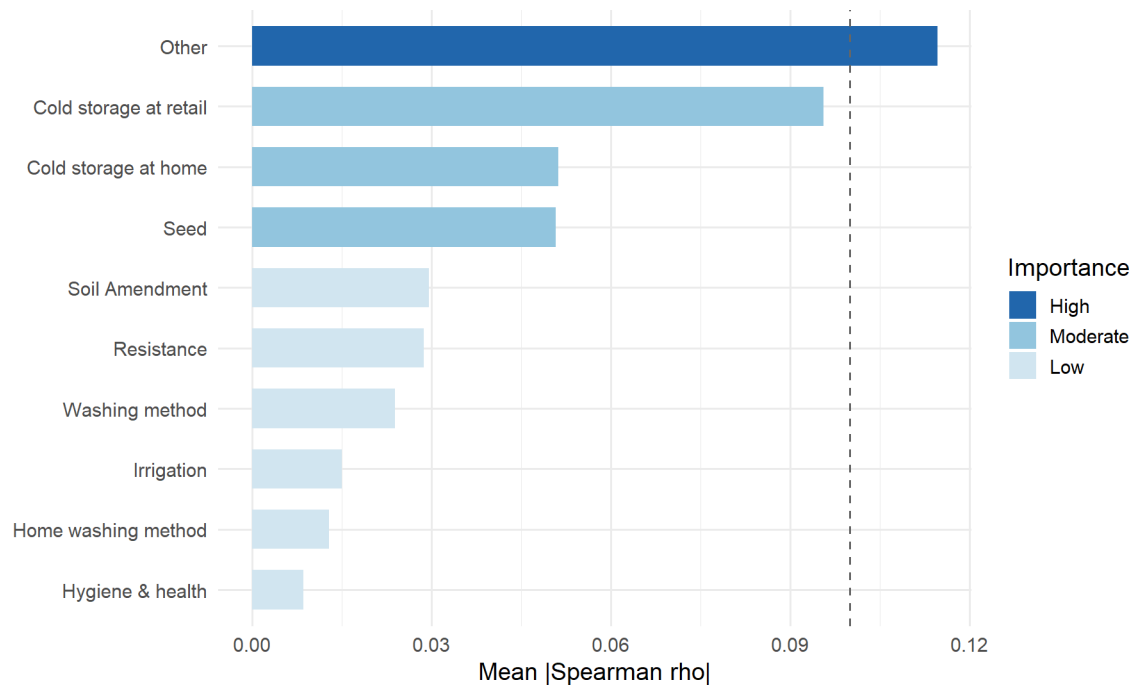


Figure 17. Overall risk pathway ranking - carrots *E. coli* ESBL human health model. Mean absolute Spearman rank correlation (mean $|p|$) across all key model outputs, aggregated by risk pathway. Dashed vertical line at mean $|p| = 0.10$ indicates the High importance threshold.

