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A field assessment of residential laundry to landscape greywater quality in the San Francisco Bay area

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ABSTRACT

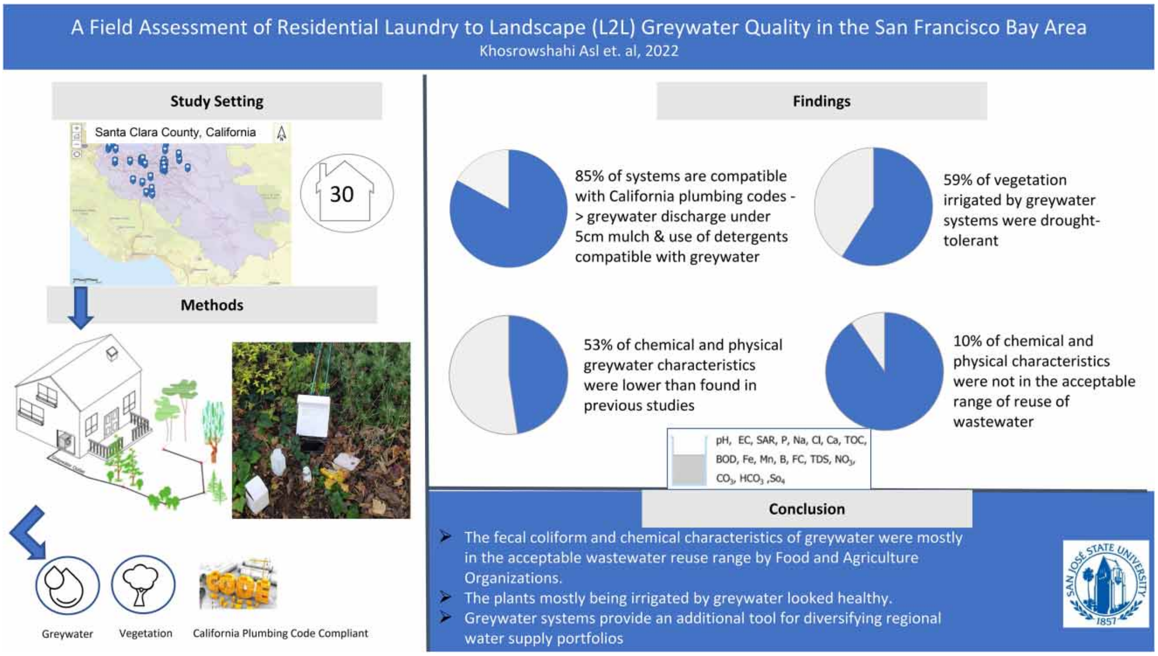
Potable water scarcity is a global issue. Recent and ongoing droughts in the Western United States make residential water conservation crucial. Several water agencies have invested in conservation programs that educate residents on non-traditional water sources, such as laundry-to-landscape (L2L) greywater systems, which reuse washing machine water for outdoor irrigation. This study analyzed landscape vegetation and 21 greywater characteristics of 30 households with L2L systems in Santa Clara County, California. Greywater from most residential systems, even ones decades-old and unmaintained, had acceptable reuse values for major water quality parameters tested. Overall, 89% of fecal coliform counts fell within the acceptable range for water reuse, although counts were higher in non-code-compliant systems than in code-compliant L2L systems. The mean values for coliform counts, electrical conductivity, total dissolved solids, total organic carbon, magnesium, sodium, chloride, and sodium adsorption ratio were lower than the means previously reported for L2L systems. Analysis of water samples indicated high levels of iron and calcium, which merits further investigation. Outdoor vegetation appeared diverse and healthy. The promising results here indicate a high potential for expanding L2L programs. Wider system adoption can diversify regional water supply in service areas where the residential sector accounts for significant water use.

Key words: Drought, Fecal coliform, Greywater, Greywater characteristics, Irrigation, Laundry to landscape

HIGHLIGHTS

- Samples from systems compliant with California Plumbing Code had lower fecal coliform levels, and most chemical characteristics were in the acceptable reuse range for outdoor irrigation.
- Homeowners did not typically change their landscaping after installing greywater systems.
- Laundry to landscape programs provide an additional tool for water agencies to diversify regional water supply portfolios and conserve potable water.

GRAPHICAL ABSTRACT



INTRODUCTION

Potable water scarcity is a global issue, as demonstrated by recent and ongoing droughts in Egypt, Iran, Yemen (Kharraz *et al.*, 2012), Europe (Estrela & Sancho, 2016), and the US West (National Drought Mitigation Center *et al.*, 2021), including California. Faced with heightened water scarcity and concerns about the increased frequency and severity of droughts associated with climate change, alongside an increase in population, the California Department of Water Resources (2019) is now promoting expanded use of non-conventional water sources such as rainwater catchment and greywater. Greywater availability is not dependent on the weather, unlike rain catchment systems (Oteng-Peprah *et al.*, 2018).

Residential users comprise 63% of the water use in California's urban areas (Cooley, 2020). Average household water use is 362 gallons per household, 53% of which is used outdoors (DeOreo *et al.*, 2011). Reducing outdoor water use is thus one of the most effective ways to conserve household water. Gleick *et al.* (2003) showed that outdoor residential water use in California can be reduced by 25–40% with better management, policies, and conservation practices. Greywater diverted to the landscape can be an important source of irrigation water in the face of water shortages (Wu *et al.*, 2021).

Laundry, washbasin, and shower water are considered greywater in California (California Department of Water Resources, 2019). The reuse of household greywater without pre-treatment is not uncommon (ADEQ, 2011; Valley Water, 2016). Where this practice is allowed, policies usually require that irrigated vegetation be watered using underground watering systems to lower the chances of human contact with greywater (World Health Organization, 2006), edible parts of a plant should not come into contact with greywater (Allen, 2015; Ludwig, 2015), and greywater should not be stored for more than 24 h (Rose *et al.*, 1991).

In California, greywater reuse was first legalized in 1989 in Santa Barbara (Ludwig, 2015). In 2009, the California Building Standards Commission adopted greywater guidelines into Chapter 15 of the California Plumbing Code (CBSC, 2016). Programs that teach residents to use non-traditional water sources, such as laundry-to-landscape (L2L) greywater systems that reuse washing machine wash water for outdoor irrigation, have garnered substantial policy interest among local water agencies. In California, L2L greywater systems that do not alter existing plumbing can be installed without a building permit (CBSC, 2016). Based on California Plumbing Code, L2L systems are code-compliant if the untreated laundry drainage hose is connected to a three-way diverter valve that directs water outside the residence to exterior landscapes for irrigation through mulch, if the greywater stays on the property, if the greywater discharge is under a 5-cm cover of mulch, and if greywater does not drain directly onto the ground (Figure 1).

Laundry greywater accounts for 15–20% of most California households' greywater generation (Christova-Boal *et al*., 1996; Allen, 2015). In 2021, Wu *et al*. estimated that the reuse of laundry greywater in the landscape could reduce potable water use by 17 l (4.5 gallon) per person per day. Also, greywater reuse decreases pollutants entering municipal sewer systems (Oteng-Peprah *et al*., 2018).

