

Investigation into citrus packhouse raw wastewater quality in the Cape Winelands, South Africa

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Untreated wastewater from citrus packhouses in the Cape Winelands region of South Africa was assessed as a first step towards identifying suitable treatment options for fungicide reduction and potential wastewater reuse. Global literature on citrus processing wastewater is limited, and this research aimed to contribute to filling that gap. This study was not conducted to identify pollution sources or culprits but rather to establish a baseline understanding of citrus packhouse wastewater. Raw effluent samples collected from 3 packhouses were analysed for key physical, chemical and microbiological parameters, including *Escherichia coli* (*E.coli*), total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), pH, electrical conductivity (EC), and the postharvest fungicides imazalil (IMZ) and fludioxonil (FLU). The results indicate high variability in wastewater characteristics both within and between packhouses, particularly for *E. coli* (coefficient of variation (CV) = 4.67); TSS solids (CV = 1.49) and IMZ (CV = 1.8). Notably, mean values for total suspended solids and chemical oxygen demand exceeded established South African wastewater discharge limits. This, along with the presence of imazalil fungicide residues, emphasises the importance of responsible wastewater management for mitigating risks and exploring reuse opportunities in packhouse operations. This study informs the global development of cost-effective, practical wastewater treatment solutions that help packhouses meet regulatory environmental safety requirements while maintaining operational efficiency. By addressing wastewater management challenges proactively, packhouses can enhance sustainability, regulatory compliance, and resource efficiency, ultimately aligning with global trends toward more responsible water use and effluent treatment practices. Recommendations for further research include: the investigation of wastewater treatment technologies suited to citrus packhouse effluent, the testing of additional postharvest fungicides, distinguishing between soluble and insoluble chemical oxygen demand, expanding the study across multiple seasons and a wider range of packhouses and a detailed risk analysis for long-term sustainability of citrus wastewater management.

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INTRODUCTION

Rationale

South Africa is one of the largest global exporters of fresh citrus, shipping approximately 70% of its total production volume – 2.2 million tons in the 2023 season – to key markets in Europe, Asia, the Middle East, and North America (CGA, 2024; Serfontein, 2018). To ensure extended shelf life during transit, postharvest fungicide treatments are widely applied in citrus packhouses (CA, 2022b). Additionally, pre-harvest fungicides applications are utilised in citrus orchards to help control diseases that could compromise crop yield and marketability (Truter, 2010; Junior et al., 2016).

While both pre- and postharvest fungicide use is essential for maintaining citrus quality, the adequate management of packhouse wastewater, which may contain residual fungicides and other contaminants, is critical for environmental and public health and regulatory compliance. Most wastewater management in citrus packhouses involves a conventional ‘take–make–use–dispose’ model, whereas global regulatory trends, particularly in the European Union (EU), are shifting towards a ‘take–make–use–reuse’ approach that emphasises wastewater-appropriate treatment and reuse (Lucia et al., 2022). In South Africa and globally, research into suitable treatment technologies for fungicide removal in citrus packhouse effluent remains limited. As environmental regulations become stricter and sustainable practices gain priority (Kanarek et al., 2024), there is a critical need to further understand and develop efficient methods for fungicide removal from packhouse wastewater effluent. It must be noted that the scope of this study is not the actual impact of wastewater on the environment nor a specific focus on South African environmental standards, but rather future compliance with EU regulations through effective packhouse effluent management and ultimately international best practice. This is not meant to diminish the concept of environmental impact in any way. Rather, it is hoped that improvement in packhouse effluent handling towards international best practice would also have a positive effect on effluent quality.

This study provides insight into raw effluent quality from citrus packhouses within the Cape Winelands region of South Africa, laying the groundwork for future research into effective treatment solutions. By characterising key water quality parameters, this research aims to support the development of strategies for improved wastewater management and potential reuse in packhouse operations.

Research focus

Literature on general fruit and vegetable processing wastewater quality is limited, particularly regarding citrus packhouse effluent. This study investigates typical raw wastewater quality from

citrus packhouses in the Cape Winelands region of South Africa to address this knowledge gap. The findings provide a foundation for future research on effective and environmentally appropriate fungicide treatment technologies for wastewater.

The intention of this research was not to identify pollution sources but rather to characterise wastewater quality and variability. Samples were collected from 3 packhouses to offer a snapshot of conditions in a specific geographical area. Given the many factors influencing wastewater composition – including fungicide use, water sources, market requirements, fruit types, packhouse size, and processing methods – this study did not attempt to represent all citrus packhouses but serves as a baseline for further investigation.

The study focused on key quality parameters, including postharvest fungicides, microbial indicators, solids, organic content, and standard water quality indicators in raw citrus packhouse effluent. While pre-harvest fungicides are acknowledged as a potential contaminant of packhouse wastewater, their presence may depend on residue on fruit surfaces, persistence and solubility. The investigation of these fungicides was not included in the scope of this study due to time limitations. Further to this, secondary processing, such as peeling, and non-citrus fruit were excluded from the scope. Additionally, informal observations on water usage within packhouses provided contextual insights into wastewater generation and management.

