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Review

Waterborne contaminants in high intensity agriculture and plant production: A review of on-site and downstream impacts

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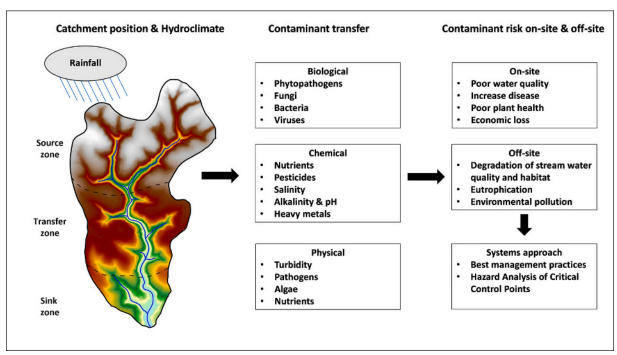
HIGHLIGHTS

- Emerging waterborne contaminants in production nurseries was reviewed.
- Catchment characteristics and hydroclimate influence the transfer of contaminants to nurseries.
- Irrigation water quality impacts plant growth and health.
- Leachate runoff from nursery containers can negatively affect downstream ecosystems.
- Management strategies may reduce contamination risk to nurseries and the environment.

GRAPHICAL ABSTRACT



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ABSTRACT

Waterborne contaminants pose a significant risk to water quality and plant health in agricultural systems. This is particularly the case for relatively small-scale but intensive agricultural operations such as plant production nurseries that often rely on recycled irrigation water. The increasing global demand for plants requires improved water quality and more certainty around water availability, which may be difficult to predict and deliver due to variable and changing climate regimes. Production nurseries are moving to adopt best management practices that recycle water; however, the risks associated with waterborne contaminants of various types, including nutrients, pesticides, plant pathogens, micro-plastics, and toxic metals, are not well understood. We review and synthesise the physical and biogeochemical factors that contribute to waterborne contaminant risk, and the main types of contaminants that are likely to require management, at plant production nurseries. Catchment characteristics (i.e., topography, land use), hydroclimatic factors (i.e., storms, floods, droughts), and landscape hydrological and sediment connectivity influence surface runoff, sediment transport, and associated contaminant transfer and storage. High hydrological connectivity can increase the risk of contaminant transport from the surrounding landscape to nurseries, with potential negative impacts to water quality in reservoirs and in turn plant health. High connectivity may also increase the risk of contaminants (e.g., sediment, pesticides, and phytopathogens) being transferred from nursery farms into downstream waterways, with consequences for

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aquatic ecosystems. Like all intensive agricultural operations, nurseries need to consider sources of irrigation water, water treatment and management strategies, and catchment and hydroclimatic factors, to mitigate the spread of contaminants and reduce their impacts on both plant production and the surrounding environment. Further research is needed to quantify contaminant loads and transfer pathways in these agricultural systems, and to better understand the threshold levels of contaminants that adversely affect plant health and which may result in devastating economic losses.

1. Introduction

Water is a critical resource for agricultural production and plays an important role in global food security (Food and Agricultural Organization of the United Nations, 2014). Agriculture accounts for approximately 70 % of the world's freshwater resource withdrawals (Fuglie et al., 2024). While large quantities of water are used for agricultural irrigation, substantial proportions are lost to the environment through runoff. Given constraints on global water availability, due to population growth and climate variability, in conjunction with increasing public and regulatory pressure, producers have been driven to capture and recycle runoff for irrigation to ensure the sustainability of agricultural production (Obreza et al., 2010; Zhang et al., 2015; Poudyal and Cregg, 2019). However, there is a growing concern by producers regarding the suitability of recycled water owing to elevated risks of waterborne contaminants (Hong and Moorman, 2005; McOmber et al., 2023). The term 'contaminant' broadly refers to any undesirable change in the natural quality of water as a result of biological, chemical, or physical factors and include nutrients, pesticides, plant pathogens, micro-plastics and toxic metals (Bukola and Zaid, 2015). Waterborne contaminants in irrigation water can pose significant risks to plant health and production, and operational efficiency. These risks include reduced growth, increased susceptibility to disease and plant death, decrease in economic value, and increased treatment costs (Raudales et al., 2014; Poudyal and Cregg, 2019). Within the agricultural sector, plant production nurseries are particularly at risk from waterborne contaminants due to their concentrated, polyculture production methods (Abdi and Fernandez, 2019). While many production nurseries adopt water treatment systems to reduce contaminants, there is still limited knowledge of the water quality dynamics and types and sources of contaminants present in recycled water and their effects on plant health and productivity. Therefore, it is important to understand and identify the waterborne contaminants that are present in irrigation water and how they affect plants, as well as mitigation strategies aimed at reducing contamination.

While irrigation water is an important conduit for contaminant spread in agricultural systems including nurseries, other factors, such as catchment setting as well as hydroclimate, also play a role in the transport and fate of contaminants. The position of the nursery within the landscape (e.g., hillslope or floodplain) and the surrounding land use (e.g., agriculture or natural vegetation) can affect surface water runoff and erosion dynamics with potential consequences for contaminant transfer (Singh and Sinha, 2019). Hydroclimatic factors, particularly floods and droughts, can also influence contaminant dispersal from the catchment to nursery sites. For instance, volume and timing of floods can increase hydrological connectivity, resulting in contaminated surface runoff flowing through catchments (Covino, 2017) and into nursery water storage reservoirs. While nursery sites may be at risk of receiving contaminated water from the surrounding landscape with its varying land uses, they may also be responsible for contaminant transfer to the environment, with consequences for downstream surface and groundwater bodies. Flooding may flush contaminants from nursery production sites to nearby rivers and lakes with implications for aquatic ecosystem functioning and biotic integrity (Macklin et al., 2006; Sultan et al., 2023). Therefore, when assessing risks posed by waterborne contaminants at nursery production sites and the surrounding environment, it is necessary to consider the source of irrigation water and management strategies, as well as the catchment setting and hydroclimatic factors to evaluate which factors contribute to contaminant introduction and dispersal.

This review focuses on plant production nurseries and evaluates the effects of waterborne contaminants on plant health as well as the offsite implications of contaminated runoff from nurseries on the environment. Contaminated runoff from nurseries is considered non-point source pollution and an emerging critical issue that requires more attention. This review encompassed many scientific journal articles found primarily on Google Scholar and Scopus. Keywords including "waterborne contaminants, pathogens, persistent organic pollutants, emerging contaminants, production nurseries, aquatic ecosystems, contaminant runoff, and plant health" were employed as search terms to find relevant studies. A thorough examination of the references cited in the journals was also conducted to identify additional relevant papers. Several literature reviews considered the effects of biological contaminants (i.e., phytopathogens) in irrigation water on plant production, and alternative water treatments to control pathogens in irrigation systems (Hong and Moorman, 2005; Stewart-Wade, 2011; Raudales et al., 2014; Majsztrik et al., 2017; Poudyal and Cregg, 2019). Other reviews addressed specific effects of chemical contaminants (e.g., pesticides, nutrients, salinity) (Grattan and Grieve, 1998; Poudyal and Cregg, 2019; Trejo-Téllez and Gómez-Merino, 2012) and emerging contaminants (e.g., microplastics and persistent organic pollutants) (Liu et al., 2014; Vergani et al., 2017; Liu et al., 2018; Qi et al., 2018; Sajjad et al., 2022) on plant health. However, the role of landscape position and connectivity in the retention and accumulation, or release and dispersal of waterborne contaminants, both biological and chemical, to and from nursery production sites has previously been overlooked.

Understanding the influence of landscape position and connectivity enables mitigation strategies to be implemented at optimal locations on nursery sites where contaminants can be reduced (e.g., vegetative buffer strips to intercept the flow path or filter the water) to minimize on-site and off-site impacts (Opoku et al., 2024). This paper (1) presents a framework characterising the effects of waterborne contaminants at plant production nurseries; (2) assesses the role that landscape position and connectivity plays in waterborne contaminant transfer both on- and off nursery production sites; (3) reviews published literature to identify types of waterborne contaminants that pose a risk to plant production nurseries and aquatic ecosystems; and (4) provides a conceptual diagram and systems approach strategy that outlines best management practices that growers can implement to reduce contaminant risks.

2. Catchment characteristics and hazard risks

Physical hazards, including catchment characteristics and hydroclimate, can have substantial impacts on water quality and nursery production within the catchment area (Fig. 1). For instance, catchment position and geomorphic characteristics (i.e., topography, vegetation, surrounding land use type) can influence hydrological and sediment connectivity and thus infiltration and runoff dynamics (Saco et al., 2018; Wohl et al., 2019). Connectivity refers to the dynamic interactions of land cover, climate, geomorphology, surface runoff, and anthropogenic activities, which is crucial for the transfer of energy and matter (Wainwright et al., 2011). For example, increased connectivity can occur when natural vegetation is modified into agricultural land or during the dry season when vegetation biomass is reduced, resulting in reduced infiltration and increased surface runoff (Wohl et al., 2019). A study investigating the influence of landscape connectivity on water dissolved organic carbon (DOC) content in farm pond catchments in China, found that the average water DOC content was higher during the dry season (5.35 ± 2.03 mg L^{-1}) compared to the wet season (4.27 ± 1.40 mg L^{-1}) (Liu et al., 2024).

Heavy rainfall can result in infiltration excess and surface runoff from the catchment, which can transport contaminated wastewater and sediments to nursery sites. Depending on the catchment position and degree to which the catchment is connected, nurseries can either be at a higher or lower risk of receiving contaminated runoff (Fig. 2A). Nurseries located near the catchment divide (source zone) (Fig. 2B) will be less prone to receiving run-off from the surrounding landscape and thus have a lower hazard risk, whereas nurseries located in the middle part of the catchment (transfer zone) (Fig. 2C) will have greater exposure to run-on from hillslopes, and rainfall. In contrast, nurseries located near the bottom of the catchment (sink zone) (Fig. 2D) will have a higher hazard risk due to exposure to run-on from hillslopes and flood waters from the river and rainfall. In all cases, a major concern for nurseries is the production of run-off into tributaries and rivers, which needs to be managed to prevent contaminant spread to the environment.

Importantly, climate and anthropogenic factors can alter physical factors. For instance, anthropogenic activities that alter vegetation coverage can lead to increased erosion and sediment transfer, which, when coupled with climate variability, can heighten the intensity and frequency of flooding events, thereby enhancing hydrological connectivity across the landscape (Fryirs, 2013; Covino, 2017; Khan et al., 2021a) and contaminant dispersal with implications for water quality in nursery storage reservoirs. For instance, heavy rainfall on deforested hillslopes may exceed infiltration capacity and increase surface runoff and erosion (Singh et al., 2017; Saco et al., 2018), potentially enhancing contaminant transfer. Similarly, removal of riparian vegetation along river banks increases river-floodplain connectivity and potential contaminant transfer during riverine flooding events (Jackson et al., 2022). Therefore, consideration should be given to the position of the nursery within the landscape, as well as the catchment setting and surrounding land uses to assess risks from physical hazards on nursery plant production. For instance, nursery properties situated downstream of agricultural, urban or industrial regions may be at risk of receiving contaminated surface runoff due to heavy rainfall or over-bank flooding. Floodwaters containing toxic metals from surrounding mining areas, have led to crop losses in farms situated on floodplains downstream (Marrugo-Negrete et al., 2015). In turn, an understanding of the influence of catchment characteristics on hazard risk and possible contaminant input and output can help nursery growers identify the types and sources of contamination in nurseries, and thus implement targeted management strategies to reduce contamination (e.g., open earth dams).