Many annuals and perennials – including fruits, vegetables, ornamentals, grasses, herbs, shrubs, and trees – can be irrigated and even thrive using greywater (Allen, 2015), but some plants do not fare well. Although various studies document the effects of greywater on annual crop plants such as tomato, green pepper, Swiss chard, carrot, lettuce, and red pepper (Finley *et al*., 2009; Misra *et al*., 2010; Pinto *et al*., 2010; Alfiya *et al*., 2012), most have been conducted in simplified environments like greenhouses. Very few studies indicate what types of plants are used *in situ* in installed greywater systems. Lubbe *et al*. (2016), however, document a range of plants that can be irrigated in yards with greywater systems by homeowners who change to greywater-compatible landscaping, and they suggest alternating irrigation between greywater and tap water to help leach salts.

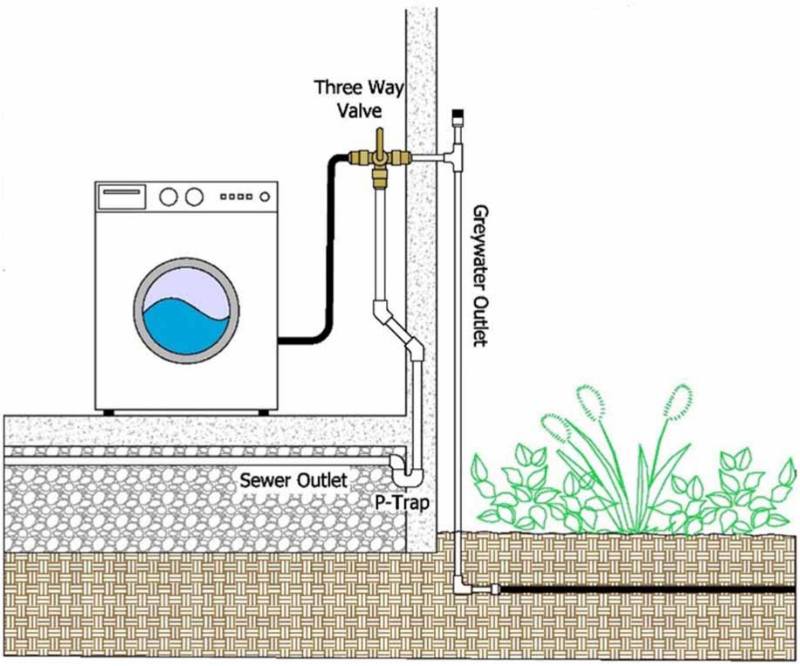


Fig. 1 | Three-way valve to direct water to landscape or sewer system.

Greywater quality can be assessed through three categories: physical, chemical, and microbial (Gross *et al.*, 2015; Table 1). Although greywater can be a great source of plant nutrients (World Health Organization, 2006), reusing untreated greywater can sometimes increase the accumulation of pathogens, salts, and metals in soil and plants, and these components can degrade soil quality over time (Finley *et al.*, 2009; Misra *et al.*, 2010). The level of salt and electrical conductivity (EC) is essential for plants; if these parameter values are high, they can cause plant stress (LeCompte *et al.*, 2016). Several studies found microbial contaminants such as fecal coliform (FC) levels in greywater in varying amounts. Madungwe & Sakuringwa (2007) reported low levels of pathogens, whereas Kotut (2011) reported high levels of FC from 3,000 to 7.4 million CFU/100 ml. Finley *et al.* (2009) found no detectable difference between bacterial contamination in crops irrigated with treated and untreated greywater, suggesting that irrigation with greywater does not pose a bacterial contamination risk. Rose *et al.* (1991) found the FC level to be 10^6 CFU/100 ml. The World Health Organization (WHO) recommends that levels of FC be lower than 1,000 CFU/100 ml. The primary sources of fecal coliforms in greywater are diapers and undergarments in the laundry (Kotut, 2011). The households with more children have more bacterial counts; however, if the house members are chronically ill, chemical loads are higher in greywater (Ghaitidak & Yadav, 2013).

Table 1 | Previously reported ranges for greywater quality.

	Finley *et al.* (2009) **Untreated greywater** **1 Experimental site** **8 weeks** **Canada**	**Christova-Boal *et al.* (1996)** **Laundry greywater** **4 Experimental sites** **2 years** **Australia**	**Gross *et al.* (2005)** **Untreated greywater** **1 Household** **Samples collected biweekly for 9 months** **Israeli**	**Ghunmi *et al.* (2008)** **Laundry samples** **6 Households** **4 months** **Jordan**
Temperature (°C)	–	25	–	35
pH	6.7–7.6	9.3–10	6.7 ± 0.1	9.6
Electrical conductivity (μS/cm)	–	190–1,400	1.4	4.54
BOD (mg/l)	–	48–290	270 ± 60	1,266
Phosphorus (mg/l)	0.24–1.02	0.062–42	17.7 ± 5.1	–
Potassium (mg/l)	2.2–2.5	1.1–17	–	10
Magnesium (mg/l)	8.0–9.9	1.1–2.9	–	31
Chloride (mg/l)	–	9.0–88	–	300
Sodium absorption ratio	4.2–5.8	–	4.8	6
Carbonate Alkalinity (mg/l)	–	83–200	–	
Sodium (mg/l)	20–27	49–480	–	220
Calcium (mg/l)	30–44	3.9–12	–	50
Boron (mg/l)	–	–	0.6 ± 0.2	–
NH_4–N (mg/l)	1.2–6.2	–	–	–
Iron (mg/l)	0.09	0.29–1		–
Manganese (mg/l)	ND	1.1–2.9		–
Fecal coliform (CFU/100 ml)	4.7×10^4–8.3×10^5	110–3.3×10^3	$10^6 \pm 10^5$	–

Note: ND, not detected.

Laundry greywater consists of detergents, bleach, oil, and non-biodegradable fiber from clothing (Shaikh & Ahammed, 2020). Further, high levels of dissolved solids in laundry greywater cause high electric conductivity and turbidity (Oteng-Peprah *et al.*, 2018). While high levels of metals and phosphate (PO_4) can be present (Nolde, 2000), nitrogen is usually lacking in greywater (Couto *et al.*, 2015). Sodium (Na), PO_4, and aluminum levels can also be high in greywater from laundry (Christova-Boal *et al.*, 1996). Additionally, various organic carbon pollutants can be present in greywater, such as total organic carbon (TOC) and biochemical oxygen demand (BOD) (Hernández Leal *et al.*, 2007; Noutsopoulos *et al.*, 2018).

Sample sizes used to assess water quality characteristics in previous studies have been small and the variability of data is high, limiting their generalizability and indicating that larger sample sizes are needed. The quality of greywater also depends upon household detergent use, the number of family members, and household practices (Eriksson *et al.*, 2002; Mohamed *et al.*, 2013; Spychała *et al.*, 2019).