Citrus production and fungicide use in South Africa

Citrus cultivation occurs across all 9 provinces of South Africa, though production is concentrated in specific regions. In the 2023 season, citrus exports were primarily produced in Limpopo (40%), the Eastern Cape (25%), the Western Cape (19%), and Mpumalanga (7%), with the other provinces collectively contributing 9% (CGA, 2024). The Free State produces less than 1% of the national citrus crop, with no significant exports. The Western Cape Province, which is the focus of this research, produces a diverse range of citrus varieties, including lemons, navels, soft citrus, and Valencia/midseason oranges (CGA, 2024).

Citrus growers face various challenges, including environmental conditions and susceptibility to pests and diseases (Truter, 2010).

In order to maintain fruit quality and meet export standards, both pre- and postharvest fungicide treatments are widely used. Pre-harvest applications primarily target diseases such as citrus black spot (CBS), which can significantly affect yield and marketability (Truter, 2010). Therefore, growers undertake extremely costly and strict fungicide spraying programmes in order to retain market access. Pre-harvest chemicals for CBS control measures often involve strobilurins and fixed copper-based fungicides (Junior et al., 2016; Truter, 2010).

Postharvest spoilage diseases such as blue mould, green mould, and sour rot are major concerns for exporters (CA, 2022b). To prevent spoilage during long shipping periods, packhouses apply registered fungicides, including imazalil (IMZ), pyrimethanil (PYR), azoxystrobin (AZO), and fludioxonil (FLU), among others, which are registered for use in South Africa, each unique in its target disease (Serfontein, 2018). The specific fungicides and application rates used depend on regulatory requirements in destination markets (Serfontein, 2018).

Postharvest process in citrus packhouse

Once harvested, citrus fruit is transported from orchards to packhouses, where it undergoes various processing steps to ensure high quality and marketability in compliance with export requirements (CA, 2022a). While packhouse layouts and operations may vary depending on size and design, the typical export process includes the following key activities shown in Fig. 1 (CA, 2022a; CA, 2022b; ENRB, 2014; Junior et al., 2016; Truter, 2010):

- Receipt of citrus fruit: Harvested citrus is delivered in picking trailers or bulk bins stacked on trucks.
- Degreening (if required): Fruit may be exposed to ethylene gas to enhance colour development, often accompanied by pre-packhouse fungicide treatment.
- Initial washing: Depending on the system used, fruit is either submerged in a sanitising solution (wet tip system) or placed on a conveyor belt and brushed and sprayed with a sanitising solution (dry tip system).
- Pre-sorting: Damaged, soiled, or undersized fruit is removed before further processing.

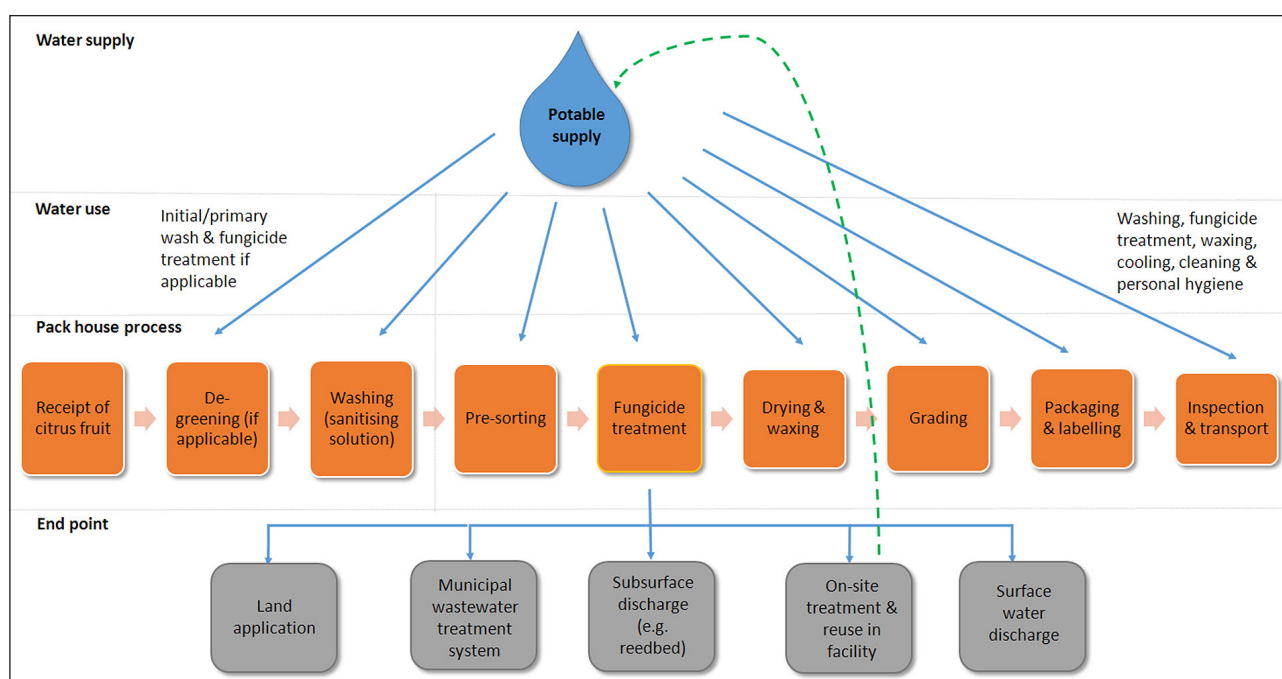


Figure 1. Typical citrus packhouse water usage (adapted from CA, 2022a; EBRD, 2014 and Robertson et al., 2017)