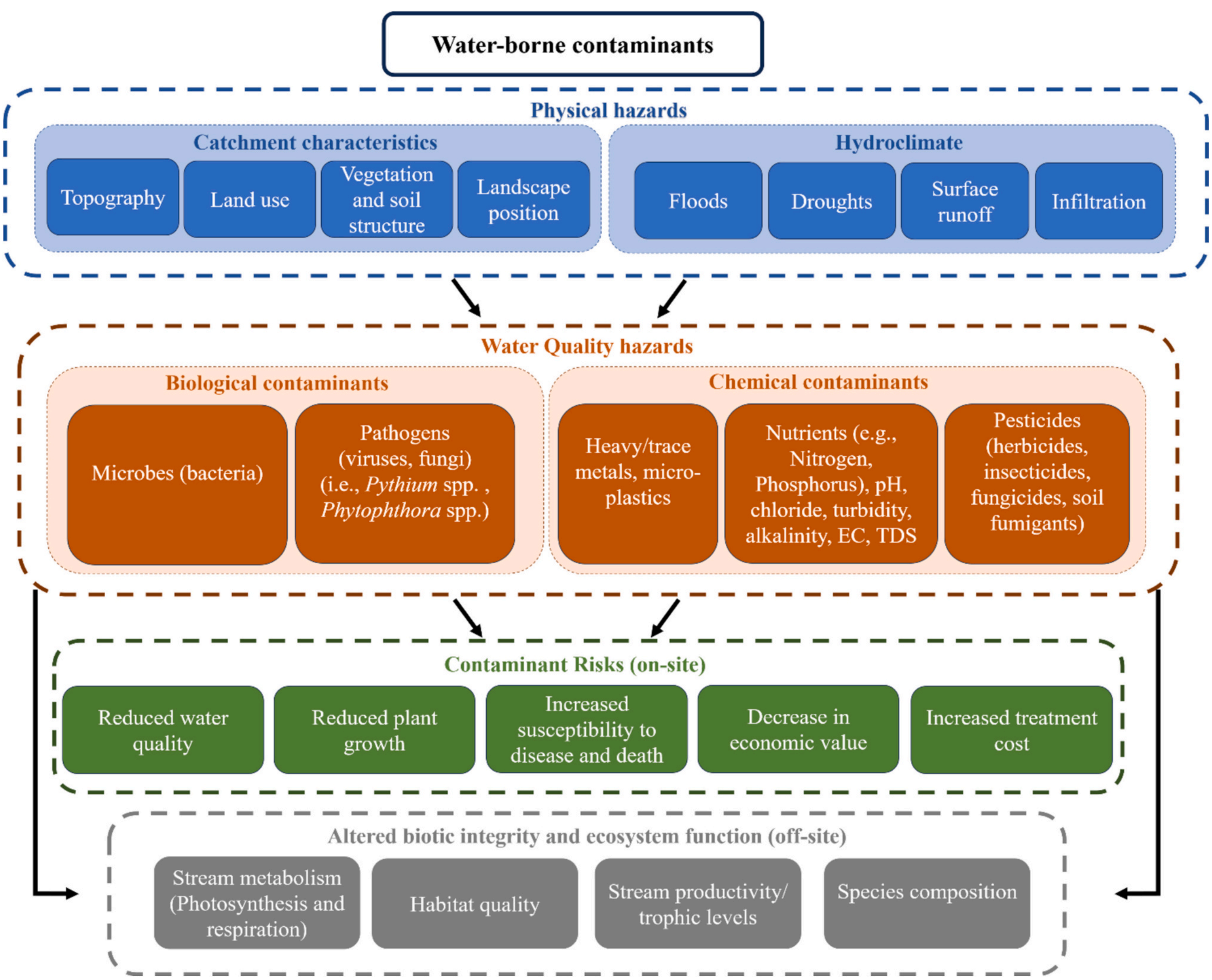

Fig. 1. Conceptual model illustrating the impacts of catchment characteristics and hydroclimate (blue boxes) on water quality (orange boxes), and how contaminant hazards pose a risk to nursery plant production (green boxes), and biotic integrity and ecosystem functioning (grey boxes). Arrows indicate pathways of influence. Dashed boxes represent distinct levels of impact, and boxes within them represent the main components pertaining to that risk.

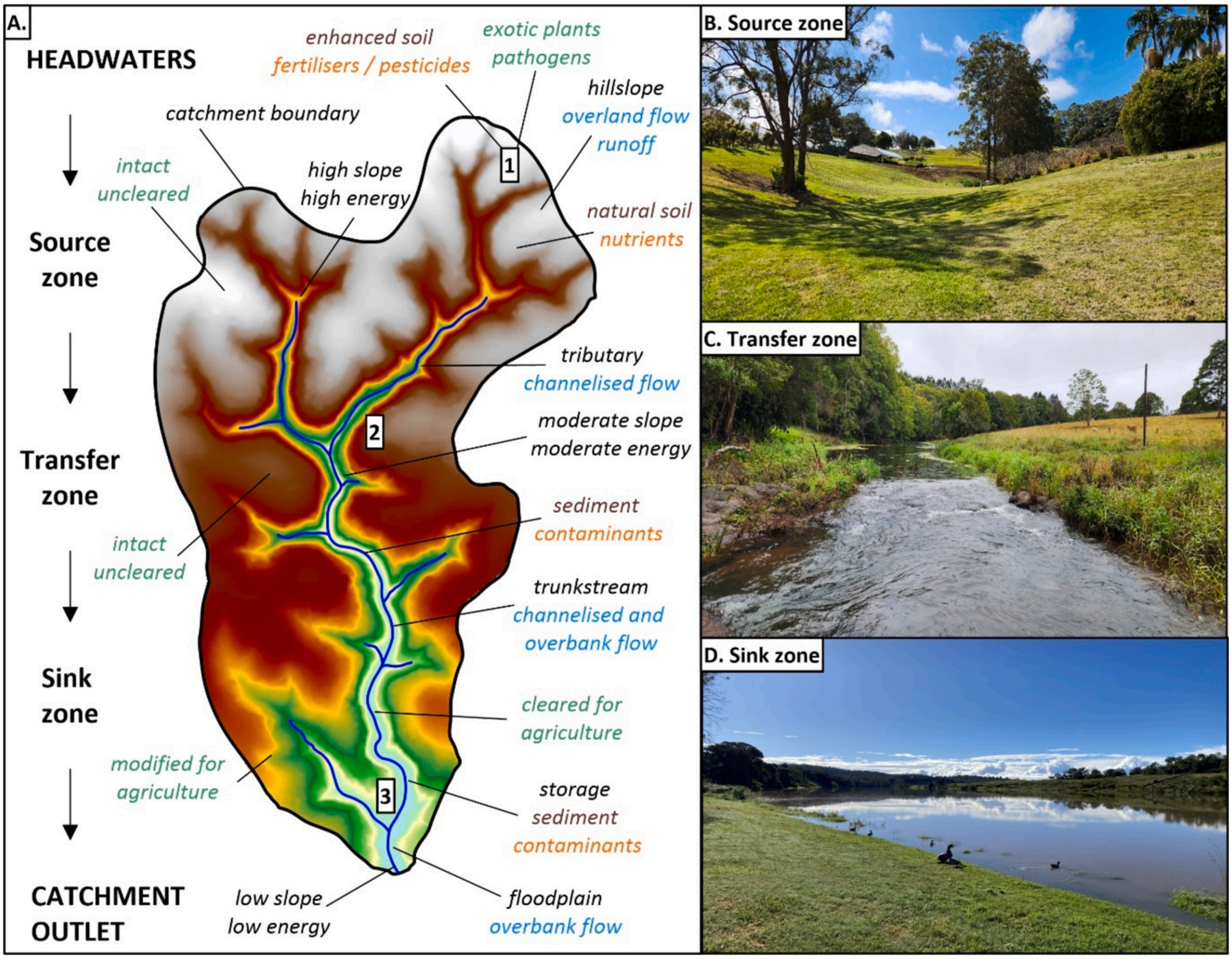

Fig. 2. Schematic of (A) catchment location, characteristics and processes and how they may influence the transfer of contaminants. For example (B) a farm located near the catchment divide (source zone) is only exposed to rainfall, and generates run-off; (C) a farm located in the middle part of the catchment (transfer zone) is exposed to run-on from hillslopes, and rainfall and generates run-off into tributaries; and (D) a farm located towards the bottom of the catchment (sink zone) is exposed to run-on from hillslopes, flood waters from the river, and rainfall and generates run-off into the river. Colours represent physical features (black), soil/sediment processes (brown), water processes (blue), contaminant/nutrient processes (orange), and vegetation processes (green).

3. Irrigation and production systems

3.1. Irrigation water

A major consideration for contaminant dissemination in nurseries is the source and quality of irrigation water. The quality and suitability of irrigation water for nursery production is critically important to produce high quality yields (Bilderback, 2002). Therefore, nursery growers need to ensure they have access to sufficient water of high quality to meet the demand of the irrigation requirements. The water volume required to irrigate container nursery plants averages >5 to 6 million gal/acre per year (47 million L/ha per year) for growers irrigating 1 in. per day (2.54 cm per day) between 160 and 200 days per year (Fulcher et al., 2016). Containerised plants in particular, require high quantities of water due to the high porosity and restricted root volumes in the growing substrate (i.e., soilless media), resulting in lower plant available water (Owen and Altland, 2008). Irrigation water can be sourced from municipal water, well water, groundwater, or surface water supplies (i.e., ponds, lakes, rivers, and reservoirs). Municipal water is a reliable source of good quality water and typically favoured by growers, as the pH is typically ideal (pH 7.5) and it has been treated to remove suspended solids, colour, odour, and pathogenic bacteria (Majsztrik et al., 2017). However, municipal water is becoming increasingly expensive and is not always readily available for the large volume of irrigation water required. In a study of eight surveyed greenhouse operations, the cost of municipal water ranged from US$3.94 to US$6.43 per 3785 L, which was much higher than US$0.02 for pond or well water (Raudales et al., 2017). In some Australian states, for example, there are restrictions on irrigation licences and new enterprises are legally required to purchase water rights for their irrigation (Productivity Commission, 2003). Permanent water courses (i.e., rivers) are generally the cheapest option for growers, but the water quality may vary as it may contain large quantities of organic and suspended matter, and organic and inorganic material including effluent, from land use activities in the catchment (Raudales et al., 2014). During stormflow or flooding, streams and rivers are likely to contain suspended clay and algae and dissolved nutrients, while low- or no-flow conditions may lead to concentration of chemical pollutants, reducing its suitability for irrigating plants. Groundwater from aquifers is also commonly used for irrigation, but in most cases, it is insufficient for the volume required and the quality may be poor (Raudales et al., 2014). Treated effluent from sewage treatment plants is another alternative source of irrigation water, but the quality varies greatly and it may contain high quantities of nitrogen and phosphorus, which may result in algal growth and blocked irrigation equipment.

