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Growers' irrigation practices, knowledge, trust, and attitudes toward wastewater reuse in Lebanon, Jordan, and Tunisia through a food safety lens

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ABSTRACT

Maximizing water reuse requires addressing legal and regulatory frameworks, but growers' understanding of water as a vehicle for pollutants and safe practices is vital in this process. A cross-sectional survey of 85 growers in Lebanon, Jordan, and Tunisia explored these factors. Results showed that 70.6% of growers had limited knowledge about the transmission of pathogens, pesticides, and pharmaceuticals to food crops via treated wastewater (TWW). Additionally, 55% of farmers used TWW for irrigation, while 65.9% believed that it poses health risks to consumers when applied to crops eaten raw. A positive attitude toward TWW was a determining factor for maximizing water reuse applications. However, the limited access and unavailability of treatment plants were the primary reasons for not using TWW (32.9%). More concerning, less than half controlled the quality of irrigation water using microbiological tests (32.9%), chemical tests (37.6%), and turbidity tests (29.4%). Meanwhile, only 40% trusted local authorities' control of TWW quality and 69.4% had no access to regulatory information. The present study showed the importance of prioritizing growers' awareness of potential risks and establishing the practice of monitoring of water quality indicators and contaminants. These should be at the forefront of water reuse expansion strategies to mitigate associated risks.

Key words: growers' attitudes, irrigation, risk perception, treated wastewater, water pollutants, water reuse

HIGHLIGHTS

- The majority of growers lacked training in good agricultural practices.
- Less than half of the growers monitored the quality of water.
- Only 40% trusted local authorities' control of treated wastewater (TWW) quality.
- For some growers, TWW poses health risks if applied to crops eaten raw.
- Positive attitude toward TWW maximizes water reuse.

1. INTRODUCTION

Water scarcity is a significant global challenge expected to worsen due to climate change, rising temperatures, and drought-related events (Stringer *et al.* 2021). The Middle East and North African (MENA) countries are particularly affected by the shortage of renewable water resources. The growing populations, increased urbanization, uneven rainfall, pollution, and salinization, all compounded by poor governance of water policies and climate changes (Lahn & Shapland 2022), have led to unsustainable water use. There is an estimated withdrawal of more than 80% of available freshwater reserves for agriculture, industry, and urban needs every year (Wael Mualla 2018; WRI 2019; UNICEF 2021).

The availability of the appropriate water quality is vital to achieving food safety, which is essential for food security. While the Gulf countries explore the possibility of Arab food self-sufficiency by investing in countries such as Sudan for crop production (Woertz 2020), some MENA countries have agricultural potentials that rely on water availability and shall benefit from water reuse. Hence, exploring non-conventional water resources and adopting efficient practices in water use for agricultural production, such as the reuse of treated wastewater (TWW), are among the critical solutions to alleviate water scarcity which is essential to achieving food security (Qadir *et al.* 2007).

A crucial requisite for scaling up wastewater reuse is the institutionalization of wastewater management and treatment and the effective implementation of legal frameworks and available technologies. For instance, Jordan implemented an aggressive campaign to rehabilitate and improve wastewater treatment plants (WWTPs) as Jordan's export market was impacted in 1991 when countries in the region restricted imports of fruits and vegetables irrigated with inadequate TWW. Alongside the investments in WWTPs, Jordan has introduced enforceable standards to protect the health of farmers and consumers and enhanced regional and international trade (Molden 2013). Nevertheless, the direct use of TWW is still not widespread in Jordan due to institutional fragmentation that jeopardizes the design and implementation of effective reuse schemes and the existing technical standards, which are particularly relevant when small-scale treatment and reuse schemes are considered (Breulmann *et al.* 2020).

The application of inadequate TWW in agriculture is prevalent in low- and middle-income countries due to lacking infrastructure, technical, and institutional capacity and financing (Qadir *et al.* 2007; WWAP 2017). Moreover, the absence of a binding legal framework could exacerbate such on-farm high-risk practices. For example, although rich in water resources, Lebanon is falling under severe shortages due to mismanagement of water supply and resources and poor coordination among stakeholders responsible for water governance. As a result, some farmers reportedly use the effluents from WWTPs, sewage channels, or polluted rivers to irrigate vegetables posing health risks to consumers (Faour-Klingbeil *et al.* 2016b; Dagher *et al.* 2021).