- Fungicide treatment: Fruit is treated in a bath or through a flood system with fungicides to prevent postharvest decay.
- Drying and waxing: A drying tunnel removes excess moisture before a water-based wax is applied, followed by another drying phase. This improves shelf life and enhances fruit appearance. Fungicide can also be mixed with wax, providing another control point for fungal infections.
- Grading and sorting: Fruit is categorized by size and quality using either manual inspection or automated sorting technologies.
- Packaging and labelling: Fruit is packed according to market specifications and labelled for traceability.
- Final inspection, storage and dispatch: Packed fruit is inspected, stored under optimal conditions, and transported to ports for export.
- Exporting: Bulk shipping or cooled containers are used to export fruit.

Water plays a crucial role throughout the packhouse process (Mundi et al., 2018), where it is used for washing the raw produce, fungicide application, waxing, sorting, cooling, and maintaining general health and hygiene standards through handwashing and cleaning of process areas and equipment (CA, 2022a; ENRB, 2014; Robertson et al., 2017).

According to Robertson et al. (2017), untreated/non potable water can potentially be used for initial washing activities, while potable supply is required for all other activities. South African citrus packhouses certified under GlobalG.A.P., including its Produce Handling Assurance (PHA) and Integrated Farm Assurance (IFA) standards, however, are required to use potable grade water for all washing steps (GlobalG.A.P, 2024).

The disposal and management of packhouse wastewater vary depending on infrastructure and regulatory requirements. Endpoints for citrus wastewater may include land application, subsurface discharge, reuse in the facility once treated to potable standards, or the municipal wastewater treatment works (ENRB, 2014; Robertson et al., 2017). Understanding water usage patterns in packhouses is essential for evaluating wastewater characteristics and identifying opportunities for improved management and potential reuse. Figure 1 is a schematic of typical postharvest water usage in citrus packhouses.

Characterisation of citrus packhouse wastewater and associated risks

Wastewater generated in citrus packhouses contains a complex mixture of physical, chemical, and microbiological constituents. This includes fungicide residues, other pesticide residues, organic matter, suspended solids, oxygen demand, nutrients, pathogens, microbes, and sanitising agents from both fruit washing and facility cleaning processes. If not properly treated, these pollutants can have environmental impacts, particularly when discharged into natural water bodies (ENRB, 2014; Meneses et al. 2017; Mundi et al., 2018).

Several studies have highlighted the potential environmental and public health risks associated with fungicide residues in wastewater. Excess fungicides can pose a threat to soil biodiversity, plant health, and aquatic ecosystems, while posing risks to terrestrial organisms (Rad et al., 2022; Zhang et al., 2024; Zubrod et al., 2019). In terms of public health; while the acute toxicity of fungicides to humans is generally low, improper handling or exposure may cause skin, eye and respiratory irritation (Lorenz, 2022). Chronic exposure to certain fungicides, on the other hand, has been linked to adverse health effects (Lorenz, 2022). Additionally, if wastewater is not effectively managed, fungicide residues could enter water sources through runoff or infiltration,

potentially contaminating drinking water and contributing to bioaccumulation of fungicides in the food chain (Rad et al., 2022; Sudoma et al., 2021).

With key drivers such as a growing global demand for food and water, food safety regulations, climate change, stricter effluent discharge standard regulations, environmental advocacy, and trade restrictions, the management of wastewater from fresh produce packhouses is becoming increasingly important (Mundi et al., 2018; Schoen et al., 2017). Understanding the challenge posed by large water footprints and variable effluent quality is essential for developing sustainable wastewater treatment solutions.

Due to the limited research on citrus packhouse effluent, wastewater characteristics from tree fruit in general were sourced from literature. These studies indicate that wastewater composition is highly variable and site dependent. A comprehensive study by Mundi et al. (2017) on wastewater from Canadian fruit and vegetable processing facilities, for instance, found significant variation influenced by multiple factors. These factors can include the origin of the fruit, the spraying regimes of the growers, weather conditions, fruit varieties, pre- and postharvest treatments, packhouse operations, cleaning product types, fruit quality received, storage duration, treatment requirements, nozzle pressure, washing flow rates and wastewater management practices (Mundi et al., 2017; Mundi et al., 2018; Borja and Banks, 1994; CA, 2022a; ENRB, 2014; Robertson et al., 2017). In addition to these qualitative differences, wastewater characteristics also fluctuate quantitatively due to factors such as water consumption per weight unit of processed fruit, processing volumes, water management practices, agricultural production, market trends, and plant operations (Lucia et al., 2022; Mundi et al., 2018).