L2L systems are not widespread in Santa Clara County (SCC), California. One estimate of the total number of households with greywater systems installed in the last 5 years is 138 households (Wu *et al.*, 2021). However, because permits are not required for such systems, there may be considerable data gaps regarding understanding the scale and scope of such systems (Kehoe & Rhodes, 2013). Lack of education (Gross *et al.*, 2015) and a lack of resident involvement in water reuse policy decisions (Hurlimann & Dolnicar, 2010) are both barriers to L2L adoption. New conservation plans and ordinances encourage municipalities and some cities to have pre-plumbed greywater systems on all new construction single-family homes for water reuse (Wu *et al.*, 2021). Studying systems' compliance with codes when they are built is critical, since once the systems are installed, it becomes harder to implement new rules on existing systems (Gross *et al.*, 2015).

The objectives of this study were to ascertain the following: What are the ages of L2L greywater systems? To what extent do existing L2L greywater reuse systems in SCC comply with California Plumbing Code? What types of vegetation are being irrigated by residential greywater systems? What is the range of FC in greywater, and is it within levels of recommended use? What are the physical and chemical qualities of residential greywater, and how do these values compare to accepted criteria for reuse?

METHODS

For this research, SCC, the sixth most populated county in California, was the study site. ValleyWater, Santa Clara Valley's wholesaler, offered a rebate for installing laundry greywater and a direct installation program for customers installing greywater systems along with a rebate for replacing turf grass with climate-appropriate or drought-tolerant plants (Wu *et al.*, 2021). Households with L2L greywater systems in SCC, California (Figure 2) were included in the study.

Study design and data collection methods

To assess the policy, we reviewed and summarized existing ordinances and regulations pertaining to L2L greywater systems in SCC. Since greywater quality largely depends on household resident behavior, product choices, and source water quality (Eriksson *et al.*, 2002), obtaining an adequate study sample size was essential to achieve the desired representativeness of findings, to understand greywater system properties, landscape associations, and water quality. The goal of this study was to sample 30 households with L2L systems. To identify enough households, this study adopted snowball sampling. Valley Water, the county's wholesale water management agency, and the non-profit organization Ecology Action helped researchers locate the households that had installed greywater systems. All homeowners and sample collectors signed a release statement agreeing that no change would be made to the existing system during the sample collection. As a gesture of gratitude for permitting the research, homeowners were notified of their greywater quality results, if they were interested.

Fig. 2 | SCC with sampling locations. *Source:* County of Santa Clara (2016).

Between September and December 2019, samples of greywater were collected, and laundry detergent types and the plants irrigated directly by greywater were recorded at 30 sites. The system's compliance with relevant state plumbing codes was also recorded (CBSC, 2016). The type of landscape vegetation and landscape photographs were taken for each site, and major plant types were categorized as perennial or annual, native or non-native, and edible/non-edible based on the work of Costello & Jones (2014).

Greywater sampling

Each household was visited once during sampling in the morning; these households used only laundry greywater to irrigate their crops. The temperature was recorded from the first greywater outlet at the site after the remaining greywater was pushed out by the first cycle. In the laundry, the wash cycle is usually the dirtiest and the rinse cycle the cleanest, so samples were collected from both wash and rinse cycles and mixed in one container (Misra & Sivongxay, 2009). The container was rinsed with greywater during sample collection and then filled as a general precaution. For greywater samples, households were asked to have their usual dirty laundry wash and samples were collected preferably from the first outlet of greywater in the landscape. Laundry greywater samples were collected using a 150-ml sterile container for collecting FC samples and a 1-l container for samples for other characteristics of greywater. All samples were labeled and logged in a field logbook with the date and time of collection.

Greywater samples were refrigerated and taken to the Control Laboratory in Watsonville, California, within 2–3 h of sampling collection. Control Laboratory performed analyses based on Eaton *et al*. (1995) for the following parameters: pH, EC, sodium adsorption ratio (SAR), nitrogen, Na, calcium (Ca), FC, magnesium (Mg), potassium (K), chlorine (Cl), total dissolved solids (TDS), NO_3 (as nitrate), phosphorus, carbonate CO_3 as ($CaCO_3$), bicarbonate HCO_3 as (HCO_3), TOC, BOD, iron (Fe), manganese (Mn), boron (B), and sulfate (SO_4).

Data analysis

T-tests conducted using IBM SPSS Statistics (Version 25) were used to analyse whether there was a difference between young systems (0–2 years) and older systems (>2 years) and code-compliant versus non-code-compliant systems. Data collected from the study's residential systems were compared to greywater quality values from previous related literature and wastewater reuse guidelines developed by the Food and Agriculture Organization of the United Nations (FAO, 1985).

RESULTS AND DISCUSSION

The findings from this study shed light on the performance and compliance of existing residential laundry-to-landscape (L2L) greywater systems in SCC, California. This includes an assessment of the diversity of irrigated vegetation, the presence of FC, and the overall quality of the greywater. These findings contribute to a deeper understanding of greywater reuse practices within SCC and hold relevance for policymakers, water management agencies, and homeowners seeking to implement effective greywater systems.

Greywater delivery, hardware, and operations

Most of the greywater systems were installed recently; 20 of the 30 residences (66%) had greywater systems installed in the last 2 years, and the rest of the designs were more than 2 years old; the oldest system was installed in 1995 (Table 2). Most of the systems were also based on California plumbing codes or code-compliant systems.

Type of vegetation and landscape

One of the essential objectives of this research was to identify plants irrigated with greywater. Generally, system owners although they might have added one or two plants, they did not alter the entire landscape significantly. Most of the plants irrigated by greywater were perennial and mostly drought-tolerant, and about half (51%), including herbs, native plants, and fruit trees, were edible. Additionally, 59% of the plants irrigated by greywater were drought-tolerant. The plants irrigated by greywater included a wide variety of fruit trees, rose bushes, native plants, trees, and turfgrass (Figure 3).

Table 2 | Characteristics of greywater systems in SCC.

Code-compliance	Code characteristic	No. of houses	Comment
Code-compliant	a – subsurface irrigation	23	Since they were installed recently, they mainly were code-compliant.
	b – applied to non-consumable trees and bushes	9	Most of the households were using greywater to irrigate edible plants.
	c – Mulch basin	15	Although many households had recently installed greywater systems, not all had a mulch basin around the outlet.
Non-code-compliant	a –stored greywater	2	Greywater was stored in tanks.
	b –surface irrigation	5	Greywater was either irrigated by a hose or water running through the soil's surface.
	Non-functioning system	1	In one of the households, the greywater system was not working. This household was removed from the study.