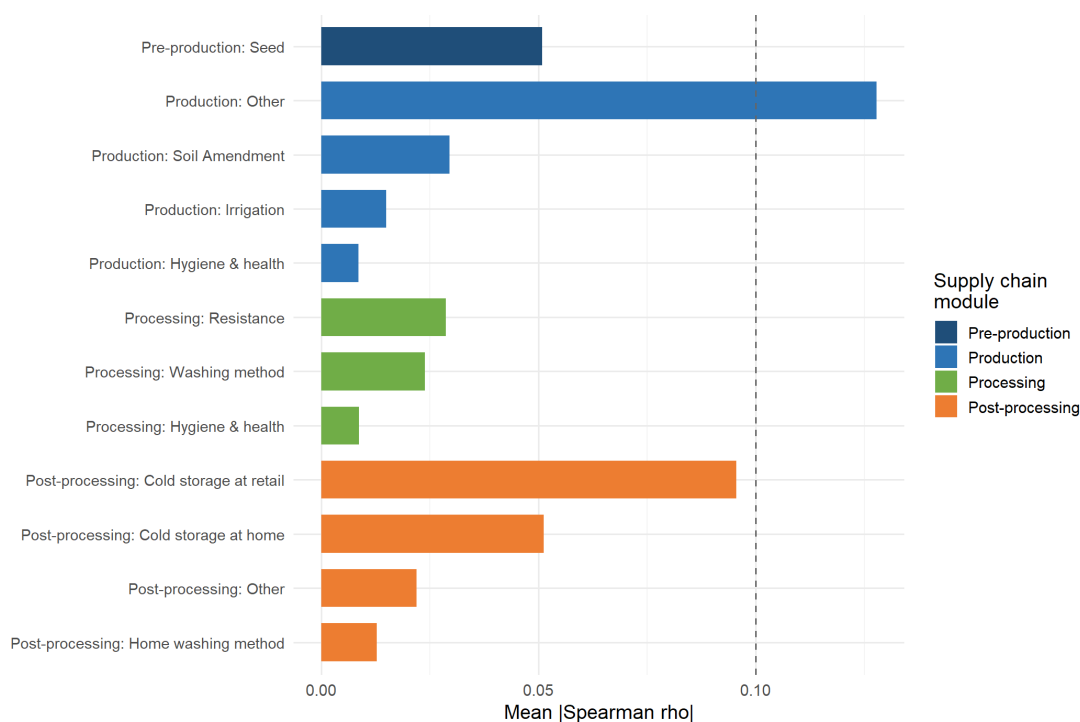


Figure 18. Risk pathway ranking by supply chain module - carrots *E. coli* ESBL human health model. Mean absolute Spearman rank correlation (mean $|\rho|$) for each pathway, disaggregated by supply chain module.

Appendix 3D

Behaviors and Practices Associated with AMR Risk

The following behaviors and practices were identified through the risk assessment, grower practice survey data, and published literature as potentially contributing to the emergence or spread of AMR organisms across the three levy crop supply chains.

Chemical management

The risk of selecting fungicide resistance is a function of pathogen risk and fungicide risk. Pathogen risk is defined by the epidemiology of the target pathogen and inherent genetic factors; fungicide risk is determined by the chemical structure and mode of action of the fungicide under consideration (Brent & Hollomon, 2007). Pathogen and fungicide risk are impacted by field disease management decisions. Additional resistance selection pressure can result from application of sub-label rates or off-label application of products, leading to exposure of pathogens to sub-lethal doses of fungicide that favor resistant individuals without providing adequate disease control. Late-season applications of products with short pre-harvest intervals can effectively reduce the period during which natural crop die-off can reduce pathogen and *E. coli* populations prior to harvest. Increased fungicide resistance selection pressure can also arise from failure to rotate modes of action between the last spray in one season and the first spray in the next season. This becomes particularly relevant where the same chemistry has been applied across multiple consecutive seasons, progressively increasing soil resistance burden. Each application in the presence of resistant inoculum further enriches the resistant fraction of the population. The primary driver of fungicide resistance selection in plant pathogen populations is repeated application of the same FRAC group active ingredients.

The FRAC of the global agrochemical industry, represented in Australia by CropLife Australia, has developed strategies aimed at minimizing the risk of selecting for fungicide resistance in order to maximize product longevity. These strategies have been developed since the introduction of benzimidazole fungicides last century and recommend using mixtures of chemicals with different modes of action, alternation of products with different modes of action, avoiding over-reliance on single-site mode of action chemistries, timely application of fungicides, and integration of fungicide use with other control methods such as disease-resistant crop varieties and crop rotation. The industry has promoted these strategies widely to growers since the late 1970s and all fungicide labels include specific use recommendations in line with the strategies based

on the mode of action of the active ingredient(s) in each product. To simplify communication and adoption of these strategies fungicides are identified using an alphanumeric classification system (FRAC, 2026) which differentiates between products on the basis of fungicidal biochemical mode of action (letters) and target site (numbers). This alphanumeric coding is provided on all product labels which also carry specific directions for use reflecting the fungicide resistance management strategies pertinent to that product.