Nursery growers will often use a combination of water sources depending on accessibility, availability, and quality, as each source differs with regard to water-use regulations as well as contamination risk (Redekar et al., 2019). However, increasing water scarcity and government regulations has placed pressure on growers to adopt efficient water-use strategies, such as recapturing and recycling runoff water collected in storage reservoirs (Poudyal and Cregg, 2019). Advantages of recycling water include minimising the depletion of water sources and potential environmental contamination from runoff. Recycled water may contain recycled mineral nutrients and fertiliser salts that can be beneficial to plants. However, nursery growers are often hesitant to adopt recycling technologies or change their practices due to concerns about increased contamination risks from the reintroduction of pathogens, plant growth regulators, and pesticides, as well as installation costs of treatment systems (Majsztrik et al., 2017). In addition, growers' perceptions of risk associated with these contaminants are a major barrier to adoption and use of recycled water.

3.2. Irrigation systems

The irrigation method and scheduling are also important considerations for contaminant dissemination in nurseries. The irrigation system affects the irrigation application efficiency, which refers to the proportion of water applied that is available for plant uptake, and thus, determines whether excess water will leach from containers or not (Mathers et al., 2005). Irrigation efficiency depends on several factors, including the irrigation equipment (i.e., overhead sprinklers, drip emitters, micro-emitters, or spray stakes), irrigation scheduling, uniformity of irrigation, container size, spacing and substrate media, and system design and maintenance (Fig. 3A, B) (Mathers et al., 2005). Overhead sprinkler irrigation systems are typically favoured by nursery growers as they are reliable and economical, and can be used to irrigate a variety of container sizes within an area (Mathers et al., 2005). However, these systems tend to be less efficient as containerised plants have limited root zones and require frequent irrigation, which impacts the irrigation application efficiency of overhead irrigation. Depending on container spacing and size, up to 80 % of water applied through overhead irrigation systems is lost as runoff Mathers et al. (2005). In contrast, micro-irrigation systems (i.e., drip emitters or spray stakes) reduce irrigation runoff from larger containers (>19 L), cut operating costs, reduce disease and pathogen spread, and improve fertiliser application efficiency (Beeson, 1992). Uniformity of water delivery is also an important component of irrigation efficiency, as uneven water application requires increased irrigation duration to ensure all containers receive sufficient water, which may lead to overwatering of some containers and leaching of nutrients and pesticide residues.

Excess water or agrichemicals (i.e., fertilisers, pesticides, and plant growth regulators) that is applied to saturated container plants will drain from containers, or will fall between them, and enter surface runoff. Approximately 16 % - 30 % of pesticide granules that fell in non-target spaces between containers subsequently entered surface runoff and retention ponds (Wilson et al., 2005). Runoff from production sites can either be drained into retention ponds to be treated and reused or discharged to the environment (Pittis and Colhoun, 1984). Storage water retention ponds can either be semi-natural, unsealed dams, with vegetation around the perimeter of the dam or fully sealed artificial dams with minimal vegetation surrounding the perimeter of the dam (Fig. 3C, D). Water stored in retention ponds requires specific treatment to reduce contaminant spread to plants irrigated with recycled water. Production nurseries contain hundreds of potential host species growing across several microenvironments and thus untreated recycled water is likely to facilitate the spread of phytopathogens that can easily be distributed in irrigation water. Therefore, growers are encouraged to treat irrigation water and regularly test water for the presence of contaminants (Parke and Grünwald, 2012).

Where water is discharged to the environment, it also requires

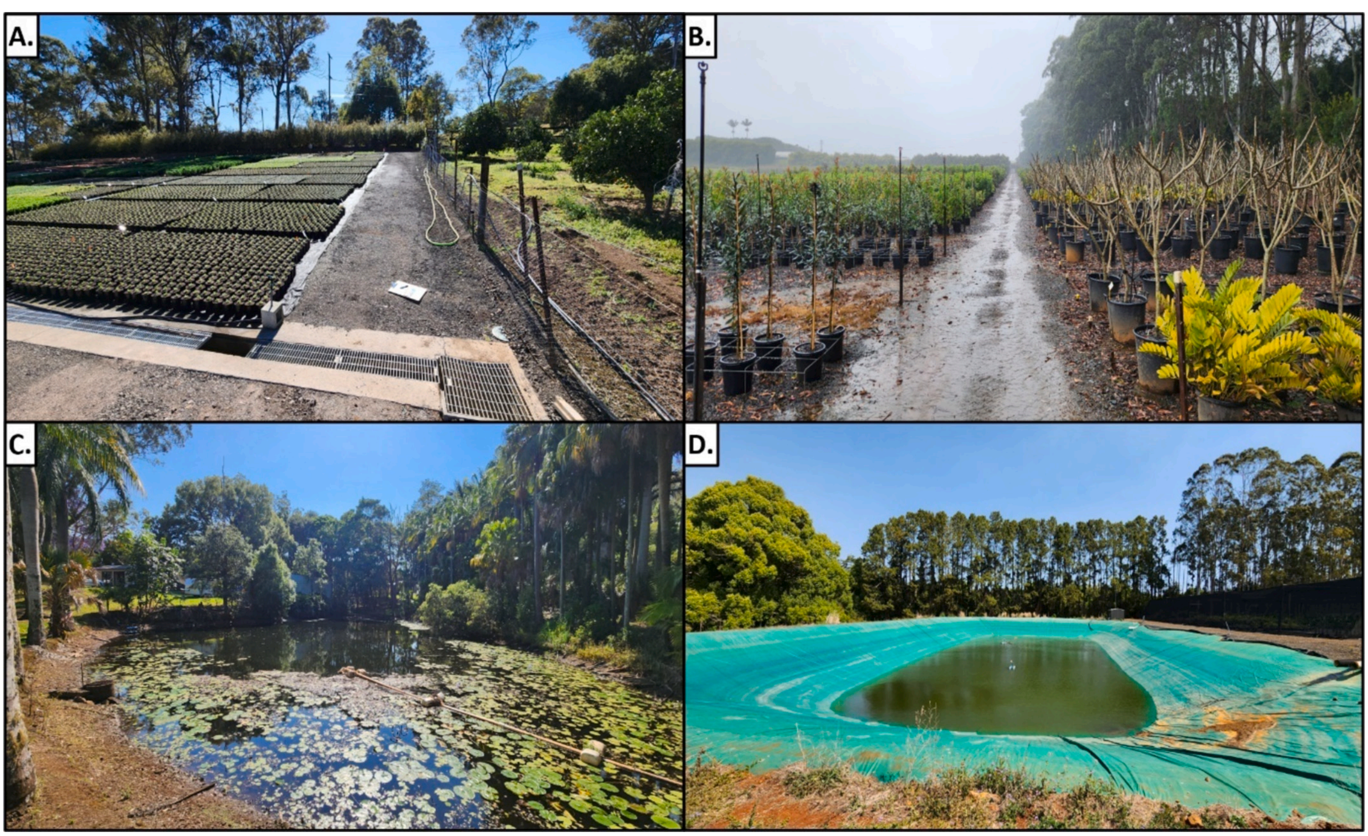

Fig. 3. On-ground images (A) and (B) of plant production nurseries illustrating both natural and anthropogenic modifications to enhance surface water collection (e.g., irrigation systems, drains, and plastic lining), (C) unsealed, vegetated-lined, semi-natural dam, and (D) fully lined and sealed, with minimal vegetation.

treatment to reduce contaminant loading of receiving waterways downstream of the discharge point. Runoff from nurseries is considered non-point source pollution, which poses a significant risk to the environment as it can transport sediment, fertiliser, pesticides, and phytopathogens (Sánchez-Bayo et al., 2016). Nutrient-laden runoff, particularly nitrogen (N) and phosphorus (P), can lead to environmental problems such as algal blooms and eutrophication (Majsztrik et al., 2017). Strict water use regulations require nursery growers to capture and treat all runoff before it can be released into the environment (Qadri and Faiq, 2020). Sustained and consistent management of water quality and irrigation systems is critically important to ensure growers can maximise irrigation efficiency and reduce runoff and potential water contamination transfer.

3.3. Production systems

Managing contaminant spread in plant production nurseries is challenging due to the extreme plant heterogeneity and high plant

Table 1
Key waterborne contaminants affecting plant production nurseries.

Type	Contaminant	Sources	Impacts on plant	Treatment	References
Biological	Phytopathogens (e.g., *Phytophthora*, *Phytopythium* and *Pythium* species), fungi, bacteria and viruses	Inhabit primary aquatic and moist soil habitats. Transported via irrigation water.	Blights, damping off, downy mildews, root rot, chlorosis, stunting, wilting, and plant death.	Prevent pathogen introductions. Implement a systematic monitoring plan to assess nursery plant health. Sterilise all equipment. Heat treatment. Destroy diseased plants.	(Hong and Moorman, 2005; Cooke et al., 2007; Weiland, 2021; Kline et al., 2022; Lanning et al., 2023)
Chemical	Nutrients	Organic and inorganic fertilisers providing Nitrogen, Phosphorus and Potassium.	Sufficient nutrients are essential for normal plant growth and development, protein development and chloroplast structure and function. Nutrient deficiencies result in yellow leaves, due to lowered synthesis of protein and chlorophyll. Excessive nutrients can lead to impaired root growth.	Reduce excess nutrient application. Split applications minimize N losses due to leaching or volatilization.	(Barker and Pilbeam, 2015)
	Pesticides	Fungicides, herbicides, and insecticides.	Phytotoxic damage, reduced photosynthesis and growth. Delays in flowering times and reductions in flower production.	Reduce high-toxicity low-dose pesticides. Improve irrigation to reduce leaching of pesticides. Use disease-resistant plants.	(Boutin et al., 2014; Alengebawy et al., 2021; Yin et al., 2023)
	Salinity	Over extraction of groundwater, underlying geology, saltwater intrusions, percolation of salts into aquifers, and anthropogenic activities.	Stunted growth, chlorosis, impaired seed germination, inhibition of photosynthesis, nutritional and hormonal imbalances, oxidative stress, electrolyte leakage, and membrane disorganization.	Efficient irrigation management, exogenous application of nutrients and osmolytes, shading and the enrichment of CO_2 can reduce salinity stress on plants.	(Munns and Tester, 2008; García-Caparrós and Lao, 2018; Majeed and Muhammad, 2019)
	Alkalinity and pH	Fertilisers	Renders micronutrients (i.e., Fe, Zn, Cu, B, Mg) insoluble affecting plant growth. High pH irrigation water results in necrosis of mature leaves and significant growth reduction.	Efficient irrigation management. Alkaline water can be treated with acidification treatment before applying disinfectant treatments, such as chlorine gas, peroxygen compounds, and ozone. Acidic water can be treated with agricultural lime (calcium carbonate). Alternatives include changing or blending water sources.	(Trejo-Téllez and Gómez-Merino, 2012; Valdez-Aguilar et al., 2009)
	Heavy Metals	Sedimentary rocks, volcanic eruptions, soil formation, rock weathering, industry, agriculture, mining, and domestic effluent.	Suppresses root growth, restricts the uptake of nutrients by plants. Reduce photosynthetic activity, plant mineral nutrition, and activity of some enzymes.	Exogenous application of nitric oxide may protect plants against heavy metal stress by enhancing their antioxidative defense system. Constructed wetlands to filter heavy metals from water.	(Mader et al., 2022; Pande et al., 2022)
	Microplastics, pharmaceutically active compounds and persistent organic pollutants	Industrial, agricultural, hospital, and household sources. Plastic mulches, biosolids and atmospheric deposition.	Degrades soil structure, affecting nutrient and moisture transport in the soil. Reduces nutrient availability, and plant and root development. Reduces the transport of fertiliser and water between soil and plants.	Well-constructed and maintained wastewater treatment plants can efficiently eliminate microplastics in wastewater streams. Biological adsorbents, oxidation, ultraviolet degradation, reverse osmosis and nano-filtration.	(Vergani et al., 2017; Qi et al., 2018; Sajjad et al., 2022; Vinayagam et al., 2022; Hoang et al., 2024)
Physical	Turbidity	Weather and, soil erosion, runoff containing sediment, and anthropogenic activities.	Suspended solids can transport pesticides and other contaminants that have adsorbed to particle surfaces. Reduces ultraviolet radiation, increasing active ingredients of oxidizers and biocides such as chlorine dioxide, copper, and hypochlorous acid.	Particle filtration in conjunction with sanitation technology.	(Meador et al., 2012; Zhang et al., 2015; Huang and Fisher, 2019)