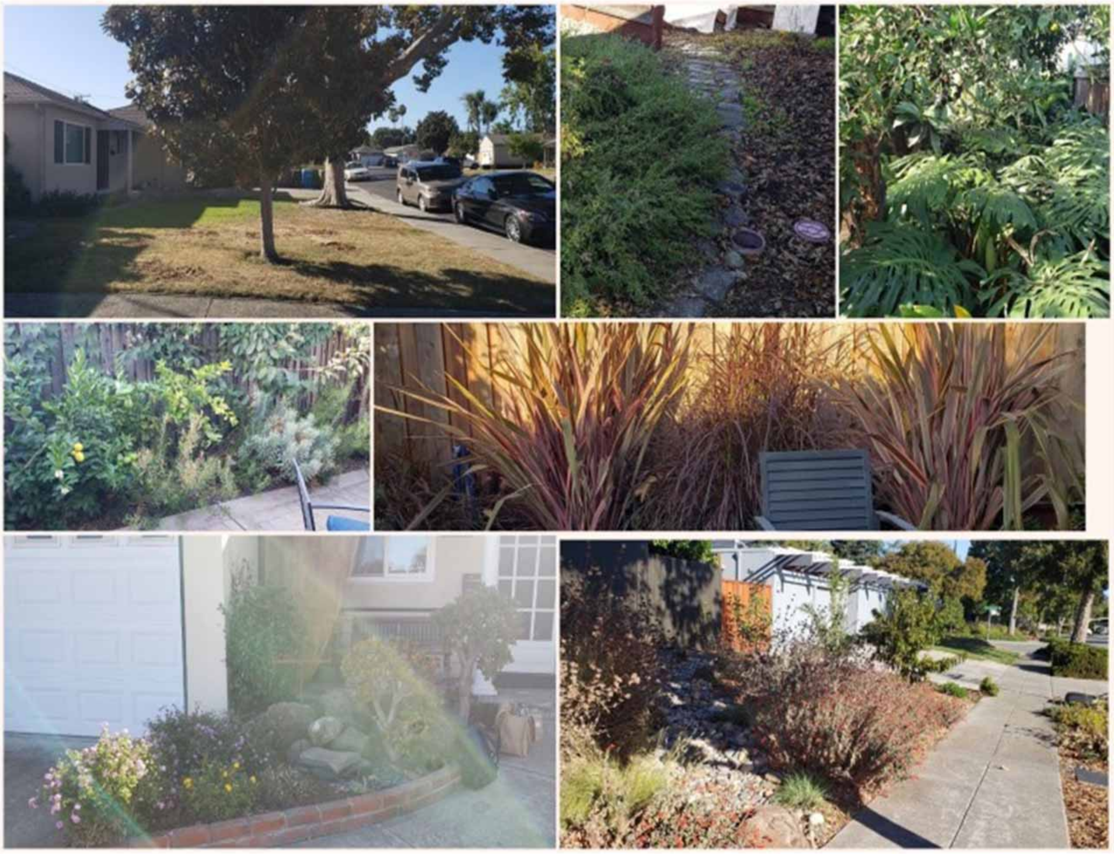


Fig. 3 | Vegetation landscapes irrigated by greywater.

Nearly 45% of the plants in L2L landscapes were shrubs (Table 3). After installing the L2L greywater system, most households retained their original landscape and plant composition without replacing them with plants more compatible with greywater.

Table 3 | Plant types.

Type of Plant	Number of Households	Number of Plants Per Instance	Edible		Native		Drought-Tolerant	
			Yes	No	Yes	No	Yes	No
Trees	26	42	27	15	10	32	14	28
Bushes, shrubs, and vines	29	50	19	31	14	26	40	10
Turf, ground cover, and grass	5	5		5		5		5
Herbs, vegetables, and annuals	8	8	8		2	6	3	5
Unknown	5	5						

Raw greywater can potentially affect plants with phytotoxicity, affecting leaf and flower appearance and growth (Wiel-Shafran *et al*., 2006; Reichman & Wightwick, 2013). Plants also can experience increased levels of several micronutrients and metals (Reichman & Wightwick, 2013). In a study by Alfiya *et al*. (2012), ryegrass growth did not change based on different greywater irrigation or tap water sources. However, Misra *et al*. (2010) observed an increase in the biomass of tomatoes in plants irrigated with greywater. As for non-edible plants, greywater is suggested as an alternative to potable water to irrigate green façades (Chung *et al*., 2021). In our study, we saw a pomegranate tree not responding to over-irrigation with greywater. However, we found no visible damage in the rest of the plants in this study. This suggests that plants can respond differently to irrigation with greywater based on plant and soil conditions. In addition, because of the macronutrients, greywater can act as a fertilizer (Kariuki *et al*., 2012). There are two main reasons why no signs of phytotoxicity were observed in plants irrigated with greywater in SCC. Firstly, most systems were relatively new, and plants may exhibit phytotoxicity symptoms at a later stage. Secondly, many households use biodegradable laundry detergents.

Inorganic and organic characteristics of greywater

Microbial, physical, and chemical characteristics of the greywater collected during the study are presented in Table 4 (Khosrowshahi Asl 2023). These characteristics were compared to previous studies' findings and to the acceptable use range for recycled irrigation water that undergoes centralized treatment.

The following sections provide the additional context for understanding the values found for key parameters.

Microbial characteristics

In this study, FC was the main microbial characteristic studied because of its importance as an indicator of bacteria. Previous research showed a high level of FC in greywater produced by families with small children 10^6 cfu/100 ml (Rose *et al*., 1991). This study's results ranged from 2 to 110,000 mpn/100 ml ($M = 4{,}421$ mpn/100 ml, SD = 21,123; Figure 4); 41% of samples were within the range reported in previous studies, and the rest were lower than those recorded in previous studies.

However, according to FAO (1985) guidelines, the acceptable range of FC for the irrigation is less than 1,000 CFU/100 ml (CFU/100 is equivalent to mpn/100), and less than 200 CFU/100 ml in the case of irrigating edible plants or public places. Given the 1,000 CFU/100 ml recommendation, 88.89% of the sample fell within this range; however, under the stricter guideline of 200 CFU/100 ml, 81.48% of the samples fell within the range. One of the data points – 110,000 mpn/100 ml – could have resulted from the presence of dog feces, which were visible around the greywater outlet for one residence. In this case, discharge at the system outlet generated surface runoff, meaning this household was not considered code-compliant. It was challenging to collect a water sample not mixed with other materials surrounding the outlet. Household practices and having younger children are also associated with FC levels (Rose *et al*., 1991).

The second-highest value for fecal coliforms was 5,000 mpn/100 ml. In this case, the household system was not code-compliant because it stored greywater for more than 24 h. This system was built in 1998 when no permit L2L system guidance was present in state plumbing codes. The state code did not happen until 2009. One of the reasons code-compliance calls for subsurface irrigation is to avoid FC contamination to any above-surface part of edible plants (FAO, 2017). To further clarify, the California Water Board's position is that irrigating with water that has FC levels of less than 2.2 mpn per 100 ml is safe for human contact.

Independent sample *t*-tests were conducted on code-compliant vs non-code-compliant greywater systems. Mean FC rates differed between the code-compliant and non-code-compliant systems [$t\,(25) = -2.470, p < 0.05$; Figure 5].