Grower understanding of and compliance with fungicide resistance management strategies was explored and documented in all three crop systems via the P012 survey.

Irrigation and water management

Irrigation water quality is the top-ranked risk pathway for plant health in leafy greens, and a major contributing source for human health contamination, though harvesting (blade transfer) ranks as the single highest-sensitivity pathway for human health specifically. Surface water of unverified microbiological quality risks simultaneously introducing ESBL-carrying *E. coli* and copper-resistant bacteria onto edible leaf surfaces at every irrigation event. Irrigation close to harvest minimizes the pre-harvest withholding time during which *E. coli* populations naturally decline. The on-leaf die-off rate applied over Time_hold demonstrates that a longer withholding period meaningfully reduces viable *E. coli* counts at harvest.

Soil and input management

Use of incompletely composted organic amendments can introduce *E. coli* and resistance genes into soil. The soil amendment pathway ranked High importance in the leafy greens copper model and Moderate across all plant health scenarios.

Seed sourcing without pathogen status verification is particularly important given the dominance of Frac_res_preprod across all *E. coli* models. Seed-borne *Pythium* on carrot seed and ESBL-carrying *E. coli* on transplant material both constitute direct introduction pathways for resistant organisms. Short crop rotation intervals can impact resistance selection pressure e.g., maintaining continuous *Pythium/Phytophthora* selection pressure in carrot soils without the inoculum dilution effect of a non-host rotation period.

Post-harvest and consumer practices

Ambient retail storage of cucumbers: Cold storage at retail was the dominant human health risk pathway for cucumbers (mean $|p| = 0.228$, High). It is not uncommon for cucumbers, carrots, and leafy greens to be stored and displayed at retail outlets in sealed plastic bags or punnets (Figure 19.). Storing cucumbers at ambient temperature allows *E. coli* to grow on contaminated produce after all farm-level interventions.



Figure 19. Storage of cucumbers at ambient temperature.

Inadequate consumer washing: Home washing method ranked Moderate for cucumbers (0.063). Effective washing under running water reduces dose per serving substantially.

Appendix 3E

Industry Stewardship Programs (Deliverables 3.9)

Existing programs and frameworks

FRAC guidelines

FRAC publishes resistance risk classifications and use guidelines, including for the chemical groups assessed in this project: FRAC Group 4 (phenylamides) and FRAC Group 11 (strobilurins) both carry HIGH resistance risk ratings; copper compounds carry a medium-to-high designation. Rotation guidelines recommend limiting applications per season, alternating between groups with different modes of action, and integrating non-chemical controls. In Australia FRAC guidelines are reviewed, adapted for local use, and issued by the Expert Committee on Fungicide Resistance (ECFR) of CropLife Australia. CropLife Australia members adhere to these guidelines and recommend agreed fungicide resistance management strategies to their distribution networks and growers through publications, promotional material, grower meetings, and individual product stewardship programs. The guidelines are also specifically referenced in product labels but compliance is voluntary and not systematically monitored.

FreshCare and food safety certifications

Compliance with FSANZ and FreshCare (and equivalent schemes including GlobalG.A.P. for export operations) require documentation of chemical use, chemical registers, and compliance with label requirements. These schemes address residue management and food safety but do not specifically address AMR stewardship, they do not require rotation of chemical modes of action or ESBL testing of irrigation water or inputs.

Integrated Disease Management programs

State agriculture departments and commodity levy bodies publish integrated disease management (IDM) guidelines for the assessed crops. These encourage crop rotation, varietal selection, and integration of biological controls alongside chemical management. AMR-specific content (FRAC rotation, resistance monitoring) is inconsistently incorporated.