While raw water quality can differ between regions, packhouses in South Africa certified under GlobalG.A.P. rely on a potable water supply, which minimises variability in influent water quality and ensures compliance with health and safety standards (GlobalG.A.P., 2024). Consequently, the observed variations in wastewater quality are more likely attributed to packhouse-specific operations rather than differences in raw water sources.

METHODOLOGY

This study was performed in the Cape Winelands region of South Africa and followed the methodological approach outlined below.

The research design encompassed the iterative planning and preparation for the collection of water quality samples from citrus packhouses (Fig. 2). This step entailed the selection of packhouse locations and applying for relevant access requirements, the design of sampling procedures and frequency, the identification of water quality parameters and the preparation for sample collection, transport, storage and testing.

Data collection

Three citrus packhouses located in the Cape Winelands region of the Western Cape Province, South Africa, were identified and approached. These packhouses represented a range of operational scales, from small on-site facilities to larger exporters receiving fruit from multiple farms in the surrounding area.

The number and frequency of samples were influenced by logistical constraints, including budget limitations, packhouse access, and the seasonal nature of citrus harvesting and processing. On average, sampling was undertaken on alternate week-days over a 4-week period.

Sampling was conducted at key points within the packhouses to capture wastewater characteristics at different stages of the

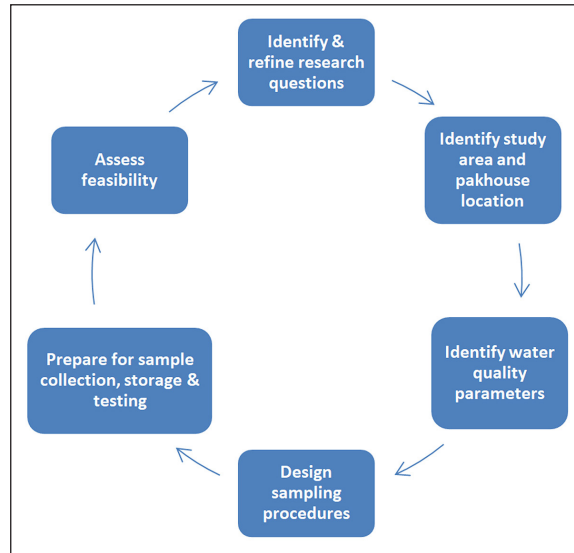


Figure 2. Research study design

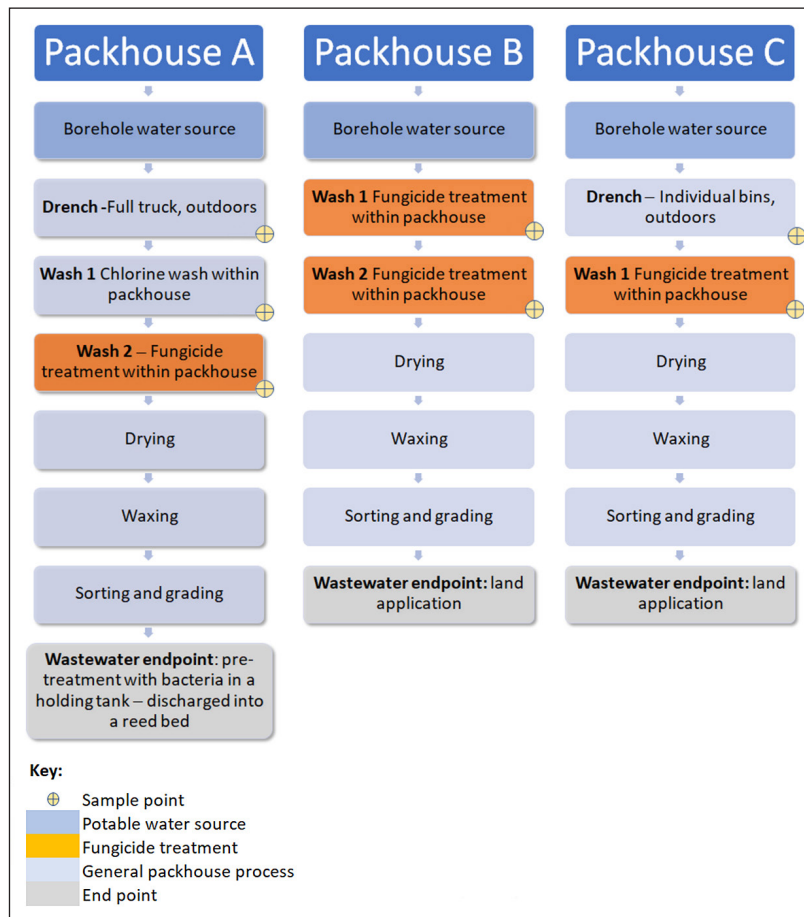


Figure 3. Process flow diagrams for Packhouses A, B and C

postharvest process, such as after initial washing and fungicide treatment (see Fig. 3). Three grab samples per point were collected in disinfected sample bottles, labelled, preserved and transported accordingly.