Wastewater contains macro-and micronutrients, such as nitrogen, phosphorous, potassium, and heavy metals. The accumulation of some toxic elements may have ecological impacts and causes soil structure degradation and salinization (Bartkowiak *et al.* 2017; Alengebawy *et al.* 2021). Moreover, unplanned reuse of wastewater for irrigation is reportedly implicated in foodborne illnesses such as *Ascaris* infections, skin infections, and gastroenteritis in farmers and consumers (Adegoke *et al.* 2018). Additionally, there is a large body of evidence on the presence of a broad spectrum of pathogenic microorganisms and emerging contaminants such as pharmaceutical compounds, microplastics, per-and polyfluoroalkyl substances, antibiotic-resistant genes, and bacteria in fresh produce irrigated with wastewater (Von Sperling & de Lemos Chernicharo 2005; Mojid *et al.* 2010; Adegoke *et al.* 2018; Al-Mashaqbeh *et al.* 2020; Podder *et al.* 2021; Sengupta *et al.* 2021). Hence, several international regulations established microbial quality standards for irrigation water and laid down conditions for water use and reuse, e.g., monitoring frequency of water quality, quality parameters and critical values, and the applicable restrictions concerning the method of irrigation, type of crops, and classes (Alcalde-Sanz & Gawlik 2017; Ritter 2021).

So far, affordable technologies that ensure safe wastewater and a societal capacity and maturity for using these technologies are not adequate in many countries of the MENA region, particularly low- and medium-income countries, to ensure their effective use (Morris *et al.* 2021). To enhance the reuse while minimizing the health risks resulting from human exposure to pathogens in wastewater, the World Health Organization has introduced guidelines for the safe use of wastewater, excreta, and greywater (WHO 2006; FAO & WHO 2021). These guidelines serve as a framework for countries with limited treatment technologies for a risk-based approach in developing national standards and integrating a combination of post-treatment control measures (WHO 2006; FAO & WHO 2021). Nevertheless, a risk-based approach to water reuse entails risk assessments, identification of pathogens, verification of operational systems' effectiveness, and microbial reduction measures to prevent foodborne diseases. These constitute significant challenges particularly in low- and middle-income countries (Drechsel *et al.* 2022), due to the deficit capabilities and capacities for surveillance and detection of hazards and inefficient wastewater treatment (WWT).

Most theories now accept that risk attitudes, perception and their interaction are fundamental determinants behind risk management, the use of specific risk management tools and the predictions of farmers' compliance or responses to policy (Kallas *et al.* 2010). In practice, farmers' awareness of risks is reported to be often low (Qadir *et al.* 2020) and was shown to be a critical challenge that calls for intervention to support the adoption of safe practices (Drechsel *et al.* 2022). Therefore, understanding the farmers' attitudes and perception of risk is key to interventions aiming at on-farm practices for microbial risk mitigation. Still, little is known in the MENA countries about the growers' attitudes toward TWW reuse and practices in the context of food safety and their awareness of waterborne contaminants' impact on food safety and consumers' health. Given the limited information in this area in the MENA region, this study was designed to fill a gap in the literature by shedding light on the local practices and attitudes that may deter or drive safe water reuse in agricultural production. The current study focused on exploring the growers' irrigation practices, knowledge about crop contamination via water reuse, their perception of health risks, attitudes toward TWW reuse for irrigation and local authorities' monitoring and surveillance of water quality. It also examined the association between growers' attitudes and their willingness to apply TWW in agriculture when it is accessible.

The scope of this study was limited to Jordan, Tunisia, and Lebanon, middle-income countries in the Arab region, as they face the challenges of reduced water availability and have socio-cultural similarities. Additionally, their agricultural sectors play a major role in their economies, with fresh produce being a vital component of their international trade.

2. MATERIALS AND METHODS

2.1. Survey design

A structured web-based questionnaire was developed using Google Forms, a survey administration app included in the Google Drive office suite. The questionnaire was based in some of its parts on the good agricultural practices (GAP) audit checklist from the University of Idaho (Kimberly Research & Extension Center 2022) with modifications and additional sections around the wastewater reuse theme. It was designed to be completed as a self-administered online survey tool or by the researchers interviewing the participants and initially prepared in English before creating the digital Arabic version. To ensure the quality of the translation, native Arabic speakers reviewed the Arabic version: the senior author of this study performed a back-translation, and the research group members and other native speakers validated this version.