Appendix 3F

Awareness and compliance (Deliverable 3.10)

Adoption of fungicide/ bactericide resistance management strategies:

Responses to the grower survey conducted as part of P012 suggest that there is a high level of understanding and adoption of resistance management strategies but that compliance is somewhat inconsistent. All 13 growers who participated in the survey stated that they understand how herbicide, fungicide, and insecticide resistance management practices work. When the same growers were asked if they implement resistance management strategies in their vegetable production systems, 9 of 13 respondents agreed with the statement 'always - resistance management strategies form the basis of all our spray programs and management practices' and 4 agreed with the statement 'sometimes - we generally follow resistance management strategies but not if it means we might end up with a disease, pest, or weed problem'. None of the respondents agreed with the statement 'not at all - we don't worry about resistance management because the chemical companies always come up with new products if resistance becomes a problem'. These results are reflective of the finding that strobilurin resistance (near-100% post-treatment resistance for cucumbers) is consistent with international reports of poor FRAC Group 11 rotation compliance in cucurbit production. While the near-universal copper treatment failure result is inconsistent with a grower base applying copper with resistance management intent this may be a function of long-term use of copper sprays for control of fungal pathogens selecting for resistance in bacterial pathogens. Lack of availability of alternative chemistries and cost considerations can limit grower adoption of resistance management strategies.

While growers can implement recommended strategies in their own production chains the purchase of seeds or seedlings introduces vulnerabilities. Fungicide treatments applied to seeds or seedlings must be accounted for in strategy implementation however, particularly in cases where growers purchase seedlings from a seedling producer, they generally have no visibility as to what fungicides may have been applied to the plants prior to purchase. Similarly, while seed packaging must state what fungicide products (if any) have been applied to the seed (Figure 20), there is no information available regarding fungicides which may have been applied to the crop from which the seed was produced.