This difference can be explained by storing greywater, contributing to bacteria growth. The level of FC was much lower than in previous studies, contradicting the findings of Friedler (2004). More study needs to be

Table 4 | Ranges of greywater quality, previous research, and accepted irrigation water quality.

Characteristic[a]	Unit	*N*	Study sample range	Previous research[a]	Range in recycled irrigation water standards[b]
Temperature	°C	24	15.6–35.2		
pH		30	6.27–9.38	7.5–10	6.5–8.4
EC	μS/cm	30	7.8–107.3	190–1,400	70–300
TDS	mg/l	30	50.7–697.45	603.3	0–2,000
TOC	mg/l	30	2.08–448	100–811	
BOD	mg/l	14	34–975	48–1,266	0–30
Phosphate (PO_4^{3-})	mg/l	30	0.18–15.78	9	0–6.13
Potassium (K)	mg/l	30	1.47–28.55	1.1–23	0–2
Magnesium (Mg)	mg/l	30	0.78–48.95	1.1–61	0–5
Chloride (Cl)	mg/l	30	5.25–133.25	300–450	4–10
SAR		*30*	0.31–8.77	6–15.25	
Carbonate Alkalinity (CO_3)	mg/l	30	0–12		0–0.3
Bicarbonate Alkalinity (HCO_3)	mg/l	30	0–63.4		0–610.2
Sodium (Na)	mg/l	30	6.11–180.9	220–667	3–9
Calcium (Ca)	mg/l	30	5.18–82.3	19–50	0–20
Boron (B)	mg/l	30	0.014–5.11	0.4	0–3.0
Sulfate (SO_4)	mg/l	30	1.74–90.16		0–960
Nitrate (NO_3)	mg/l	30	0–63.4		0–44.27
Iron (Fe)	mg/l	30	0.03–6.28		0–5
Manganese (Mn)	mg/l	30	0.0004–0.26	0.4	0–0.2
Cations	Meq/l	30	0.81–11.91	–	–
Anions	Meq/l	30	0.81–10.86	–	–
FC	mpn/l	27	2–110,000	$110–4 \times 10^6$	0–1,000

[a]Christova-Boal *et al*. (1996), Gross *et al*. (2005), Howard *et al*. (2005), Jamrah *et al*. (2006), Wiel-Shafran *et al*. (2006) and Kariuki *et al*. (2012).
[b]FAO (1985), ANZECC & ARMCANZ (2000) and EPA (2013).

done on the fate of microbial pollutants in plants (Benami *et al*., 2016), although there is no difference in illnesses between households using greywater or potable water (O'Toole *et al*., 2012; Busgang *et al*., 2015). However, it is recommended greywater installers and policy makers educate homeowners on minimum exposure to greywater.

Physical characteristics

One of the essential physical characteristics of greywater is temperature. While doing laundry, it is recommended that the clothes washing machines linked to L2L systems be run at cooler temperatures (e.g., lower than 30 °C). Higher temperatures can lead to bacterial growth (Gross *et al*., 2015). This variable is highly dependent on the temperature households set for their washing machines (e.g., hot, cold) and the distance from the washing machine to the first outlet point outside the house. The recorded temperatures for this study's greywater systems ranged from 15.6 to 35.2 °C (SD = 6.07; Figure 6). The reported temperature range in previous literature was similar, at 18–35 °C (Oteng-Peprah *et al*., 2018). Of the 24 data points for temperature, 83.3% fell within the previous study's range. In 79.17% of the samples, the temperature was lower than 30 °C (Figure 6).

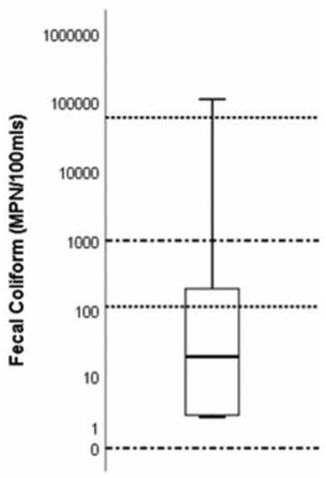


Fig. 4 | Fecal coliform. ------ The acceptable range for reuse of wastewater prescribed by FAO and – · – · the range of greywater from previous studies.

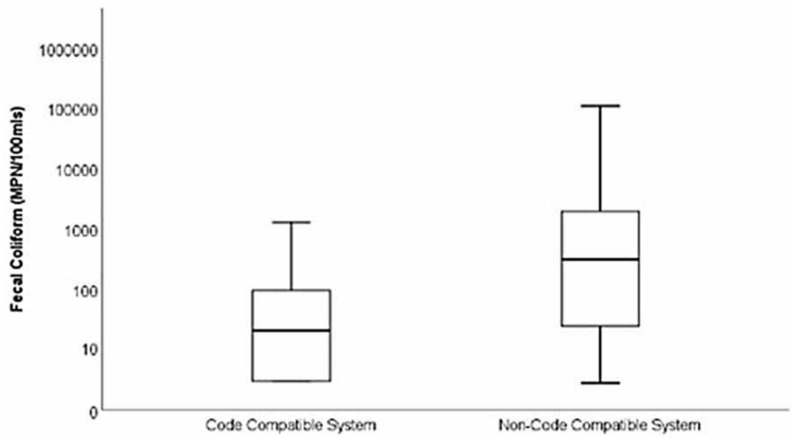


Fig. 5 | Effects of code-compliance on fecal coliform in greywater.

Chemical characteristics

The chemical characteristics of greywater and its ranges as shown in Table 4 are explained as follows.

pH

pH is used to measure alkalinity or acidity of greywater; if the pH level is abnormal, more evaluation needs to be done on that source of water, which can cause a nutritional imbalance in soil and, therefore, plants. The range of the pH for study samples was 6.27–9.38 ($M = 7.48$, $SD = 0.529$; Figure 7). This is a lower pH value than the maximum of 9.6 found in previous studies (Ghunmi *et al.*, 2008). In a study by Christova-Boal *et al.* (1996), the pH values for greywater ranged from 9.3 to 10; only one of the data points fell within this range. Of this data set, 43% was lower than 7.5, the minimum found in previous research. On the other hand, when study pH values

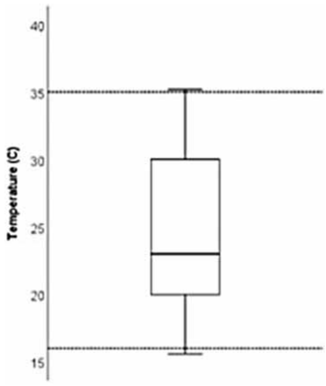


Fig. 6 | Temperature taken at the source.

were compared to the accepted range for wastewater reuse, which is 6.5–8.4 (FAO, 2017), 93.33% of the data fell within the accepted range, with only 2 out of 30 data points falling outside the recommended range. The results of this research suggest that the potable water supplied at home could have influenced the average pH value of the sample and that it was slightly higher than neutral because of the ingredients present in the laundry detergents (Christova-Boal *et al.*, 1996; Roesner *et al.*, 2006; Mohamed *et al.*, 2014).