density. Nurseries may grow >500 different plant taxa in relatively small plot sizes when compared to large, monoculture agricultural production (Parke and Grünwald, 2012). While recycled irrigation water is a primary pathogen inoculum source, the reuse of unsterilised containers, lack of proper drainage, and contact of containers with contaminated ground are the most common pathways for pathogen spread (Parke and Grünwald, 2012). In addition, contaminants can be introduced into nursery production systems indirectly through contaminated stock, growing media or equipment, or carried on the foot wear and vehicles of employees or visitors (Hong and Moorman, 2005). The potential for pathogen introduction and dissemination is heightened in nurseries as propagative material may originate from domestic or international production facilities and is often acquired from multiple sources, including seeds, cuttings, tubers, bulbs, grafted rootstocks, and tissue culture (Parke et al., 2019). Within nursery production sites, propagation areas can create suitable environmental conditions for pathogens and microbes to spread, for instance overwatering and poor drainage in areas where containers are concentrated can lead to rapid pathogen development (Hong and Moorman, 2005; Stewart-Wade, 2011). Infected plants may host and disseminate large numbers of infective propagules into leachate water, which are stored, recycled and eventually redistributed to plants during irrigation. Plants moved during different phases of development, for example from the propagation area to production greenhouses to container field sites, may also disseminate pathogens to uninfected areas (Stewart-Wade, 2011). All these factors make it difficult to manage pathogen spread throughout the nursery and growers should implement regular monitoring and testing to reduce contaminant spread.

4. Waterborne contaminants

Waterborne contaminants can be classified into biological, chemical, and physical contaminants (Table 1). Biological contaminants refer to pathogens and microbes, which include bacteria, viruses, fungi, parasites and other toxic organic substances (Stewart-Wade, 2011). Whereas, chemical and physical contaminants refer to nutrients, metals and metalloids, radionuclides, pesticides (which collectively include insecticides, fungicides and herbicides), and turbidity. The effects of waterborne contaminants on nursery production, include reduced water quality, reduced plant growth, increased susceptibility to disease and plant death, decreased marketability, and increased treatment cost (Hong and Moorman, 2005; Stewart-Wade, 2011; Raudales et al., 2014). Here we discuss some of the more common waterborne contaminants and how they affect nursery container plant production. Additional research is required to assess the biological threshold and pathogenicity of certain pathogens in irrigation water and their effects on host-parasite interactions. It also remains unclear whether there are additive, synergistic, or antagonistic effects that occur among pathogens and the effects these may have on host-parasite interactions, and this remains an important area for future research.

4.1. Biological contaminants

(i) *Phytopathogens*

Waterborne plant pathogens, which include fungi, bacteria, and viruses are commonly found in streams, rivers, and recycled irrigation water (Hong and Moorman, 2005). However, not all phytopathogens have been associated with causing disease in plants and many have an undetermined pathogenicity (Hong and Moorman, 2005; Hong et al., 2008). It is possible for numerous phytopathogens to be present in water storage reservoirs without causing disease to irrigated plants. Disease causing phytopathogens require three factors to effectively infect nursery production, including a susceptible host plant, a virulent pathogen, and favourable environmental conditions (Stewart-Wade, 2011). The most common disease causing phytopathogens, include *Phytophthora*, *Phytopythium* and *Pythium* species. These phytopathogens are responsible for diseases related to blights, damping off, and downy mildews, which result in crop losses, and reduced plant quality, production, and marketability (Hong and Moorman, 2005; Stewart-Wade, 2011; Parke et al., 2019). There are >100 *Phytophthora* species, many of which are transported in water and reside in the soil, where they infect and kill roots, leading to above-ground symptoms of chlorosis, stunting, wilting, and plant death (Weiland, 2021). *Phytophthora* species have been implicated in causing devastating diseases in both agricultural and natural ecosystems (Bush et al., 2003; Hong et al., 2008). Notable examples of the devastating impacts of *Phytophthora* species to natural ecosystems globally, include *P. ramorum*, which led to sudden oak death and ramorum blight of common ornamentals in California and Oregon in the USA (Frankel, 2008; Harris et al., 2018). In the UK, *P. ramorum* shifted behaviour spreading from nursery plants to woodlands and forests, resulting in widespread infection and mortality of larch tree plantations (*Larix* spp.) (sudden larch death) (Harris et al., 2018). Within an agricultural setting, *P. infestans* caused late blight of potato in the 1840s in the US and Europe and was also responsible for the Irish famine (Kline et al., 2022). *Phytophthora infestans* remains a concern as it is responsible for late blight on potato and tomato plants, which currently threatens global food security worldwide. The introduction of *P. lateralis*, which was brought into southern Oregon on infested nursery stock in the 1950s, continues to infect and kill Port Orford cedar (*Chamaecyparis lawsoniana*), with ecological and economic consequences, across its native range (Hansen et al., 2000). Similarly, *P. cinnamomi*, which causes severe root rot problems, has severely impacted eucalypt forests in Western Australia, and chestnut pine (*Diselma archeri*) and short-leaf pine (*Pinus echinata*) in the eastern United States (Kline et al., 2022).

Numerous studies have found *Phytophthora* and *Pythium* species in irrigation water to be the causal agent for infecting heathy plants grown in nurseries (Goss et al., 2009; Hong et al., 2008; Lanning et al., 2023; Parke et al., 2019). These pathogens are part of the phylum Oomycota and are commonly referred to as the 'water molds' because they possess swimming zoospores, are well adapted to the aquatic environment, and complete their life cycle and spread in water (Hong and Moorman, 2005). However, not all *Phytophthora* species readily form zoospores nor reside in water for long periods and can easily persist in soil or air (Brasier et al., 2022). Under moist conditions sporangia release short-lived, single-celled zoospores that disperse in thin films of water on leaf surfaces or in soil pores to infect new hosts (Postma et al., 2009; Lanning et al., 2023). Excessive irrigation and rainfall often lead to an increase in the severity and spread of *Phytophthora* diseases (Brasier et al., 2022). Heavy rainfall can lead to leachate runoff containing pathogens from containers, which increases the activity of fungi and oomycetes resulting in root rot as well as the susceptibility of the host (Hong and Moorman, 2005). Extended periods of leaf wetness also provide favourable conditions for foliar disease outbreaks.

Temperature also influences the spread of disease. Rainfall in conjunction with temperatures between 15 and 20 °C have been reported as optimal for *Phytophthora* species sporulation and infection. However, in plant nurseries from South Florida and North Carolina a higher temperature range was found to support the persistence of *Phytophthora* but overall temperature had less of an effect on the incidence of these oomycetes (Campoverde et al., 2017). Extreme weather patterns can also lead to favourable conditions for disease outbreaks. For example, El Niño conditions, which are associated with increased wet conditions in south Florida, resulted in an unusually high incidence (12.5 %) of diseases on ornamental crops caused by *Pythium* and *Phytophthora* compared with 3.3 % during the three previous years with normal weather conditions (Campoverde et al., 2017). Moreover, water quality parameters such as pH, electrical conductivity (EC), and dissolved oxygen may impact the survival of *Phytophthora* species. For example, Kong et al. (2009) found that some species of *Phytophthora* are tolerant to acidic conditions whereas others favour basic pH. *Phytophthora ramorum, P. alni* and *P. kernoviae* survived better in water with higher EC (Kong et al., 2012). The zoospore survival rate of *Phytophthora* species decreased with increasing intensity of hyperoxia and hypoxia conditions, depending upon exposure time (Kong and Hong, 2014). However, information regarding the number of propagules and their infectivity in recycled irrigation water, as well as the economic importance of these diseases is limited and presents an important research gap. This information is required to test the effectiveness of disinfestation treatments against known concentrations of propagules (Stewart-Wade, 2011).

(ii) *Fungi*

Fungal plant diseases pose a lower risk to horticultural and agricultural industries compared to other phytopathogens, but can still result in plant damage and yield loss. For example, some pathogenic strains of *Fusarium oxysporum,* which is widespread in different soil types, lead to global crop die-off and significant economic loss (Borrero et al., 2017). Notably, *F. oxysporum* f. sp. *cubense* tropical race 4 (TR4) is responsible for Panama disease of banana (*Musa* spp.), threatening the availability of banana in some regions of the world. Other fungi of importance to crops, recorded in recycled irrigation water, include *Olpidium brassicae* (a vector for the virus causing lettuce big vein disease), *Alternaria, Botrytis*, *Ascochyta*, *Rhizoctonia*, and *Verticillium* (Hong and Moorman, 2005; Stewart-Wade, 2011). The fungal pathogen *Botrytis cinerea Pers*. was common in irrigation water used in forest nurseries leading to diseased seedlings (Marčiulynas et al., 2020). While many fungal propagules are commonly present in all water sources and are introduced by runoff contaminated by debris from agricultural fields (Calderon et al., 2023; Pittis and Colhoun, 1984), most fungi are aerobic and do not persist in anaerobic environments, such as flooded soils. However, they may persist as dormant spores, germinating once flooding subsides.

(iii) *Bacteria and viruses*

Plant pathogenic bacteria are single-celled organisms, which can cause leaf spots, vascular wilts, tumours, dieback, cankers and soft rots. Only a few bacterial plant pathogens do not present symptoms or they may reflect latent symptoms, such as *Ralstonia solanacearum* and *Clavibacter michiganensis* (Hong and Moorman, 2005). The primary causing bacterial pathogens may be difficult to identify as they make the plant susceptible to secondary pathogens or saprophytes that colonise dead and decaying plant tissue (Hong and Moorman, 2005). Bacterial plant pathogens differ to fungi as they do not form spores but rather persist as active cells on plants, or among their root zones, or as less active cells within the plant (i.e., endophytes, latent forms), and they require moisture and wounding to spread and gain access to plant tissues (Hong and Moorman, 2005). Numerous plant pathogenic bacteria have been recorded in irrigation water and are associated with causing disease on crops. A well-known example is *Erwinia* species, which has caused soft rots of potatoes and ornamental species in the USA (Harrison et al., 1987; Norman et al., 2003). Other disease-causing bacteria species, such as *Ralstonia solanacearum* (Wang et al., 2023) and *Clavibacter michiganensis* (Gartemann et al., 2003), have commonly been recorded in irrigation water and can persist in recirculating nutrient solutions for long periods of time. Interestingly, some naturally occurring bacteria have the ability to increase or suppress phytopathogenic *Pythium* in soilless systems (Postma et al., 2009). Burgos-Garay et al. (2014) found that *Pythium* grew slower in the presence of attached root-colonising bacteria. This study also identified bacteria isolates that stimulated the growth of the three *Pythium* isolates; however, these experiments were conducted in-vitro and the results were not replicated in greenhouse experiments. Nevertheless, the results from this study highlight the potential use of microorganisms to suppress phytopathogenic *Pythium* species survival and could be explored as a potential treatment of recycled irrigation water in greenhouses. Therefore, further research is required to assess the microbial diversity in recycled irrigation water to better understand synergistic or antagonistic interactions between *Pythium* and bacteria.