The following water quality parameters were identified and tested for either on-site or at a certified laboratory:

- Postharvest fungicides: IMZ and FLU used in the packhouse drenching and fungicide baths
- Microbial indicator: *Escherichia coli* (*E. coli*)

- Solids: total suspended solids (TSS) and total dissolved solids (TDS)
- Organic content: chemical oxygen demand (COD)
- Standard water quality parameters: pH, electrical conductivity (EC)

In addition to the sample collection, informal discussions with packhouse staff and visual assessments were conducted to gather insights on general water usage, fungicide treatments, citrus origins, and operational practices. This contextual information helped inform the study's objectives and interpretation of results.

Statistical analysis and comparison to wastewater limit values

The wastewater quality data collected from the 3 packhouses were analysed to determine typical parameter ranges and overall effluent characteristics. Basic descriptive statistical methods were utilised to gain insights into central tendencies and variability of the wastewater quality data, including means, medians, variance (s^2), standard deviation (SD) and coefficient of variation (CV)- were used to summarise the dataset and assess variability both within and between packhouses (see equations in Table 1).

To evaluate effluent quality, the results were benchmarked against applicable wastewater discharge limits. Specifically, the findings were assessed against the South African authorisations for wastewater discharge into a water resource outlined by DWAF (1999) and municipal wastewater standards set by the City of Cape Town (CCT, 2013). Applicable parameters exceeding these regulatory thresholds were identified to highlight potential environmental and public health risks and inform future wastewater management strategies.

RESULTS AND DISCUSSION

A total of 56 distinct wastewater samples were collected from 3 packhouses in the Western Cape's Cape Winelands region during

2 packing seasons. Sampling occurred over 2 periods: 11 August 2023 to 23 August 2023 and 7 August 2024 to 23 September 2024. These timeframes provided a representative snapshot of wastewater quality across different packhouse operations. However, factors such as rainfall, seasonal fruit volume variations, and dust accumulation on incoming fruit were not explicitly analysed, as these fall outside the scope of this study. Future research could explore these influences in more detail.

Packhouse characteristics and sampling overview

Table 2 summarises the 3 packhouses included in the study, their processing systems, and the number of samples collected per packhouse visited.

Further details on process flow and water usage at each packhouse are presented in Fig. 3, which indicates sampling points, water sources, fungicide treatment points, and wastewater end points.

Variability in wastewater quality

A total of 29 samples were analysed for pH and 49 for EC. Thirty (30) samples were analysed for TSS, 48 samples for TDS, 40 for *E. coli* and 30 for COD. Additionally, 54 samples were tested for the postharvest fungicide IMZ, one of the primary postharvest fungicides used in the packhouses. A summary of the tested

Table 1. Equations used to calculate basic statistics

Basic statistics	Equation
Mean	$\text{Mean} = \sum \frac{x_n}{n}$ $n = \text{sample size}$ $x_n = \text{the number of values in the data set}$
Median	$\text{Median} = \left(\frac{n+1}{2} \right)^{\text{th}} \text{ (if } n \text{ is odd)}$
Standard deviation (SD)	$\text{SD} = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}$ $x_i = \text{each value from the sample}$ $\bar{x} = \text{sample mean}$ $n = \text{sample size}$
Variance (s^2)	$s^2 = \frac{\sum(x_i - \bar{x})^2}{n-1}$ $s^2 = \text{sample variance}$ $x_i = \text{the value of the one observation}$ $\bar{x} = \text{sample mean}$ $n = \text{sample size}$
Coefficient of variation (CV)	$\text{CV} = \left(\frac{\text{SD}}{\text{mean}} \right) \times 100$

Table 2. Packhouse descriptions and number of samples collected per packhouse

Packhouse	General description	Number of distinct samples
A	<ul style="list-style-type: none"> Large packhouse (peak citrus volumes of >200 000 kg/week) Receiving fruit from within a 200 km radius Dry tip system - fruit emptied on a conveyor belt and sprayed IMZ fungicide in use Water changed twice weekly on a fixed schedule 	42
B	<ul style="list-style-type: none"> Medium-sized packhouse (peak citrus volumes of <200 000 kg/week) Receiving fruit within a 100 km radius Wet tip system – fruit submerged in baths IMZ fungicide in use Water changed once a week 	8
C	<ul style="list-style-type: none"> Small-to-medium packhouse (peak citrus volumes of <100 000 kg/week) Processing on-site fruit and from neighbouring farms Dry tip system – fruit emptied on a conveyor belt and sprayed IMZ and FLU fungicides used, interchanged throughout the year Water changed weekly depending on throughput quantities 	6

parameters and the compliance of results with wastewater discharge guidelines (DWAF, 1999; CCT, 2013) is provided in Table 3. Shaded values indicate exceedances of regulatory limits. Samples were taken and measured according to equipment availability and laboratory capacity. In some cases, data gaps occurred due to technical issues with equipment and these are indicated as 'NM' (Not Measured) in Table 3.