Electrical conductivity

EC is one of the common methods for measuring salinity in irrigation water. The range of EC in the study samples was 7.8–107.3 μs/cm ($M = 58.36$ μs/cm, SD = 26.76) as shown in Figure 7. Christova-Boal *et al.* (1996) suggested a recommended range of 190–1,400 μs/cm for the EC of laundry greywater. The maximum level for EC of earlier studies is 1,400, removed for better visualization in Figure 7. The data for this study show an EC level that was much lower than in previous research. According to FAO (2017), water reuse is not recommended when the salinity is higher than 300 μs/cm. If the salinity is lower than 70 μs/cm, no restrictions are needed, and slight to moderate restrictions are necessary if salinity is between 70 and 300 μs/cm. Using this classification rubric, no L2L systems studies required strict irrigation restrictions for the use of their greywater. The EC level for 66% of systems meets no restrictions category, and 34% of the systems fell into the slight to moderate restrictions. The generally low levels of EC for the systems studied indicate that the detergents used contained low quantities of salt.

Sodium adsorption ratio

SAR affects the infiltration of the soil. The range of the SAR was 0.31–8.77 ($M = 2.22$, SD = 1.95; Figure 7). The range of the SAR for previous studies was 6–15.25 (Misra & Sivongxay, 2009; Mohamed *et al.*, 2014; Gross *et al.*, 2015). The SAR value in this study was much lower than in previous studies. Only 7% of the data fell in this category, and the rest were lower than this. According to FAO (2017), the SAR and EC need to be compared to see whether the wastewater is suitable for reuse since it can affect the soil's infiltration rate. Table 5 includes the SAR and EC values; FAO's acceptable range for SAR is not included in Figure 7. Based on the data measured in SCC, 86.67% of the samples fell in the category of zero to moderate restriction on use, and in the case of moderate restriction, only slightly more care or filtration needed to be applied to the greywater; 13.34% of the data fell in the category of severe restriction on use, potentially affecting the infiltration rate of the soil over time, resulting in plants not having enough water. Although our samples have low Na levels, we must mention that high calcium levels in SCC's potable water (SCVWD, 2019) can also cause low SAR.

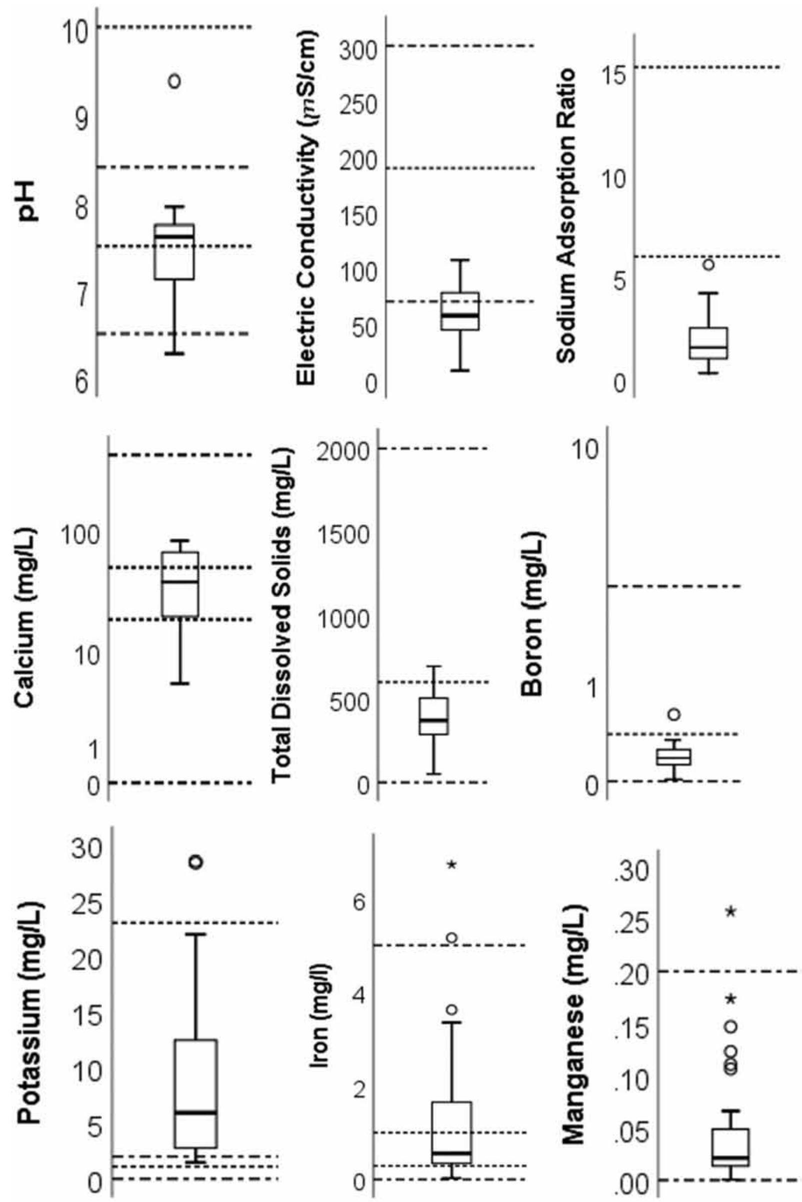


Fig. 7 | Range of chemical characteristics of greywater in SCC. *Note:* ------ The acceptable range for reuse of wastewater is prescribed by FAO and – · – · the range of greywater from previous studies.

Total dissolved solids

According to FAO (2017), if the TDS is lower than 450 mg/l, no restrictions on irrigation applications are needed. 70% of this study's samples were lower than 450 mg/l. The FAO recommends slight to moderate irrigation restrictions if TDS levels are between 450 and 2,000 mg/l. Two of the maximum TDS encountered in this study's sample population were 697 and 670 mg/l. In one of the cases, the system was not code-compliant, and a hose was used

Table 5 | Sodium adsorption ratio and electrical conductivity.

Sodium adsorption ratio and electrical conductivity SAR	EC (dS/m)	Degree of restriction on the reuse of wastewater (greywater)	Percentage of Santa Clara Valley's greywater data in this category
0–3	>0.7	No restriction	26.67
	0.7–0.2	Slight to moderate restriction	43.33
	<0.2	Severe restriction on use	13.33
3–6	>1.2	No restriction	–
	1.2–0.3	Slight to moderate restriction	10%
	<0.3	Severe restriction	–
6–12	>1.9	No restriction	–
	1.9–0.5	Slight to moderate restriction	6.67
	<0.5	Severe restriction	–
12–20	>2.9	No restriction	–
	2.9–1.3	Slight to moderate restriction	–
	<1.3	Severe restriction	–

FAO (1985).

to irrigate greywater. Four dogs were seen during data collection, which makes sampling location very difficult. In another case, although the system looked code-compliant, it was not installed correctly, and greywater would reach the soil directly with a small quantity of runoff. For this case, the L2L system did not have a mulch basin, which can affect soil quality over time. Mulch basins surrounding greywater outlets serve as filters. They also help spread the greywater and reduce the risk of pooling/surfacing greywater. TDS values of more than 2,000 mg/l indicate severe irrigation restrictions are needed. Three of the 30 samples in this study (10%) were between 600 and 700 mg/l, and none of the three systems were code-compliant. As shown in Figure 7, TDS has one data point of earlier studies.