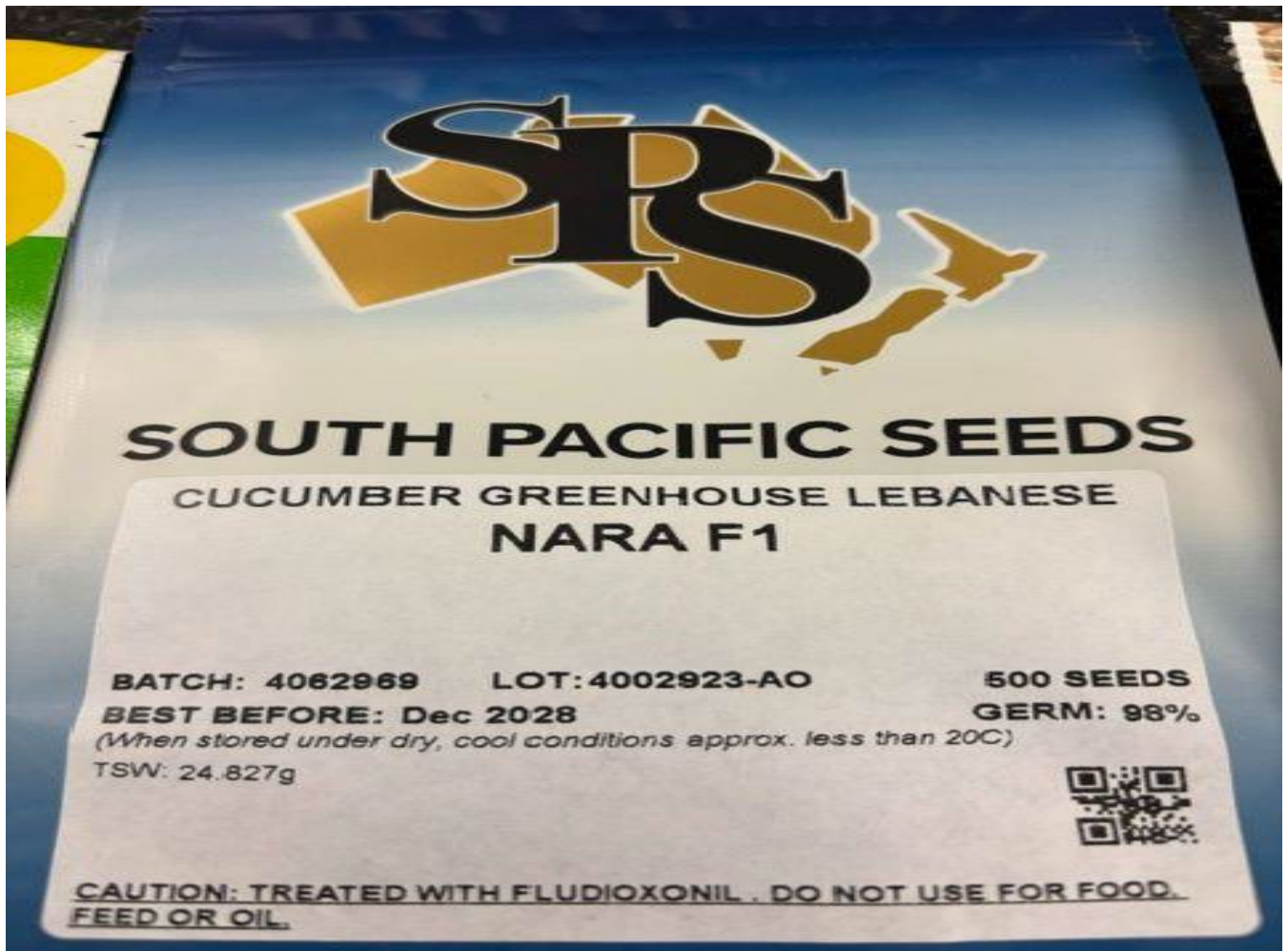


Figure 20. Seed package indicating seed has been treated with fludioxonil fungicide.

Pre-treatment of seed may also limit the options available to growers regarding the products they can use for disease control if they wish to comply with resistance management strategies.

An additional challenge to the effective implementation of fungicide resistance management strategies comes from the potential for spray drift to impact non-target vegetable crops, either from different crops grown on the same property or from neighboring properties.



Figure 21 Mixed fruit tree orchard adjacent to vegetable production, introducing the potential for spray drift from the orchard to the vegetable crop.

Adoption of irrigation water testing

There is no irrigation water testing for AMR indicators: growers who test irrigation water typically do so for general *E. coli* as a hygiene indicator, not for ESBL-producing strains or copper-resistant bacteria. The key risk input identified in the SLRA is therefore invisible to current monitoring.

Food safety certification

Industry-standard food safety certifications do not address AMR. While the key industry certification schemes require spray diaries to be kept, these function as records of what chemicals have been applied to the crop to ensure compliance with Maximum Residue Limits and withholding periods. There is a clear opportunity to incorporate AMR stewardship elements into existing certification requirements. The information currently captured by spray diaries could be used to measure compliance with fungicide and bactericide resistance management strategies but there is no facility for resistance monitoring or ESBL testing of inputs. In the past resistance monitoring and confirmation has been conducted by plant pathologists employed in the public sector such as the various state Departments of Primary Industries or Agriculture. The Australian grains industry, through the GRDC and the wine industry through the AWRI have both developed networks of relevant, skilled individuals in the public and the tertiary education sectors. However, the resources required for monitoring or confirming fungicide and bactericide resistance in Australian vegetable crops do not exist.

Adoption of Integrated disease management programs

Integrated disease management comprises crop rotation, biological control, chemical control, resistant varieties, and crop monitoring for early detection and intervention. Biological control options for plant diseases are limited at this time, but growers routinely employ crop rotation strategies, chemical spray programs utilizing resistance management principles, resistant varieties, and crop monitoring in their disease management programs. Disease resistance in vegetable varieties is an ongoing process and is seen by seed producing companies as a component of product differentiation compared to competitor products, ensuring that growers have access to the latest genetics for disease resistance.