The dataset revealed considerable variability in wastewater characteristics, with 6 of the 7 parameters tested having a CV of >50%. The data showed fluctuations both within individual packhouses and across sites in physical, chemical, and microbiological parameters, reflecting differences in operational practices, fungicide application, and water management strategies. This variability, combined with exceedances of wastewater limit guidelines for certain parameters according to DWAF (1999) and CCT (2013) (shaded values in Table 3), indicates the potential risks of untreated wastewater disposal.

Standard water quality parameters

The mean EC of the samples was 142.38 mS/m, with a median of 123.75 mS/m. EC showed moderate variance and standard deviation ($S = 6\,422.32\text{ mS/m}^2$ and $SD = 80.14\text{ mS/m}$) and a moderate to high relative variability of just over half the mean EC value ($CD = 0.56$). 63% of the samples complied with the wastewater discharge limits set by DWAF (1999), suggesting that salinity levels in the citrus packhouse wastewater may intermittently pose a risk to the receiving environment (DWAF, 1996a).

The mean pH of the samples was 7.81, with a median of 8.07 indicating a slightly alkaline average environment. pH showed low variance and standard deviation ($S = 1.56\text{ pH}^2$ and $SD = 1.25\text{ pH}$) and values in the dataset remained fairly stable across samples ($CV = 0.16$), with 2 of the 29 samples (7%) exceeding the wastewater limit values according to DWAF (1999). However, there is the possibility that the pH can occasionally swing toward non-compliance. Monitoring and control remain essential to ensure that the discharge of untreated effluent into surrounding water bodies, with the potential to alter pH levels from that normally encountered, does not negatively affect aquatic ecosystems (DWAF, 1996b).

Organic content

The mean COD concentration in the dataset was 2 566.20 mg/L with a median of 2 357.50 mg/L. All 30 samples exceeded the DWAF (1999) wastewater limit value of 75 mg/L by 500% or more, highlighting the high organic load present in citrus packhouse wastewater. Although further research is required to distinguish between soluble or insoluble COD, these findings suggest that untreated effluent could increase levels of organic matter and reduce dissolved oxygen levels in receiving water bodies, potentially harming aquatic life (Nel et al., 2022). Furthermore, the COD values were widely dispersed with high variance and standard deviation ($S = 1\,986\,660.17\text{ mg/L}^2$ and $SD = 1\,409.49\text{ mg/L}$) and there was a moderate to high level of fluctuation (by 55%) when normalised to the mean ($CV = 0.55$).

Microbial indicator

The mean *E. coli* concentration level across the 40 samples was 647.63 cfu/mL, with a median of 0 cfu/mL. While the majority of the samples showed non-detectable levels of *E. coli*, 30% of the samples reported elevated concentrations. While the source of the *E. coli* contamination is unknown and was adequately managed at the respective packhouses, it must be noted that higher *E. coli* levels, even sporadically, may present a public health risk if wastewater is not handled properly (Henze et al., 2008; Nel et al., 2022).

The sample set also displayed high standard deviation and variation ($S = 9\,137\,665.32\text{ cfu/mL}^2$ and $SD = 2\,022.86\text{ cfu/mL}$) and extremely high variability ($CV = 4.67$), recording the highest variability of all the water quality parameters tested. The erratic microbiological quality of the samples places further emphasis on the importance of adequate wastewater management for hygiene and discharge compliance.

Postharvest fungicides

Imazalil (IMZ) and fludioxonil (FLU) were the two postharvest fungicides tested for in the laboratory. The mean IMZ concentration level was 160.01 mg/kg, with a median of 5.70 mg/kg. There was wide dispersion of IMZ levels in the samples ($S = 82\,866.63\text{ mg/kg}^2$ and $SD = 287.87\text{ mg/kg}$) and extremely high relative variability ($CV = 1.8$). There was a direct correlation of detection of higher fungicide levels with the specific fungicide treatment points, particularly at Wash 2 at Packhouses A and B (see Fig. 3). Lower levels of IMZ were detected at Wash 1 and Drench in Packhouse A, likely due to cross-contamination within the facility.

A further observation is the lack of detection of both IMZ and FLU in both samples at the fungicide treatment point at Wash 1 in Packhouse C, which aligns with the packhouse's seasonal fungicide rotation to meet market requirements. While wastewater discharge guidelines for fungicide residues are not well established, studies suggest that long-term environmental exposure to residual fungicides may pose risks to aquatic and terrestrial ecosystems as (Rad et al., 2022; Zhang et al., 2024; Zubrod et al., 2019).

Solids

The mean TSS concentration was 678 mg/L, with a median of 349 mg/L, with all 30 samples from the 3 packhouses exceeding the DWAF (1999) wastewater regulatory discharge limit of 25 mg/L. Elevated TSS levels in wastewater can have detrimental environmental consequences, particularly when discharged into surrounding water bodies without proper treatment. High TSS concentrations can decrease light penetration, thereby inhibiting photosynthesis; while the settlement of suspended solids can lead to the smothering or abrasion of aquatic organisms, further impacting biodiversity (DWAF, 1996a; 1996b). The dataset also displayed high variability ($S = 1\,018\,298.28\text{ mg/L}^2$ and $SD = 1\,009.11\text{ mg/L}$) and extremely high relative variability ($CV = 1.49$).