Boron

B can affect plant health and is of concern in greywater. In this study, the range of B was 0.01387–5.106 mg/l ($M = 0.55$ mg/l, SD = 1.22; Figure 7). There is a lack of information on the impact of B on the quality of laundry greywater. As shown in Figure 7, the acceptable range for wastewater reuse for irrigation is 0–3 mg/l, and 93.33% of our data points fell in that range. The findings of FAO (2017) were more specific and indicated no need for restrictions if the measure of B is less than 0.7 mg/l. In the study, 90% of the data points were smaller than 0.7 mg/l, and the value of one data point was 1.754 mg/l (i.e., between the 0.7 and 3 mg/l value), which can be interpreted as falling into the slight to moderate irrigation restriction category. For this household, the greywater was stored in a tank and was thus non-code-compliant. Water samples from two systems had B concentrations higher than three mg/l. For one of the households, system owners mentioned having used bleach in their previous cycle, which could explain the high B content. It is recommended to switch to the sewer when using bleach. Excess B can cause toxicity in soil, which is difficult to solve (Brdar-Jokanović, 2020). In addition, most plants are sensitive to B (Khajvand *et al.*, 2022), causing plants to look and causing a decrease in plant growth (Gross *et al*., 2005). Therefore, to avoid any damage to the soil and plants, it is essential to use detergents considered compatible with greywater. Also, if the pH of the greywater is higher than 8.0, the availability of B will be reduced (Turner *et al*., 2013). In our study, only one data point has a pH above 8. However, the level of B in greywater in the same household is 0.17.

Potassium

The range of K in this study was 1.47–28.55 mg/l (M = 8.73 mg/l, SD = 7.53; Figure 7). Previous research shows a range of 1.10–23.00 mg/l (Christova-Boal *et al*., 1996; Ghunmi *et al*., 2008; Gross *et al*., 2015). In this study, 93.33% of greywater samples had K concentration values that fell within this range. FAO (1985) reported the recommended range for K in irrigation water as 0–2 mg/l; 87% of samples had values above 2 mg/l. K is often present in laundry detergents (Chan *et al*., 2014; Mohamed *et al*., 2018). The University of Southern Queensland reported that K measurement in the greywater ranged between 2.6 and 10.2, with no significant increase in K uptake in plants irrigated with greywater. Front-load washing machines had lower K than top-load ones (Howard *et al*., 2005). Although K can act as a nutrient for plants, more studies are required to ascertain the cause for the excess K in laundry greywater in SCC and examine its impact on plants. It should also be noted that the concentration of K in drinking water in SCC ranges from 4.2 to 5.9, which can affect our results (Saini, 2019).

Sodium

The range of Na in this study was between 6.114 and 180.9 mg/l ($M = 58.14$ mg/l, SD = 40.742), compared to 49–667 mg/l in previous studies. In the study, 43.33% of the sample values fell in this range, and the rest of the data were lower than 49 mg/l (which was the minimum Na range reported in previous studies). The acceptable range of Na concentration to be used for irrigation is 0–207 mg/l (FAO, 2017). Plant-friendly detergents in which the concentration of salt and B is low are recommended for greywater irrigation systems (Allen, 2015). The high value in our study belonged to a system that was not code-compliant. Although the second household was code-compliant, it used a water softener, which uses Na-based salts. The third household had been undergoing major backyard landscaping, with its greywater pipes and outlets filled with soil, which might have caused the increase in Na content.

Chlorine

The range of Cl in this study was 5.248–133.252 mg/l ($M = 56.37$ mg/l, SD = 34.613), while it was 300–450 and 9–88 mg/l in the studies by Christova-Boal *et al*. (1996) and Gross *et al*. (2015), respectively. The range of study data is much lower than the 300–450 mg/l range, and 73.33% of study data were within the range reported by Christova-Boal *et al*. (1996). If the chloride concentration is lower than 4 me/l (140 mg/l), there is no need for restrictions on greywater use. However, slight to moderate restrictions are needed if the chloride level is between 4 and 10 me/l (FAO, 2017). The data in this study revealed no need for restriction on greywater use; therefore, all the data fell in the no restriction category.

Iron

High values of Fe can reach groundwater through leaching, causing environmental risks (ANZECC & ARMCANZ, 2000). The range of Fe in this study was 0.02708–6.727 mg/l ($M = 1.26$ mg/l, SD = 1.58; Figure 7), while Fe was reported in previous studies between 0.29 and 1.0 mg/l (Christova-Boal *et al*., 1996). Only 40% of our study data fell in this range. According to FAO (2017), the maximum recommended concentration of Fe is 5 mg/l. In our study, 93.33% of the data fell in this category. As for the maximum range for this data set (6.7), there is no apparent reason why these data were high. In the case of the second-highest data point, the greywater system was not code-compliant, and the plants were watered through a hose. However, it is not obvious why a hose might cause a high quantity of Fe in greywater. The third highest data set was not code-compliant either, and the greywater could spread through the soil's surface. Because of the age of the households, the pipes might have been made of galvanized steel or copper, which might explain the high levels of Fe in the greywater samples collected from SCC. Rusty pipes and metal pollutants in laundry detergents can contribute to high levels of metals in greywater (Halip Khalid *et al.*, 2014). High Fe levels can cause soil acidification and lower the availability of nutrients such as phosphorus for the plants (FAO, 2017). In a similar study, although Fe levels were acceptable by irrigation reuse, a high level of metals such as Fe was seen in laundry greywater (Kariuki *et al.*, 2012) emphasizing the study of the source of metals in laundry greywater.

Carbonate and bicarbonate

The carbonate (CO_3) value was 0 in 29 households and 12 in one household. Therefore, the range of CO_3 in greywater was 0–12 mg/l ($M = 0.4$ mg/l, SD = 2.2). The range of bicarbonate (HCO_3) in the measured data was 31.62–381.518 mg/l ($M = 194.91$ mg/l, SD = 104.18). Not enough research has been conducted on the quality of greywater and the range of bicarbonate to find comparable data. According to FAO (2017), acceptable irrigation water reuse ranges from 0 to 518.5 mg/l, and all study data fell within this category. In a study comparing different greywater sources' quality, laundry samples were the most alkaline, suggesting laundry greywater has buffering action (Shamim, 2022).