The questionnaire consists of four sections:

- Section one is on the demographic information and training background.
- Section two on the farm information contained four multiple-choice questions on the type of produce grown and the number of farmers and open questions on the growing area's size and production volume.
- Section three included frequency questions on a five-point Likert scale (1 = Never, 5 = Always) on the water source for irrigation use, multiple-choice questions on the methods of irrigation, reasons for using or not using treated and untreated wastewater, the frequency of monitoring water quality, and farmer's knowledge on contaminants' transmission to crops and the regulatory requirements for wastewater reuse.
- Section four assessed the farmers' attitudes towards using TWW in agriculture through a set of statements on a three-point Likert scale (1 = Disagree, 3 = Agree).

2.2. Pilot study

The survey was piloted to assess readability and length, examine content clarity, and ensure it provided the desired information and valid questions.

Five participants, specialists in agricultural engineering and researchers working in local farming companies and academic institutions, were contacted to participate in the pilot study. All suggested changes were considered. The co-authors also reviewed the survey through periodic meetings to ensure content validity and clarity of the Arabic terminologies. The questionnaire was revised based on the recommendations, and minor adaptations were made.

2.3. Survey procedure and participant recruitment

A sample of farmers and producers ($n = 85$), referred to here in this study as 'growers', was recruited from different regions of Lebanon, Jordan, and Tunisia based on a purposive and convenience sampling approach (Table 1). Although it may not be representative, the sample size is adequate for parametric and non-parametric analysis techniques. The data were collected from November 2021 to February 2022, targeting fresh fruits and vegetable producers from various areas in each country.

A list of growers was obtained from various channels, such as the farmers' associations, the Ministry of Agriculture, and private contacts with the agriculture community. As the field visits were limited due to the pandemic

Table 1 | Demographic characteristics of the sampled population

	Country			
	Lebanon N (%)	Jordan N (%)	Tunisia N (%)	Total N (%)
Gender				
Female	2 (5.6)	0 (0.0)	6 (31.6)	8 (9.4)
Male	34 (94.4)	30 (100.0)	13 (68.4)	77 (90.6)
Total	**36 (42.4)**	**30 (35.3)**	**19 (22.3)**	**85 (100.0)**
Age				
19–24	1 (2.8)	2 (6.7)	1 (5.3)	4 (4.7)
25–34	8 (22.2)	4 (13.3)	2 (10.5)	14 (16.5)
35–44	7 (19.4)	8 (26.7)	2 (10.5)	17 (20.0)
45–54	10 (27.8)	9 (30.0)	6 (31.6)	25 (29.4)
55–64	6 (16.7)	7 (23.3)	4 (21.1)	17 (20.0)
>65	4 (11.1)	0 (0.0)	4 (21.1)	8 (9.4)
Total	**36 (42.4)**	**30 (35.3)**	**19 (22.3)**	**85 (100.0)**
Education Level				
Less than a high school degree	5 (13.9)	9 (30.0)	6 (31.6)	20 (23.5)
A high school degree	6 (16.7)	5 (16.7)	3 (15.8)	14 (16.5)
Vocational/ specialist diploma	2 (5.6)	6 (20.0)	1 (5.3)	9 (10.6)
Bachelor degree	12 (33.3)	8 (26.7)	1 (5.3)	21 (24.7)
Master degree	9 (25.0)	2 (6.7)	5 (26.3)	16 (18.8)
Other	2 (5.6)	0 (0.0)	3 (15.8)	5 (5.9)
Total	**36 (42.4)**	**30 (35.3)**	**19 (22.3)**	**85 (100.0)**
Position				
An employed/paid farmer	1 (2.8)	6 (20.0)	1 (5.3)	8 (9.4)
The landowner/and person in charge	25 (69.4)	13 (43.3)	17 (89.4)	55 (64.7)
Farming company owner/person in charge of the company	8 (22.2)	3 (10.0)	1 (5.3)	12 (14.1)
The contractor	2 (5.6)	8 (26.7)	0 (0.0)	10 (11.8)
Total	**36 (42.4)**	**30 (35.3)**	**19 (22.3)**	**85 (100.0)**
Are you a member of an agricultural cooperative or Farmers association?				
Yes	14 (38.9)	11 (36.7)	12 (63.2)	37 (43.5)
No	22 (61.1)	19 (63.3)	7 (36.8)	48 (56.5)
Total	**36 (42.4)**	**30 (35.3)**	**19 (22.3)**	**85 (100.0)**
Training on GAP (missing = 2)				
Yes	13 (37.1)	6 (20.0)	4 (22.2)	23 (27.1)
No	22 (62.9)	24 (80.0)	14 (77.8)	60 (70.6)
Total	**35 (41.2)**	**30 (35.3)**	**18 (21.2)**	**83 (97.7)**
Number of staff				
Less than 10	21 (58.3)	18 (60.0)	15 (78.9)	54 (63.5)
10–19	9 (25.0)	9 (30.0)	3 (15.8)	21 (24.7)
20–49	2 (5.6)	0 (0.0)	0 (0.0)	2 (2.4)
More than 50	4 (11.1)	3 (10.0)	1 (5.3)	8 (9.4)
Total	**36 (42.4)**	**30 (35.3)**	**19 (22.3)**	**85 (100.0)**