The mean TDS concentration was 991 mg/L, with a median of 1 164 mg/L. The dataset exhibited high variation ($S = 491\,356\text{ mg/L}^2$, $SD = 700\text{ mg/L}$, $CV = 0.6$), with TDS fluctuations observed at specific sample points, between sample points within individual packhouses, and across the three packhouses. While all 48 samples complied with the City of Cape Town's wastewater discharge standards (CCT, 2013), fluctuations in TDS levels in both rate and duration can pose a risk to sensitive aquatic environments, particularly in ecosystems adapted to low salinity conditions (DWAF, 1996a). Fluctuating TDS levels may also affect the osmotic balance of aquatic organisms, potentially leading to stress or habitat disruption in the event of poorly managed wastewater (DWAF, 1996a).

CONCLUSIONS

While this study provides valuable insights into the wastewater quality from citrus packhouses in the Cape Winelands region, it contributes to the global body of research on fruit and vegetable processing effluent. The findings demonstrate high variability in the physical, chemical, and microbiological parameters at specific sample points, between sample points within individual packhouses and across the three packhouses in this study.

Table 3. Raw wastewater quality at various stages of postharvest processing for the three citrus packhouses

Sample	Parameter						
	pH	Cond. (mS/m)	TDS (ppm)	TSS (mg/L)	<i>E. coli</i> (cfu/mL)	Imazalil (mg/kg)	COD (mg/L)
Discharge limits	5.5–9.5 (DWAf, 1999)	150 (DWAf, 1999)	4 000 (CCT, 2013)	25 (DWAf, 1999)	1 000 (DWAf, 1999)	N/A	75 (DWAf, 1999)
Median	8.07	123.75	991.00	349.00	0.00	5.90	2 357.50
Mean	7.81	142.38	1 163.97	678.48	647.63	160.01	2 566.20
S	1.56	6 422.32	491 356.00	1 018 298.28	9 137 665.32	82 866.63	1 986 660.17
SD	1.25	80.14	700.97	1 009.11	3 022.86	287.87	1 409.49
CV	0.16	0.56	0.60	1.49	4.67	1.80	0.55
Packhouse A							
Drench (See Fig. 3)	8.45	190.10	1 485.00	NM	NM	0.00	NM
	8.62	187.65	1 465.00	NM	NM	0.00	NM
	8.21	189.85	1 490.00	NM	0.00	0.00	NM
	8.08	175.30	1 375.00	NM	NM	0.00	NM
	8.84	153.75	1 200.00	330.00	19 000.00	0.00	4 640.00
	NM	NM	NM	440.00	0.00	0.00	4 440.00
	8.31	147.75	1 155.00	427.00	0.00	0.00	4 375.00
	NM	NM	NM	NM	13.00	9.50	NM
	NM	137.00	965.00	150.00	3 000.00	6.50	2 340.00
	NM	8.79	105.00	52.00	200.00	7.60	375.00
	NM	30.50	204.00	90.00	1 320.00	8.50	520.00
	NM	28.30	NM	6.00	350.00	8.40	372.00
	NM	187.00	1 000.00	40.00	420.00	0.00	4 175.00
	NM	191.00	1 270.00	90.00	750.00	4.60	3 555.00
Wash 1 (See Fig. 3)	7.42	52.40	409.00	NM	NM	0.00	NM
	8.99	121.40	948.50	NM	NM	38.20	NM
	9.07	150.00	1 175.00	NM	0.00	0.00	NM
	9.03	114.95	897.00	NM	0.00	0.00	NM
	9.24	105.20	827.50	553.00	0.00	0.00	1 625.00
	NM	NM	NM	1 220.00	0.00	0.00	3 090.00
	8.87	152.60	1 195.00	2 117.00	0.00	0.00	4 458.00
	NM	226.00	3 390.00	845.00	60.00	40.90	2 605.00
	NM	71.20	615.00	387.00	0.00	5.90	1 333.00
	NM	98.40	1 263.00	1 300.00	2.00	6.80	3 395.00
	NM	78.20	665.00	640.00	0.00	5.50	2 040.00
	NM	85.30	960.00	345.00	0.00	5.20	989.00
	NM	189.00	571.00	4 200.00	0.00	1.30	5 315.00
	NM	121.00	490.00	3 740.00	0.00	1.40	4 208.00
Wash 2 (See Fig. 3)	4.04	95.20	742.50	NM	NM	530.50	NM
	6.72	123.75	955.50	NM	NM	257.60	NM
	6.47	136.10	1 045.00	NM	0.00	309.90	NM
	6.43	119.65	925.50	NM	0.00	451.00	NM
	6.20	93.35	724.50	420.00	0.00	367.00	2 190.00
	NM	NM	NM	353.00	0.00	170.30	1 760.00
	6.13	129.10	1 000.00	450.00	0.00	377.60	2 505.00
	NM	281.00	2 627.00	1 055.00	0.00	609.00	3 610.00
	NM	54.20	525.00	138.00	0.00	575.90	1 236.00
	NM	102.00	1 180.00	203.00	90.00	1 000.90	2 375.00
	NM	81.30	982.00	30.00	0.00	633.40	1 680.00
	NM	98.30	942.00	214.00	0.00	727.30	2 105.00
	NM	165.00	1 150.00	235.00	0.00	1 154.70	3 005.00
	NM	92.80	705.00	205.00	0.00	896.30	2 120.00
Packhouse B							
Wash 1 (See Fig. 3)	8.07	51.75	403.50	NM	NM	0.00	NM
	7.90	91.75	714.50	NM	NM	0.00	NM
	7.86	78.70	610.00	NM	0.00	0.00	NM
	7.88	64.50	508.50	NM	0.00	0.00	NM
Wash 2 (See Fig. 3)	7.14	227.00	1 735.00	NM	NM	115.40	NM
	6.96	260.00	2 040.00	NM	NM	103.70	NM
	7.00	243.00	1 920.00	NM	0.00	111.60	NM
	7.10	228.50	1 780.00	NM	0.00	97.90	NM
Packhouse C							
Drench (See Fig. 3)	8.76	393.00	3 065.00	NM	NM	0.00	NM
	9.07	213.50	1 670.00	NM	NM	NM	NM
	NM	NM	NM	NM	NM	0.00	NM
	NM	NM	NM	79.50	NM	NM	550.00
Wash 1 (See Fig. 3)	9.77	360.50	2 800.00	NM	NM	0.00	NM
	NM	NM	NM	NM	700.00	0.00	NM