There are over 2100 plant virus species identified but not all of them cause severe disease in plants (Tatineni and Hein, 2023). The majority of plant viruses cause symptomless or mild disease with little effect on plant growth. However, certain viruses can cause extensive damage, resulting in substantial economic losses of ~US$30 billion in agriculturally important crops worldwide (Tatineni and Hein, 2023). Several highly infective viruses have been detected in recycled irrigation water and nutrient solutions, including *Arabis mosaic virus*, *cucumber green mosaic virus*, *lettuce big vein agent,* and *pelargonium leaf curl virus* (Hong and Moorman, 2005; Rosner et al., 2006; Stewart-Wade, 2011). Another virus that causes severe damage to a globally significant crop is the *cassava mosaic* virus, which poses a threat to cassava production, which is an important food source for millions of people in East Africa (Legg et al., 2015).

4.2. Chemical contaminants

(i) *Nutrients*

Nutrients are essential for plant growth and maintaining physiological processes in plants, including photosynthesis, respiration, and root growth (Bailey et al., 1999). Nutrients are divided into macronutrients (primary and secondary) and micronutrients. Primary macronutrients (particularly nitrogen, phosphorus, and potassium) and secondary macronutrients (e.g., calcium, magnesium and sulfur) are critical for plant growth but tend to be limited in the soil due to leaching and plant uptake (Bilderback, 2002). Micronutrients (e.g., iron, manganese, zinc, copper, boron, molybdenum, chlorine, and nickel) are also important for plant growth but may affect plants if levels are too high (toxic) or too low (deficient). Other micronutrients, such as sodium, silicon, vanadium, selenium, cobalt, aluminium and iodine are less important but are considered beneficial because they can stimulate growth and aid in plant resistance to stress conditions and some diseases (Trejo-Téllez and Gómez-Merino, 2012). While plants require essential nutrients, they tend to present symptoms in response to any deficiency, excess or imbalance of one or more of these nutrients. For example, nitrogen plays a fundamental role in plant growth and biosynthesis of cellular components such as proteins, enzymes, hormones, and amino acids (Stefanelli et al., 2010); however, both excess or deficient nitrogen levels can cause widespread chlorosis and growth abnormalities in plants (Furtini Neto et al., 2015). Excess nitrogen and potassium affect the length of rose stalks, affecting the quality and marketability of these plants (Furtini Neto et al., 2015). Nutrient deficiencies can also affect the colour of plant leaves, for example nitrogen deficiencies in plants result in older leaves turning yellow due to reduced chlorophyll production (Furtini Neto et al., 2015).

Another important consideration is the interaction between different nutrient concentrations and their effects on plant growth (Barker and Pilbeam, 2015). Across a range of plant species there are relatively constant ratios of tissue concentrations of phosphorus, potassium, calcium, and magnesium relative to nitrogen that support optimum growth (Barker and Pilbeam, 2015). However, deficiencies of one or more of these elements can affect the balance of the internal ratios of plants. For example, nitrogen supply affects the uptake of iron by plants, making it less available. When NO_3 is the nitrogen source it increases the uptake of nickel (Ni^{2+}), resulting in greater signs of nickel toxicity. To prevent nutrient imbalances and ensure the production of healthy plants, growers can monitor the availability of nutrients by analysing changes in the ionic composition of the substrate and assess plant nutrient uptake by analysing the nutrient content in leaves (Trejo-Téllez and Gómez-Merino, 2012).

Nutrients are gradually removed from the soil or substrate as plants grow and will often need to be replenished through the application of fertilisers to maintain or increase plant yields. In comparison to agronomic systems where annual fertiliser application rates are based on expected yield and soil characteristics, the amount of fertiliser and application method used for container plant production is dependent on a range of factors. For instance, growers need to consider the plant development stage, type of ornamental species, spatial arrangement and density of containers, container size, fertiliser application method, seasonality, and annual number of crops produced in an area (Bilderback, 2002). All of these factors make it challenging for growers to achieve optimal nutrient application and poor water and nutrient management can increase the risk of nutrients leaching from containers. If nutrient-rich leachate is not properly drained from the production site, it can accumulate around containers providing an ideal environment for pathogen development and spread. Where nutrient-rich leachate is efficiently drained, it can either be directed to retention ponds for treatment to be reused or discharged to the sewer or environment where permitted.

In retention ponds, excess nutrients can increase turbidity and provide ideal conditions for algal growth and pathogens if left untreated. Turbid water and algal blooms can diminish water quality, emit bad odours, and reduce the aesthetics of plants irrigated with the water. Algal growth can also block distribution and irrigation equipment, leading to reduced or uneven flow, which may affect plant yield and increase overall maintenance costs (Raudales et al., 2014). Similarly, when leachate is discharged to the environment without treatment, it can severely impact receiving water bodies and aquatic biota. Untreated leachate can contain high concentrations of nutrients (particularly nitrogen and phosphorus). Nutrient-rich leachate that flows into water sources, leads to excess algal or plant growth and in some cases cyanobacteria growth, resulting in severe degradation of water bodies known throughout the world as eutrophication (Wu, 1999; Savci, 2012; Dorais et al., 2016). To reduce nutrient loss from containers and prevent eutrophication, it is important for nursery growers to have an effective water and nutrient management plan.

(ii) *Pesticides*

While nursery growers are concerned about water quality and diseases, pesticides are also a major consideration when reusing or recycling runoff water. Pesticides (i.e., insecticides, herbicides, fungicides) are often applied to containerised production through irrigation systems to control pests that damage plants. Overhead irrigation coupled with pesticide application to containers that have wide spacing may result in pesticides being deposited in non-target areas and entering surface runoff. Typically, pesticide concentrations in runoff water tends to be low, and they are even lower in storage reservoirs, mainly due to the high absorption of pesticides by soilless substrates resulting in a small fraction of pesticides leaching out of containers (Alengebawy et al., 2021). Therefore, the quantity of pesticides entering surface runoff depends on the pesticide properties (i.e., solubility, volatility, and adsorption), as well as management practices (i.e., irrigation scheduling, container spacing, and groundcover) (Abdi and Fernandez, 2019). Nevertheless, continuously irrigating with runoff containing pesticides, even at low concentrations, can result in chronic plant exposure with the potential to cause plant damage. Excessive use of fungicides can adversely affect root elongation and seed germination of some plant species (Alengebawy et al., 2021). Bhandary et al. (1997) demonstrated that low concentrations of the herbicide Oryzalin resulted in a 13.5 % reduction in fountain grass biomass and continued exposure resulted in high concentrations which reduced growth by 92.7 %. The potential for pesticides to damage plants depends on factors including plant sensitivity, development stage of plants when they are exposed, pesticide type, pesticide concentration and dose, and duration of pesticide exposure. For instance, certain pesticides may be more likely to cause plant injury than others. Mathers et al. (2012) demonstrated that rose (*Rosa* sp.) plants sprayed with Isoxaben and Oryzalin showed phytotoxic damage, reduced photosynthesis and growth, whereas the pesticide Indaziflam did not cause damage. The effects of pesticides on plants are evident as chlorosis, burns, leaves twisting, stunting, and necrosis (Alengebawy et al., 2021). Herbicides cause marked delays in flowering times and reductions in flower production (Boutin et al., 2014). Therefore, all these factors need to be considered when deciding to use recycled water to irrigate plants.

(iii) *Salinity*

Salinity or total dissolved solids (TDS) refers to the total concentration of soluble salts/ions (i.e., Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-} and NO_3^-) in water (Rengasamy, 2010). Salinisation of water is caused by over extraction of groundwater, underlying geology, salt-water intrusions, percolation of salts into aquifers, and anthropogenic activities (i.e., excessive fertiliser usage, poorly managed practices, and intensified agriculture) (Payen et al., 2016). Plants differ in their tolerance of salinity stress, which is reflected in their different growth responses (Munns and Tester, 2008). Broadly plants can be categorized as glycophytes (sensitive to salinity stress) and halophytes (tolerant to salinity stress) (Majeed and Muhammad, 2019). The majority of ornamental plants are glycophytes and their response to salinity stress depends on a range of factors, including the growth phase, soil/substrate, and level of salinity (Grattan and Grieve, 1998). Ideal electrical conductivity (EC) conditions are specific for different plant species and dependent on environmental conditions; however, EC values for optimum plant growth ranges from 1.5 to 2.5 dS m^{-1}. Salinity exceeding a threshold level of EC $>$ 4 dS m^{-1} hinders nutrient uptake by increasing osmotic pressure, whereas lower salinity levels (EC $<$ 1.5 dS m^{-1}) may severely affect plant health and yield (Majeed and Muhammad, 2019). Valdez-Aguilar et al. (2009) found that elevated EC negatively affected shoot and tuberous root weight. Some plants are more tolerant to high levels of EC and proper management of EC of the irrigation water and nutrient solution can be used as an effective tool to improve plant quality.

The effects of salinity stress on plant growth response are manifested as changes in morphology (i.e., stunted growth, chlorosis, and impaired seed germination), physiology (inhibition of photosynthesis and nutritional and hormonal imbalances), and biochemical properties (oxidative stress, electrolyte leakage, and membrane disorganization), which increases plant susceptibility to diseases (Munns and Tester, 2008). Salinity stress on plants occur via two mechanisms (García-Caparrós and Lao, 2018). The first is osmotic stress, which relates to the effects of salt in the soil or nutrient solution. Increased soil salinity limits water uptake by the roots and increases the intracellular osmotic pressure which can cause the accumulation of sodium to toxic levels, resulting in delayed germination and growth abnormalities of plants (Munns and Tester, 2008). The second mechanism is through specific ion effects that involves the accumulation of toxic ions (i.e., Na^+, Cl^-, and SO_4^{2-}), which impairs nutrient uptake, exacerbating the damage to plant cells and tissues. Ionic toxicity also affects the photosynthetic capacity of plants, resulting in reduced growth rates. Tuteja (2007) reported that increased sodium ion accumulation in plant tissues resulted in impaired enzyme functions, cell membrane structure, cell division and growth. The effects of salinity stress on plants may occur rapidly or induce latent effects, but in both cases, plants will display morphological defects. García-Caparrós and Lao (2018) demonstrated that salinity stress reduced total leaf area, plant height and the number and quality of flowers. Similarly, Cassaniti et al. (2009) reported leaf burn and a decline in the aesthetic appearance of the plants in response to the accumulation of toxic elements (e.g., Na^+ and Cl^-) in leaves. These visible morphological changes of plants can provide nursery growers with useful information regarding the degree of salt tolerance of plant species and which species are suitable for the conditions available (Munns and Gilliham, 2015).

Salinity can also affect plant health through salinity-induced nutritional disorders (Grattan and Grieve, 1998), through competitive nutrient uptake, transport or partitioning within the plant. For example, salinity reduces phosphate availability in soil and thus reduces phosphate accumulation in plants (Grattan and Grieve, 1998). Similarly, salinity dominated by Na^{+} salts reduces Ca^{2+} transport to growing regions of the plant, which affects the quality of both vegetative and reproductive organs.