and limited funds to access farms in remote areas, farmers were contacted by phone and invited to complete the online questionnaire through the survey link. The questionnaire link was sent via WhatsApp for those using the app. In the case of farmers with limited access to the internet, when possible, the authors and their teams conducted direct interviews using the printed version of the questionnaire. Subsequently, the data were entered into the digital system.

The first section of the survey displayed the study details, researchers' names and affiliations, and the anonymous collection of data, including the eligibility criteria and the right of participants to discontinue at any time. Screening questions were used to ensure that participants resided or lived in one of the three countries. To continue with the survey, informed consent was obtained from participants through a check to the box 'Agree' required to confirm reading the consent information for participation and that they are above 18 years and residing in Lebanon, Jordan, or Tunisia.

2.4. Statistical analysis

All data were analysed using the Windows version of SPSS 26, Statistical Package for Social Sciences (IBM, Inc, Chicago, IL). Descriptive statistical analysis (frequencies, percentages) was performed to summarize respondents' socio-demographic characteristics and the percentage distribution of their responses.

We used the Kruskal–Wallis to compare categorical and ordinal variables related to farmers' agricultural practices between the countries. In addition, a one-way ANOVA test was employed to compare the mean scores of farmers' attitudes towards wastewater reuse for irrigation between countries.

Somers' Delta (Somers' D), an ordinal alternative to Pearson's correlation coefficient, was used to determine the strength and direction of the association between farmers' attitudes and their willingness to use TWW for irrigation.

Results with a p-value < 0.05 were considered statistically significant.

In addition, a reliability analysis test was performed using Cronbach's alpha to measure the internal consistency of the survey questionnaire. Cronbach's alpha value was 0.761 for the Likert scale variables, indicating an acceptable internal consistency level.

3. RESULTS AND DISCUSSION

3.1. The demographic information and training background

The demographic information and training background of surveyed growers are shown in Table 1. The study recruited 85 growers, 36 from Lebanon, 30 from Jordan, and 19 from Tunisia. Most growers (90.6%) were males, 69.4% aged between 35 and 64 years. Their education levels varied, with 40% having a high school degree or less and 43.5% having a bachelor's or master's degree. The growers were located across the different Lebanese governorates, in the highlands east, Jordan Valleys Zarqa river in Jordan, and from Nabeul and Tunis.

In Lebanon, a third (30.6%) of the participants were located in Mount Lebanon, while 27.8% were in the Bekaa region. Beirut and Chouf region accounted for 8% of the participants, with 11.1 and 13.9% of respondents located in the north and south of the country, respectively. In Jordan, 16.7% of the interviewed growers had farming areas in the highlands east and Jordan valleys, while the majority, more than two-thirds, were located at the Zarqa River. In Tunisia, the growers were primarily concentrated in two climatic contrasted regions: Nabeul in the north had the highest representation, with 52.6% of the growers, while the remaining 47.4% were from Tunis. Indeed, Nabeul is the cradle of the reuse in Tunisia. It is the first area where research studies on the impacts of reuse of TWW in agriculture have been investigated together with the experience of aquifer recharge applied to counterbalance sea water intrusion (P.N.U.D/O.P.E. 1987).