Nitrate

Nitrogen (NO_3) acts as a plant nutrient and can help plant growth; however, it can affect sensitive crops if the range is higher than 44 mg/l (Ayers & Westcot, 1985). The range of NO_3 in greywater in this study was 0–63.44 mg/l ($M = 6.32$ mg/l, SD = 12.19), while the range reported in previous studies was much lower at 0.10–0.6 mg/l (Christova-Boal *et al.*, 1996; Li *et al.*, 2009). Only 20% of study data fell in this category. According to FAO (1985), the usual range of NO_3 in irrigation water is 0–44 mg/l; 96.67% of study data fell into this category. Except for one outlier in the study data, the rest of the data fell in the 0–20 mg/l range.

Phosphate

The range of PO_4 in this study was 0.181–15.787 mg/l (M = 2.82 mg/l, SD = 3.28), while it was 0.186–179 mg/l in previous studies (Christova-Boal *et al.*, 1996; Friedler, 2004); 96.67% of the measured data fell within this range. According to FAO (1985), the usual range for wastewater reuse for phosphate-phosphorus (PO_4-P) is 0–6.13 mg/l. In our study, 90% of the data fell within this range. Valley water recommends that PO_4-free detergents be used, which could be the reason for the low PO_4 content in the greywater in the County, compared to previous research.

TOC and BOD

The range of the TOC in this study was 2.08–448 mg/l ($M = 107.96$, SD = 120.7). A notable decrease compared to the preceding study where TOC was 100–811 mg/l (Table 4). Only 36.67% of the present study's data fell within the range of the previous studies, suggesting that the majority of the observed values were lower.

The range of BOD in the present study was 34–975 mg/l ($M = 329.55$ mg/l, SD = 261.84), which contrasts with a prior range of 48–1,266 mg/l reported in previous research. A case study at Jordan University noted a BOD of 1,266 mg/l, necessitating treatment before the greywater could be reused (Ghunmi *et al.*, 2008). However, based on the recommendation for reusing reclaimed water for edible plants, the BOD needs to be less than 10 mg/l, and in the case of non-edible plants, less than 30 mg/l (EPA, 2013). However, none of the study data points fell into this category. Laundry detergents, a common source of chemicals in greywater, may elevate the BOD levels

(Ghaitidak & Yadav, 2013), with surfactants and xenobiotic compounds contributing to 40% of the organic matter present (Delhiraja & Philip, 2020; Khalil & Liu, 2021). Additionally, aerobic bacteria originating from sweat and other body fluids present in the laundry greywater can cause higher BOD levels (Shamim, 2022). Although the study of surfactants was outside this study's scope, removing pollutants is essential. More research needs to be conducted on the BOD and TOC of greywater to better understand its environmental impact.

In our field assessment, we observed that the majority of greywater systems in SCC were recently installed and were based on California plumbing codes (CBSC, 2016). Our study also revealed that most households did not significantly alter their existing landscape compositions when implementing greywater systems. Instead, they incorporated greywater irrigation into their current plant arrangements, with a preference for perennial, drought-tolerant and edible plants. This aligns with the principles of water-wise landscaping and highlights the potential for integrating greywater reuse with sustainable landscaping practices with regard to local plumbing codes. Our analysis of greywater quality parameters provided valuable insights into the suitability of laundry greywater for irrigation purposes. The levels of FC in the greywater samples varied among households, but overall, 88.89% of the samples fell within the acceptable range for wastewater reuse for irrigation. The highest FC values were associated with systems that were not code-compliant. Also, these systems store greywater or have greywater run on the ground with children and pets around the outlet. These results were aligned with the findings of Delhiraja & Philip (2020), emphasizing the importance of education on greywater hygiene practices, proper system design, operation, and maintenance to minimize potential health risks associated with microbial contamination.

Chemical characteristics of greywater for EC, TDS, TOC, Mg, Cl, SAR, Na, Mg, PO_4^{3-}, B were mostly within acceptable limits for irrigation purposes and were comparatively lower than previous studies (Christova-Boal *et al.*, 1996; Gross *et al.*, 2005; Kariuki *et al.*, 2012). Out of our sampling size, only two cases showed Na values outside the acceptable ranges. One of the systems was not code-compliant, resulting in higher levels of Na. Although the other system was installed based on California plumbing codes, they still had high levels of Na which were due to using water softener with Na-based salts. High Na values can negatively affect plant and soil health, emphasizing the change of Na-based salt to more compatible salts with greywater. We observed elevated levels of certain parameters, such as K, Fe, and calcium, in some samples. Further analysis is required to understand the high levels of these parameters. However, we believe that the observed high values of calcium could be related to the high levels of hardness in SCC potable water (Saini, 2019).

Despite having the largest known sample size for such research, the total number of SCC households with laundry-to-landscape (L2L) systems remains unknown. While our findings are insightful, they may not fully generalize to other regions or populations. Additionally, the high variability in household landscape conditions, including presence of pets, chickens, and children, could have influenced the greywater sample results. Future large-scale studies should further investigate the long-term impacts of greywater irrigation on plant health, soil quality, and ecosystem dynamics. Policymakers and water agencies should uphold codes and regulations for greywater reuse, system design, maintenance, and use of eco-friendly detergents to optimize greywater quality and mitigate risks. Cooperation among stakeholders, including homeowners, researchers, and agencies, is vital for advancing the adoption of greywater systems.

CONCLUSION AND POLICY IMPLICATIONS

This research provides valuable insights into the functioning and quality of laundry greywater systems in SCC. The study reveals that 83% of the greywater systems in this study population were compatible with California codes, with most of the systems recently installed, indicating a growing trend toward sustainable water practices in the region. We observed that system owners who use greywater generally do not change their landscape after installing a greywater system. In addition, most of the plants irrigated by greywater were perennial, with 59% being drought-tolerant and 51% of the plants recorded being edible. Our analysis of greywater characteristics showed that among the 21 characteristics studied, most values fell into the acceptable range for wastewater reuse based on recommendations from the Food and Agriculture Organization and previous literature. pH values were slightly alkaline but within an acceptable range. EC levels were low, indicating low salinity, which is beneficial for plant growth. SAR and TDS values were also within acceptable ranges, suggesting moderate Na content and dissolved substance concentration in the greywater. In most of our samples, the inorganic and organic contaminant concentrations were mostly lower than the accepted ranges reported in the previous studies, except for K, Fe, and calcium. System compliance was associated with FC levels, with non-code-compliant systems having higher levels.

Our study's findings indicate that code-compliant L2L systems in SCC generally work well and do not significantly impact plant health, irrespective of system age. Stakeholders can use our data to emphasize the importance of raising awareness about greywater reuse; promoting proper system maintenance, detergent selection, and plant choices; and actively engaging in education campaigns and training programs. It is worth noting that ongoing monitoring and evaluation of greywater systems are crucial for ensuring long-term performance. To validate and expand upon these findings, further studies should be conducted on a larger sample size, temporal scale, and across diverse locations to assess the long-term effects of greywater irrigation on plant health and soil and groundwater quality. Further research will help policymakers and stakeholders better understand the sustainability of greywater systems and guide future system design and management.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: https://doi.org/10.4211/hs.500448b3a57a485f8ef2197725f602f2.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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