(iv) *Alkalinity and pH*

Alkalinity and pH are major factors influencing irrigation water quality. pH is a measure of the concentration of hydrogen ions (H^{+}) in water or soil and typically ranges between 0 and 14, where water with pH below 7.0 is acidic, pH above 7.0 is alkaline and pH 7.0 is neutral (Velazquez-Gonzalez et al., 2022). Alkalinity is a measure of the level of calcium and magnesium carbonates and bicarbonates in water and refers to the water's ability to neutralize acidity. The ideal range of irrigation water is 0 to 100 mg L^{-1} calcium carbonate ($CaCO_3$) and levels between 30 and 100 ppm $CaCO_3$ are considered optimum for most plants (Ingram, 2014). Alkalinity in irrigation water acts as a buffer and prevents sudden changes in pH by increasing the pH. Continuous irrigation with alkaline water can lead to the substrate pH increasing substantially, with negative effects on nutrient solubility, resulting in deficiencies of micronutrients and unbalances in nutrient availability particularly iron. Thus, both alkalinity and pH need to be considered when addressing pH problems in containerised plant production.

While the alkalinity and pH of irrigation water are important considerations, the composition of the soil/substrate may also affect the pH environment of the plant. For instance, organic substrate media, such as peat moss and bark tend to be very acidic; whereas, inorganic media substrates, such as perlite and vermiculite tend to have neutral pH ranges and do not contribute to substrate pH. The type of fertiliser used can also significantly affect substrate pH over time. For example, fertilisers that contain urea phosphate ($CO(NH_2)_2{\cdot}H_3PO_4$), single superphosphate ($Ca(H_2PO_4)_2$) or triple superphosphate ($Ca(H_2PO_4)2{\cdot}H_2O$) may acidify the substrate when combined with low alkalinity water. Fertilisers with high nitrate content (i.e., calcium nitrate) will increase soil pH, whereas high ammonium fertiliser (i.e., ammonium nitrate) decreases the pH and can be toxic if too much ammonium is applied and absorbed by the plants (Velazquez-Gonzalez et al., 2022).

Runoff water from production nurseries may have higher pH, EC, and alkalinity than recommended owing to the leaching of soluble salts from containers (Poudyal and Cregg, 2019). Copes et al. (2017) demonstrated that runoff water entering nine different nursery retention ponds had higher pH than the recommended pH of 6.8. The pH of recycled water used for irrigation can affect the mobility of micronutrients in containerised plants. In general, water for irrigation should have a pH between 5.0 and 7.0 as it ensures nutrients remain in a soluble state (Velazquez-Gonzalez et al., 2022). However, maintaining the pH balance of the irrigation water and nutrient solution can be difficult owing to the low buffering capacity of container substrate media compared to soil. Plant roots can also cause an unbalance in anion and cation exchange, resulting in pH fluctuations in the substrate (Trejo-Téllez and Gómez-Merino, 2012). A low pH generally increases the mobility of micronutrients allowing them to be absorbed in excess of the plant's requirements, with potential toxicity impacts. Whereas, a high pH (i.e., HCO_3^- and CO_3^{2-}) alters plant growth by rendering micronutrients (i.e., Fe, Zn, Cu, B, Mg) insoluble and increasing Ca and Mg precipitates (Trejo-Téllez and Gómez-Merino, 2012). Valdez-Aguilar et al. (2009) reported that high pH irrigation water decreased the quality of three cultivars due to necrosis of mature leaves and significant growth reduction. Therefore, it is crucial to maintain an optimum pH range to ensure plant health and maximise plant growth.

(v) *Heavy metals*

Heavy metals are metals characterised by specific gravity >5 g/cm^3 (Nies, 1999; Zhang et al., 2019). Heavy metals can be sourced from natural sources (i.e., sedimentary rocks, volcanic eruptions, soil formation, and rock weathering) or anthropogenic activities (i.e., industry, agriculture, mining, and domestic effluent) (Alloway, 2013; Alengebawy et al., 2021). Agricultural sources are mainly derived from fertilisers, pesticides, livestock manure, and wastewater (Alengebawy et al., 2021). Plant uptake of heavy metals depends on the specific plant tolerance and solubility of the metals in the soil/substrate. Some plants are more tolerant to high concentrations of heavy metals in their environment and they tolerate metals through mechanisms of exclusion, inclusion or bioaccumulation (Baker, 1981).

Some heavy metals like cobalt (Co), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn) are beneficial to plants in small concentrations, but they can become toxic if they accumulate to high quantities in plant tissue and negatively affect growth and development (Khan et al., 2021b). These beneficial heavy metals serve as essential micronutrients and play a role in plant growth, development, metabolism, and productivity (Arif et al., 2016). However, when concentrations of heavy metals in plants exceed optimal levels, they can inhibit enzyme activities useful for plant metabolism, and produce reactive oxygen species leading to oxidative stress causing cell damage, which can eventually result in plant death (Chibuike and Obiora, 2014). For instance, low concentrations (25 mg L^{-1}) of Zn in the soil solution can improve growth and physiology of plants; whereas, high concentrations (50 mg L^{-1}) of Zn can reduce growth and affect physiology (Manivasagaperumal et al., 2011).

Other heavy metals or metalloids (i.e., lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As)) do not benefit plants at any concentration and are considered elements of environmental concern as they can cause detriment to plants even at very low concentrations in the growth medium (Chibuike and Obiora, 2014). Low concentrations of Hg in the soil reduced the height and tiller and panicle formation in plants (Tang et al., 2021). The availability of heavy metals in the soil/substrate solution can be affected by several factors, including the pH level and presence of organic matter. For example, increases in soil pH resulted in a decrease in the availability of Cd and Zn to the roots of *Thlaspi caerulescens* (Wang et al., 2006). Similarly, heavy metal bioavailability decreased in the presence of organic matter and hydrous ferric oxide (Yi et al., 2007). There are also many interactions between heavy metals and nutrients in water and soil solutions. For instance, interactions between Zn and boron (B) on plant nutrition and growth can be synergistic or antagonistic depending on the concentrations of the elements present in the soil. For example, in a greenhouse experiment with corn grown in a calcareous soil, Zn inputs of 5 or 10 mg kg^{-1} depressed B accumulation in shoots (Hosseini et al., 2007). Generally, the reduction in growth parameters of plants contaminated with heavy metals can be attributed to reduced photosynthetic activities, plant mineral nutrition, and reduced activity of some enzymes.

Heavy metals can accumulate to toxic levels in the roots, steams and edible parts of plants. For example, high concentrations of Cd in plants can reduce water and nutrient uptake and have toxic effects on plant morphology (reducing plant biomass), cytotoxicity (reducing photosynthesis), and metabolic processes (chlorosis and structural cell damage) (Hayat et al., 2019; Pande et al., 2022). Lead is toxic to plants even at low concentrations and can accumulate in plant tissue causing physiological and biochemical problems. The effects of lead toxicity in plants include reduced nutrient uptake, cell damage, inhibition of enzymatic activities, and reduced plant growth (Ali and Nas, 2018). Copper can decrease chlorophyll, plant productivity and crop yield by altering photosynthesis (Ebbs and Kochian, 1997). Zinc is a crucial micronutrient for plants as it influences all enzymatic activities and plays a critical role in photosynthetic redox reactions. However, hyperaccumulation of zinc in plants can cause severe damage to physiological and biochemical processes, including interveinal chlorosis in leaves (Ebbs and Kochian, 1997). Pesticides used on plants to reduce pest infections can also be a source of heavy metals and can have deleterious effects on plants if used for extended periods.

(vi) *Emerging contaminants*

Microplastics, pharmaceutical active compounds (PhACs) and persistent organic pollutants (POPs) are examples of emerging contaminants that are omnipresence in the environment (Quilliam et al., 2023). Owing to improper control/management of these contaminants from industrial, agricultural, hospital, and household sources, these effluents are discharged into the environment and can have negative impacts on ecosystems as well as human health (Nguyen et al., 2023). Microplastics are plastic fibres, particles, or fragments with a maximum size of <5 mm that can contaminate irrigation water, posing significant risks to soil health, plant growth, and the environment. Microplastics originate from various sources, including fertilisers and pesticides, compost-based soil remediation, irrigation, atmospheric deposition, plastic mulch films, and contaminated soil (Hoang et al., 2024). Their persistence in the environment is due to their extreme durability and resistance to biodegradation. Microplastics are carriers of micro-contaminants within agricultural ecosystems, and can negatively affect soil functioning, microbial communities, and plant growth. Microplastics can result in changes in the physicochemical properties of soil, including porosity, enzymatic activities, microbial activities, plant growth, and yield (Sajjad et al., 2022). Microplastics have a high specific surface area and strong hydrophobicity, which facilitates the transportation of toxic chemicals such as plasticisers, polycyclic aromatic hydrocarbons, antibiotics, and potentially toxic elements (Sajjad et al., 2022). Microplastics negatively impact soil and plants by destroying the soil structure, affecting nutrient and moisture transport in the soil, reducing nutrient availability, reducing plant and root development and reducing the transport of fertiliser and water between soil and plants (Qi et al., 2018). Microplastics can also decrease infiltration from rain and irrigation water, which can affect the water holding capacity of the soil (Liu et al., 2014). Exposure to microplastics can induce oxidative stress responses in plants, which can damage cellular components, inhibit growth, and reduce plant quality (Hoang et al., 2024). However, the specific effects of microplastics on plant health depends on factors including the profile of the plastic, plant species, environmental conditions and other chemicals. Therefore, contamination of soil with microplastics is of great concern as it not only affects soil physicochemical characteristics but also plant development and growth. Further research needs to address the interactions between microplastics and other contaminants in the soil environment.

Pharmaceutical active compounds (i.e., antibiotics) are commonly used in clinical medicine and animal husbandry to prevent or treat diseases and enhance livestock yield (Nguyen et al., 2023). Residues of PhACs from agricultural runoff are usually found in groundwater, surface water, soils, and sediments (Xu et al., 2021). The accumulation of PhACs in the soil can affect soil microorganisms, reducing agricultural efficiency. Pharmaceutical compounds have been considered as emerging micropollutants owing to their potential eco-toxicity (Bhatt et al., 2022). Owing to the persistence of PhACs they are difficult to degrade completely and may degrade water quality and impact aquatic biota. For example, Triclosan at low concentrations (<10 mg kg^{-1}) disturbs the nitrogen cycle in some soils because of its adverse effect on soil microorganisms. Moreover, antibiotic metabolites have are toxic to aquatic organisms, such as fish, green algae, microcrustaceans, and cyanobacteria (Baumann et al., 2015).

Persistent organic pollutants (i.e., pesticides and polychlorinated biphenyls), comprise twelve chlorinated organic compound families that were initially listed by the Stockholm Convention on Persistent Organic Pollutants (Stockholm Convention on POPs, 2015). In particular, polychlorinated biphenyls (PCBs) are synthetic substances produced for medical, agricultural and industrial activities and are widely utilized in various products, such as heat-exchange fluids, pesticide additives, herbicides, and fungicides. Most POPs are characterised by poor water solubility and are bioaccumulative. As such they are resistant to decomposition and are able to persist in the environment for long periods of time, causing adverse effects on plant health, ecosystems and human health (Vergani et al., 2017; Olatunji, 2019). Polychlorinated biphenyls have a high lipophilicity, meaning that they have a high affinity for the organic matter in water, sediments, atmospheric particulates and soils, where they degrade very slowly.