Most growers were the landowners and the person-in-charge (64.7%). Less than half (43.5%) were members of an agricultural cooperative or farmers' association, with the highest proportion observed among the Tunisians (63.2%). In Tunisia, farmers association, so-called GDA (Agricultural Development Group) are local structures in charge of (potable or irrigation) water distribution and ensuring the good governance and transfer of good practices to farmers. As shown in Table 1, more than two-thirds of the surveyed growers (70.6%) did not participate in training on GAP or other similar ones. As for the number of workers on-site, 63.5% of the farms had less than 10 staff, and only 11 and 10% of the Lebanese and Jordanian farms employed more than 50 workers, compared to 5.3% in Tunisia.

3.2. Growing areas, production volume and type of crops

The size of the growing areas varied, with 30.6% less than 2 ha and 47.1% between 2 and 20 ha (Table 2), and for 33% of the surveyed growers, the approximate production volume ranged between 1 and 50 tons. Different types of crops were produced, including fruits (52.9%), leafy vegetables (48.2%), and root vegetables (35.3%), while

Table 2 | The size of the growing areas and production volume of the sampled population

Total sample size ($N = 85$)	Country Lebanon N (%)	Jordan N (%)	Tunisia N (%)	Total N (%)
Size of the growing areas (ha)				
Less than 2	10 (27.8)	8 (26.7)	8 (42.1)	26 (30.6)
2.0–20	12 (33.3)	18 (60.0)	10 (52.6)	40 (47.1)
20.1–100	5 (13.9)	4 (13.4)	0 (0.0)	9 (10.6)
More than 100	4 (11.1)	0 (0.0)	1 (5.3)	5 (5.9)
Total	31 (38.7)	30 (37.5)	19 (23.8)	80 (100.0)
The approximate agricultural production on your farm/s (tonnes) (including all growing areas under your management or ownership)				
Below 1 ton	0 (0.0)	0 (0.0)	1 (5.3)	1 (1.2)
1–50	21 (58.4)	5 (16.7)	2 (10.5)	28 (33.0)
50.1–500	5 (13.9)	1 (3.3)	0 (0.0)	6 (7.0)
500.1–1,000	2 (5.6)	2 (6.7)	0 (0.0)	4 (4.7)
More than 1,000	4 (11.1)	1 (3.3)	1 (5.3)	6 (7.1)
Total	32 (71.1)	9 (20.0)	4 (8.9)	45 (100.0)

25.9% grew cereals and 22.4% fodder crops. Tunisian growers predominantly reported growing fodder crops (52.6%) and fruit trees (73.7%). Whereas leafy vegetables and fruits, mainly those eaten raw, were more prominent in the Lebanese and Jordanian surveyed areas (Table S1 – Supplementary material). The study results were in line with the previous agricultural reports, which confirm that the main annual crops in Jordan are vegetables and cereals (FAO 2008). In Lebanon, the main crops grown are fruit trees, olives, and cereals (The Lebanese Ministry of Agriculture 2010), and in Tunisia, fruit trees, cereals, and fodder are the main cultivated crops (Chahed *et al.* 2015; Frija *et al.* 2021).