Key: ■ Exceeding effluent quality guidelines (CCT, 2013; and DWAf, 1999); NM – Not measured

This aligns with observations by Mundi et al. (2017) for general tree fruit. The most variable parameters in the dataset included *E. coli*, IMZ and TSS. Certain parameters also sporadically exceeded wastewater limit guidelines, with TSS and COD levels consistently exceeding these limits (DWAF, 1999). This is due to the rapid accumulation of particles carried with fruit as they are washed and processed. While dilution may reduce concentrations in large, fast-moving water bodies, high TSS and COD levels can negatively impact aquatic ecosystems, particularly in enclosed or slow-flowing environments where organic matter accumulation and reduced dissolved oxygen levels may occur (DWAF, 1999). These concerns are being addressed throughout the industry. The variability of the dataset combined with exceedances of regulatory guidelines highlights the necessity of proper treatment of packhouse effluent to minimise potential risks and ensure regulatory compliance. The generally wide spread of the data also means that a singular characteristic effluent value for design of effluent treatment systems will most likely be elusive. Instead, designs will need to incorporate consideration of very low to very high possible concentrations.

The detection of IMZ fungicide at certain sampling points further underscores the need for targeted wastewater treatment strategies. While IMZ concentrations varied across packhouses and were influenced by operational factors, its presence in effluent highlights the importance of developing effective removal solutions to mitigate potential public health and environmental impacts. It is important to note that IMZ is sensitive to UV radiative degeneration, and as such has no persistence in the environment. However, as international regulations on fungicide residues in wastewater evolve, identifying practical and affordable treatment technologies will contribute to ensuring expedited, sustainable wastewater management in the citrus industry.

This study was not conducted to identify pollution sources or culprits but rather to establish a baseline understanding of citrus packhouse wastewater quality to contribute to the field. The ultimate goal is to inform the global development of cost-effective, practical wastewater treatment solutions that help packhouses meet regulatory environmental safety requirements while maintaining operational efficiency. By addressing wastewater management challenges proactively, packhouses can enhance sustainability, regulatory compliance, and resource efficiency, ultimately aligning with global trends toward more responsible water use and effluent treatment practices. To this end, these concerns are attended to per incident and per packhouse.

This study also highlights the need for further research into wastewater treatment technologies suited to citrus packhouse effluent. Testing additional pre- and postharvest fungicides will provide a more comprehensive understanding of fungicide pollutants in citrus packhouse effluent. Additionally, distinguishing between soluble and insoluble COD would offer a more detailed characterisation of organic load of citrus wastewater. Expanding the study across multiple seasons and a wider range of packhouses could provide a more comprehensive understanding of wastewater variability across packhouses. Ultimately, conducting a detailed risk analysis and exploring cost-effective treatment options tailored to fungicide removal and organic load reduction will provide critical insights for long-term sustainability of citrus wastewater management.

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AUTHOR CONTRIBUTIONS

The extent of contributions by the various authors of this paper was as follows:

- N Nel (primary researcher) – 60%: conceptualisation, data analysis, writing, literature review, journal selection, submission and formatting.
- A Bosman (study leader and editor) – 20%: study guidance, editing, and improving the manuscript
- I Brink (study design and review) – 15%: assistance with study design and critical review
- R Ikin (data collection) – 5%: assistance with data collection

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