4.3. *Physical contaminants*

(vii) *Turbidity*

Turbidity measures the clarity of the water and is an indirect measure of the total suspended solids that are retained on a 2 μm filter (i.e., clay particle agglomerations, silt, fine organic debris, plant pathogens, container substrate components, algae). Elevated concentrations of suspended solids affect the clarity of water or the extent to which light is scattered and absorbed by suspended particles and dissolved organic matter (Bailey et al., 1999). Abiotic suspended particles in particular reduce light penetration, and this reduces primary production in the form of algae and other aquatic plants (Jackson et al., 2022). Turbidity is affected by weather, soil erosion, and sediment re-suspension from seasonal runoff (Hong et al., 2009). Sediment and various pollutants can be transported to water bodies via surface runoff from various land uses and anthropogenic activities. Suspended particles are recognised as a pervasive water pollutant, causing degraded water quality, environmental damage, and economic costs (Colley and Smith, 2001). Suspended particles in irrigation water can clog irrigation lines and emitters, which results in nonuniformity of water distribution, plant losses from underwatering or overwatering, and increased runoff of water and fertiliser into the environment (Huang and Fisher, 2019). Meador et al. (2012) found that more than half of the total suspended solids in nursey irrigation water was composed of organic carbon materials. Suspended solids can also be associated with pesticides and other contaminants that have adsorbed to particle surfaces. Suspended particles also reduce ultraviolet radiation, increasing in active ingredients of oxidizers and biocides such as chlorine dioxide, copper, and hypochlorous acid (Zhang et al., 2015). Under these conditions, producers need to carry out particle filtration in conjunction with sanitation technology (Colley and Smith, 2001).

5. Contaminated runoff from nurseries

Stream ecosystems are products of the landscapes they drain and therefore reflect climatic or anthropogenic impacts that occur in the catchment. Near-stream and basin-wide land use changes can alter landscape-stream connectivity with implications for water quality and aquatic ecosystems (Jackson et al., 2022). As such, it is important to consider how land use changes and anthropogenic activities (such as waste water runoff) associated with nursery operations alter landscape-stream connectivity and the transport of contaminants to the environment. The management strategies of individual nursery owners, such as removal of riparian vegetation, use of gravel roads or discharge of untreated waste water can have considerable effects on water quality and aquatic ecosystems. For example, removal of riparian vegetation along river banks by nursery owners, can increase turbidity, specific conductivity, and nutrient concentrations; shifting basal resources from detritus to algae dominated, and changing the competitive dynamics of aquatic organisms (Jackson et al., 2022). Nursery owners are under increasing pressure to treat or recycle runoff leaving production sites to prevent contaminant dispersal to the environment. A range of chemical and biological treatments to reduce contaminant transfer are discussed in Hong and Moorman (2005); Majsztrik et al. (2017) and Lamm et al. (2019).

Containerised production nurseries differ to field nurseries in that plants are typically grown in individual containers, which reduces soil erosion. However, heavy rainfall and excess water application can erode sediment and cause runoff of soluble surface contaminants, such as fertilisers, nutrients, and pesticides leaching out of containers (Yang and Toor, 2016). The freshwater ecotoxicity per area (PAF m^3 d ha^{-1}) of ornamental plants grown in nurseries was significantly higher than that of field grown crops due to the high pesticide inputs (kg ha^{-1}) and ecotoxicity of insecticides and fungicides used in nursery production (Yin et al., 2023). Untreated, contaminated surface runoff from nursery production sites can pollute waterbodies downstream and have significant effects on the stream ecosystem and aquatic biota. Sediment in runoff leaving nurseries can have significant environmental impacts on waterbodies, including transport of other pollutants notably sorbed trace elements and toxic organics (Colley and Smith, 2001). In addition to potentially causing aesthetic concerns, suspended sediments can affect aquatic organisms, via benthic smothering as sediment settles out of the water column, irritation of fish gills, light attenuation reducing visual range for sighted organisms and light availability for photosynthesis, and transport of sorbed contaminants (Colley and Smith, 2001). Less light penetrating the water reduces the photosynthesis of aquatic plants, with consequences for dissolved oxygen concentrations and aquatic life (Morgan et al., 2011). Higher concentrations of suspended solids can also increase the temperature of the water, adversely affecting aquatic life.

Sediment in surface runoff can also transport nutrients from fertilisers and pesticides to the environment. For instance, increased nutrient concentrations in streams can lead to eutrophication as well as increase the nutrient content of basal resources (with a shift from detritus to algae), and nutrient-to-carbon ratios of detrital resources (Manning et al., 2015). These shifts in food nutrient content can affect higher trophic levels in the aquatic food web; for instance, a shift in nitrogen: phosphorus ratio to basal resources may be beneficial to some macroinvertebrate taxa but negatively affect others (Demi et al., 2018). Furthermore, excess nutrient concentrations in surface water bodies stimulate the growth of aquatic plants and algae, which can impede flow and cause water to stagnate allowing infectious pathogens to propagate (Qadri and Faiq, 2020). Excessive algal growth can lead to algal blooms, which reduce the dissolved oxygen content in the water during bloom senescence and contribute to serious water quality problems that can suffocate or even be toxic to benthic organisms and fish if the algal blooms consisted of toxic species of cyanobacteria (Paerl and Otten, 2013). Algal blooms can also be aesthetically undesirable, alter the species diversity of aquatic communities, and impair recreational uses of surface waters. The loss of biological activity and fish kills can have significant cultural and economic impacts on local communities dependent on recreational and commercial fisheries.

Similarly, the transfer of pesticide residues through surface runoff to the aquatic environment can significantly impact trophic food webs (Sánchez-Bayo et al., 2016). Commonly used insecticides, such as organochlorines and organophosphates have caused a number of environmental problems, including spray drift onto non-target areas, general toxicity to most organisms, fish kills, and bioaccumulation in fatty tissues of fish (Sánchez-Bayo et al., 2016). Other insecticides, such as neonicotinoids have affected aquatic ecosystems negatively, through delayed mortality and a number of sub-lethal effects on aquatic organisms, such as suppressed feeding, reduced movement and fecundity, reduced body size in macroinvertebrates and fish, and suppressed immune function in fish (Sánchez-Bayo et al., 2016). For example, a study in the Netherlands found a positive correlation between residues of the neonicotinoid imidacloprid and the decline of several arthropod taxa, including Ephemeroptera, Odonata, Diptera, and some crustaceans (Van Dijk et al., 2013). Neonicotinoids in the environment are particularly damaging because they affect non-target aquatic species and inhibit their recovery. This is evident in a mesocosm experiment that showed macroinvertebrates treated with neonicotinoids had a lower abundance compared to controls after a few months, while some species disappeared altogether (Beketov et al., 2008).

Pesticide residues can affect aquatic and terrestrial organisms with lower and higher trophic levels (Sánchez-Bayo, 2011). For instance, the removal of predatory macroinvertebrate species increases the number of prey species, which in some cases may lead to health hazards (i.e., higher numbers of mosquitos). Similarly, the removal of macroinvertebrates, which are a critical food resource, may lead to starvation of many higher trophic organisms (i.e., fish, lizards, birds) (Sánchez-Bayo et al., 2016). A study in the Netherlands showed a 3.5 % yearly decline in the bird population in areas with neonicotinoid residue levels above 20 ng L^{-1} (ppt) in water (Hallmann et al., 2014). In California (USA), up to 11 % of aquatic species are affected by the use of the pesticide imidacloprid in three agricultural areas (Starner and Goh, 2012), and in Sydney (Australia), turf farms treated with imidacloprid affected up to 14 % of the aquatic species in streams (Sánchez-Bayo and Hyne, 2014). Pesticides in surface runoff can also affect the marginal vegetation surrounding nurseries. Sublethal doses of herbicides entering runoff and reaching the natural vegetation at the margins of field sites can change plant compositions in a community (Boutin et al., 2014). Water soluble toxicants from nursery sites and leached soils that are transferred to waterbodies can either decompose, volatise, or form insoluble salts, which precipitate and settle in the sediment (Bukola and Zaid, 2015). These toxins are then easily taken up by aquatic organisms including fish and subsequently metabolised into more toxic derivatives. For example, mercury may be converted into highly toxic methyl mercury by microbial action, which is then taken up by fish. Toxins can bioaccumulate and concentrate in many aquatic organisms often without clear signs of external physical change. Metal toxicity, however, can affect individual growth rates, physiological functions, mortality and reproduction in fish (Afshan et al., 2014). These examples highlight the numerous negative effects of pesticide residues on the aquatic ecosystem. Where nursery growers are responsible for the release of untreated waste water to the environment, mitigation measures should be implemented to reduce these impacts.

6. Systems approach strategy

There are several factors to consider when assessing the waterborne contamination risk associated with nurseries, and the interaction of these factors can influence whether nurseries will have a low, medium or high risk of contamination (Fig. 4). The first consideration is the position of the nursery within the catchment (i.e., headwater vs. floodplain), as well as the surrounding land use activities and landscape connectivity. These factors indirectly influence the extent of hazard propagation (such as by floods, storm events) across the landscape and thus the intensity of the hazard. For example, nurseries located in the headwater (source region), receiving no run-on, and surrounded by minimal land use change, will have a lower risk of being affected by contaminants and may be characterised as "Low risk" (Fig. 4). In contrast, nurseries located in middle catchment or floodplain (transfer or sink regions), and surrounded by high intensity agriculture, will have a greater risk of being affected by high surface run-on and contaminant load ("High risk"). The contamination risk factor of the nursery is then compounded by the activities and management of individual nursery growers on site, such as the source of irrigation water used and management practices. For instance, if a nursery is characterised as 'High risk' due to catchment characteristics and uses recycled water for irrigation, the contamination risk factor may increase. However, should a nursery use municipal water or treat recycled water effectively, the contamination risk factor may decrease. In all scenarios, regular testing and monitoring of water quality is important to assess the contamination hazard. Where nurseries are considered "High risk", water quality should be monitored to assess the presence of contaminants and if required water should be treated before using it for irrigation to reduce contamination. Similarly, all runoff from the nurseries should be monitored and treated if contaminants are present to prevent contaminant transport to the environment. While physical hazards (i.e., catchment setting, floods) are hard to control, the on-site activities of individual nurseries can be managed to maintain the sustainability of nursery operations as well as reduce the

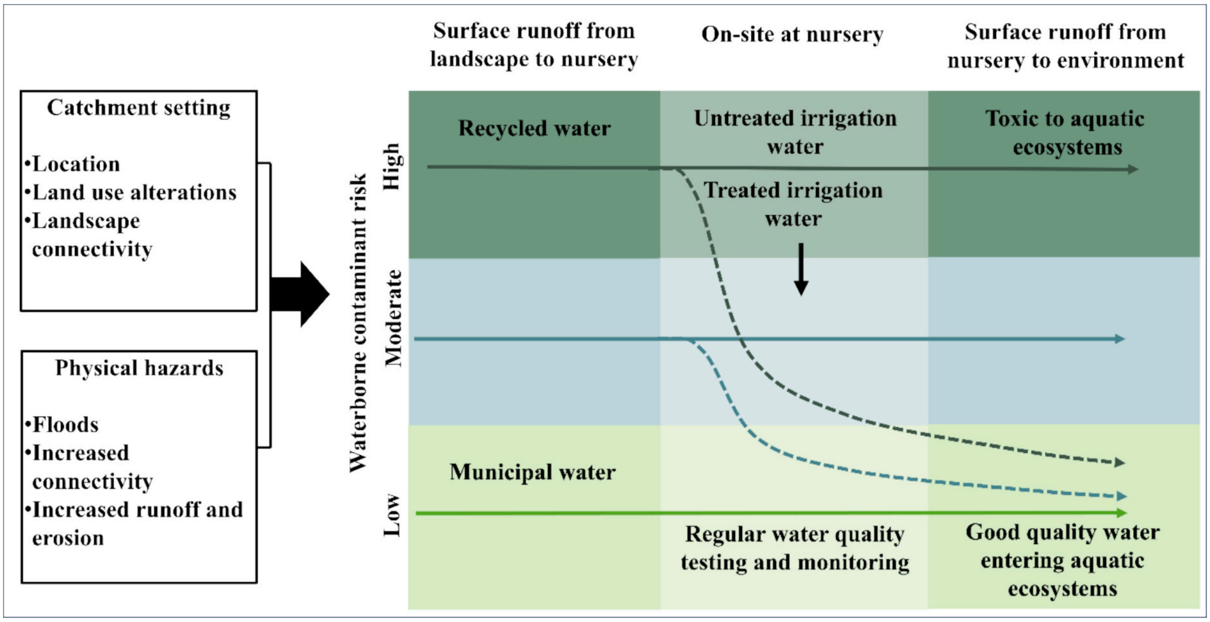

Fig. 4. Conceptual diagram highlighting the factors that influence waterborne contamination risks to and from plant production nurseries.

impact to the environment. To effectively reduce and mitigate the transport of waterborne contaminants, nurseries can implement best management practices (BMP).

Growers can adopt a systems approach framework to improve productivity and profitability, as well as to support sustainable nursery operations. A systems approach is an information driven, proactive approach which aims to prevent and reduce contamination rather than relying on a traditional endpoint inspection approach (Parke and Grünwald, 2012). The systems approach framework can inform best management practices and is based on concepts borrowed from the Hazard Analysis of Critical Control Points (HACCP), which is a risk management program originally developed for the food industry to identify and control potential sources of food-borne contaminants (Griesbach and Kipp, 2012). The core idea of the HACCP program is that prevention of contamination is cost-effective and sustainable for nursery operations compared to fixing the problem later. The HACCP approach is applied to each stage of production cycle and provides systematic steps to identify, evaluate, and reduce sources of hazards that may affect the final product (Parke and Grünwald, 2012). Critical control points (CCPs) refer to any step or process within the production cycle where hazards can be prevented or reduced. Identification of the hazards and CCPs allows directed management to change production processes where hazards are identified. The Australian horticultural industry has been successful in implementing a HACCP-based program called BioSecure HACCP, to prevent pathogens and pests from affecting nursery production (Bradshaw and Rogers, 2005). Nurseries that reported implementing the BioSecure HACCP program had success producing healthy plants and thus greater access to international export markets.

Based on concepts from HACCP, a proactive systems approach can be used to minimize and prevent contamination hazards in plant production nurseries (Parke and Grünwald, 2012). The main HACCP steps include: (1) Identify all potential contamination hazards that can be introduced or controlled in each stage of the production cycle. During this step a detailed outline of all stages in the production cycle needs to be developed. This requires site visits and working with growers to identify all possible sources of contamination at each stage of production. While all nurseries follow a general production sequence, each nursery has to be assessed on an individual basis to identify unique problems. (2) Evaluate the severity and probability of each contamination hazard identified in step 1. This step requires spatial and temporal assessments of each stage of production (i.e., propagation area; greenhouse and field growing area), as well as the different components involved in the growing cycle (i.e., symptomatic and asymptomatic plants; containers and growing media; irrigation water; and ground cover beneath containers). (3) Defining CCPs that can be managed to prevent or reduce contamination hazard to acceptable levels. Results from step 2 are used to identify the most important points of contamination in the production cycle of nurseries. Again, this step requires working with nursery managers to develop CCPs to address the source of each contamination hazard. For example, water is a common contamination hazard where several possible CCPs may be identified to reduce contamination, such as contaminated irrigation water, splash zones resulting in the dispersal of pathogens, or contamination of water accumulated in waterways.

Once the CCPs are identified, best management practices (BMPs) are developed to address them (Parke and Grünwald, 2012). For example, in the case of water contamination, growers can implement BMPs that recapture and treat irrigation water using an approved method; prevent standing water by adjusting the irrigation system to prevent overwatering, fix drainage problems, raise containers off the ground, and place gravel and liners below containers. (4) Establish critical limits for CCPs where possible. This step can be difficult to achieve for all CCPs identified as plant production nurseries have a wide diversity of products, growing conditions, and management strategies and thus is recommended where possible. For example, development and adoption of protocols that state the specific treatment (i.e., chlorine, UV light, heat) to disinfect contaminated irrigation water in retention ponds or the correct temperature and time required to effectively pasteurize substrate media and containers. (5) Establish monitoring protocols and record and verify all information. Implementation of regular testing of irrigation water quality and phytopathogen presence from different regions of the nursery (i.e., standing water around containers or gravel below containers). Records of the processes that occur during the production cycle and when testing occurs are important for monitoring whether or not best management practices are successful over time. Effective implementation of HACCP systems requires significant management commitment. Nursery managers need to ensure that the correct procedures are in place and that staff are adequately trained to complete the tasks outlined in the HACCP framework (Parke and Grünwald, 2012).

6.1. Best management practices

Best management practices are specific guidelines or activities designed to help nursery growers improve their irrigation and nutrient management practices to decrease fertiliser runoff and contamination of surface or groundwater (Bilderback, 2002). The purpose of implementing BMPs is to address water quality or water and nutrient management problems identified at specific sites or CCPs, increase plant production efficiency, decrease costs of treatment, and protect the downstream environment (Mack et al., 2019). While BMPs provide broad guidelines, they can be modified and adapted for the site-specific needs of individual nursery facilities. Some of the major concerns of nursery growers include fertiliser and pesticide runoff to the environment which is directly related to irrigation efficiency. Irrigation efficiency depends on the irrigation infrastructure that determines the quantity of water that enters containers, application uniformity, and water retention capacity of the substrate following irrigation. The management of irrigation systems is also important, as poor management of an efficient system can reduce system efficiency and increase contaminated runoff. As such, BMPs can be implemented into the production cycle to address these concerns and reduce runoff and contaminant transport both within the nursery as well as off-site. Here we outline broad BMPs that can be adopted by nursery growers to improve irrigation efficiency and reduce contamination risk while maximising production yield and reducing economic loss. Importantly, these BMPs can be modified by nursery growers to suit their specific requirements.

(i) *Maximise irrigation efficiency and minimize leaching.* Poor irrigation uniformity results in uneven application of water, resulting in areas being overwatered or underwatered (Mack et al., 2019). Regularly checking irrigation uniformity can ensure irrigation efficiency is achieved and help growers recognise when systems are not operating optimally. Another way to ensure irrigation efficiency is to monitor the leaching fraction from containers, which is the amount of water leached from the container divided by the amount of irrigation applied. Monitoring is recommended every 2 to 4 weeks and the leaching factor should not exceed 15 % (Bilderback et al., 2013). By reducing the irrigation duration, it is possible to achieve the required leaching factor and maintain plant quality while reducing the amount of water and fertiliser used (Bilderback et al., 2013).

(ii) *Cyclic irrigation.* Nurseries usually irrigate on a daily basis where water is applied continuously in a single application. An alternative and more efficient method is cyclic irrigation which involves irrigating multiple times throughout the day with scheduled time intervals between watering (Bilderback et al., 2013). Cyclic irrigation increases irrigation efficiency and plant water use, while reducing the total leachate fraction from containers. Reducing runoff volume from containers reduces fertiliser loss and thus economic loss, while reducing the risk of environmental pollution. Water use efficiency of plants can increase as irrigation volume decreases (Warsaw et al., 2009).

(iii) *Plant organization.* Growers can maximise irrigation efficiency by arranging containerised plants based on water requirements and plant canopy size and structure (Bilderback et al., 2013). Grouping plants in this way reduces low water-use plants from receiving excess water. However, when grouping by water use is not possible, containers can be grouped by volume which ensures that plants with similar water needs are grouped.

(iv) *Water storage reservoirs.* Runoff from nursery production sites is typically captured and drained through runoff trenches to on-site storage reservoirs where the water is treated before it is discharged to the environment or reused for irrigation. Minimising contact of runoff with the ground is important to reduce contamination, and so runoff trenches should be lined with an impermeable material. In the case that nursery growers do not capture or reuse water, alternative methods can be used to filter water before it is released to the environment, such as vegetated buffer zones, grass strips, and constructed wetlands. Constructed wetlands buffer the degradation of water quality by filtering and intercepting the transfer of nutrients and pesticides between nursery sites and surface waters (Préau et al., 2022). Production areas can be sloped to prevent water accumulation and to allow runoff to flow to vegetative buffers or wetlands for filtering. These methods also capture sediment, helping to reduce the contaminant load entering the environment (Bilderback et al., 2013).

Growers can significantly reduce contaminant spread in nurseries by implementing a systems approach management strategy that includes best management practices. Regular monitoring can assist growers to identify the sources and types of contaminants present in irrigation water and the production area, as well as facilitate adaptive management to reduce contaminant spread. In addition, growers can monitor surface water runoff entering storage reservoirs to determine whether contaminants are being introduced via this pathway. Mitigation measures, such as vegetative buffer strips or retention ponds can be implemented to reduce contamination from runoff. There is limited knowledge or awareness with regards to threshold levels of contaminants that cause disease in plants and research is required to address this. Also, the pathogenicity and ecology of the common pathogens found in irrigation water is little known. Further research is also required to understand interactions among pathogens and how that affects host-pathogen interactions. For example, an understanding of whether interactions among pathogens or between pathogens and other microbes can have additive or synergistic effects on hosts plants. By addressing this knowledge gap, growers will be able to achieve sustainable water and contaminant management.

7. Conclusions

This review assessed waterborne contaminant risk to plant production nurseries and the management strategies that can reduce contaminants both on-site and to the environment. Container production nurseries rely on large volumes of good quality water to produce high quality yields. Stricter water-use regulations in many regions of the world have forced nursery growers to capture and reuse drainage water from production sites. While this option reduces depletion of water sources and the potential environmental contamination from runoff, adoption of recycling technologies by growers is poor owing to their perceived increase in contamination risk. Catchment location in conjunction with hydroclimatic factors, including heavy rainfall and flooding, can influence the contaminant risk of water storage reservoirs at nurseries. Key contaminants, such as phytopathogens, excess nutrients, metals, and salinity can significantly affect plant health and production, resulting in decreased marketability and economic loss. Regular monitoring at nursery sites can help identify where contaminants are most abundant and the types of contaminants that are present, allowing growers to construct a directed management plan. Through the implementation of best management practices that promote sustainable water use and effective water treatment technologies, growers can ensure the long-term sustainability of nursery operations while ensuring the production of healthy plants as well as protecting downstream ecosystems. Further research will focus on developing a decision support framework and toolbox to improve the effectiveness of managing and monitoring waterborne contamination in nurseries. Decision support tools will include a catchment-scale identification of nursery risk; passive sampling for tracking contaminants on and off nursery sites; and guidelines for determining the risks of different contaminants.

CRediT authorship contribution statement

Megan Gomes: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Timothy J. Ralph:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Marc S. Humphries:** Writing – review & editing, Supervision. **Bradley P. Graves:** Writing – review & editing, Data curation. **Tsuyoshi Kobayashi:** Writing – review & editing. **Damian B. Gore:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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