3.3. Sources for water use and reuse in irrigation

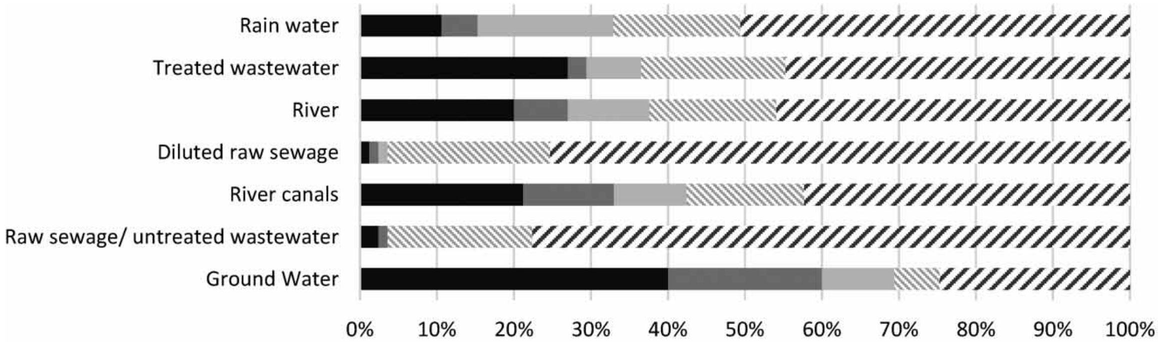
3.3.1. Sources of irrigation water

When asked if more than one source is used for crop irrigation and the reasons, 17.6 and 32.9% of the growers reported the application of mixed irrigation from different sources to improve the quality of crops and overcome water shortages, respectively. The latter was a principal reason for the Tunisian growers (42.1%), followed by the Jordanians (36.7%) and Lebanese (25%).

In general, groundwater constituted one primary source of irrigation with 60% of the growers reporting that it is often or always used. This is followed by TWW (29.4%), river canals (27%), and rainwater (14.7%) (Figure 1). It is worth noting that the Jordanian farmers near the Zarqa River used the river water, which is purely a receiving body for the TWW discharged by the As-Samra treatment plant. The use of untreated and diluted wastewater was the least observed, with 2.4–3.6% of farmers reporting that they often or always use it for irrigation. However, 18.8 and 21.1% of farmers occasionally irrigate their crops with diluted raw sewage and untreated wastewater, respectively.

Table 3 clearly shows that most of the growers in this study were willing to reuse the TWW. However, the limited accessibility to TWW and the unavailability of treatment plants were among the primary reasons for not using TWW for 32.9% of the growers (Table 3).

At the country level, a higher proportion of Lebanese growers (80.5%) always or often used groundwater than the Jordanians (60%) and Tunisian growers (21.1%). Kruskal–Wallis H test showed a statistically significant difference between the countries, $\chi^2(2) = 22.697$, $p = 0.000$, with significant differences between Tunisia and Lebanon ($p = 0.000$) and Tunisia and Jordan ($p = 0.008$). At the same time, the Lebanese (61.1%) and Jordanian growers (76.7%) also reverted to river canals in times of shortage but in varying frequencies. Our findings align with a recent study conducted by Jaafar & Kharroubi (2021), which revealed that farmers in Lebanon utilized different water sources for irrigation, with a significant preference for groundwater (68.6%) and a smaller proportion relying on canal water (12.1%).



	Ground Water	Raw sewage/ untreated wastewater	River canals	Diluted raw sewage	River	Treated wastewater	Rain water
■ Always	40.0%	2.4%	21.2%	1.2%	20.0%	27.0%	10.6%
■ Often	20.0%	1.2%	11.8%	1.2%	7.0%	2.4%	4.7%
■ Sometimes	9.4%	0.0%	9.4%	1.2%	10.6%	7.1%	17.6%
Occasionally	5.9%	18.8%	15.3%	21.1%	16.5%	18.8%	16.5%
Never	24.7%	77.6%	42.3%	75.3%	45.9%	44.7%	50.6%

Figure 1 | The frequency and type of water sources used for irrigation.

Table 3 | Reasons for using or not using treated wastewater

Total sample size ($N = 85$)	Country: Lebanon N (%)	Country: Jordan N (%)	Country: Tunisia N (%)	Total N (%)
1 – If you use treated wastewater for irrigation, state the primary reason				
– Incentives provided, subsidized	1 (2.8)	0 (0.0)	1 (5.3)	2 (2.4)
– Protect water resources	3 (8.3)	3 (10.0)	4 (21.1)	10 (11.8)
– Limited fresh water supply	2 (5.6)	5 (16.7)	8 (42.1)	15 (17.6)
– Rich in nutrients (enhance production)	0 (0.0)	4 (13.3)	4 (21.1)	8 (9.4)
– To improve livelihood	0 (0.0)	0 (0.0)	1 (5.3)	1 (1.2)
Total number of responses	6 (16.7)	12 (33.3)	18 (50.0)	36 (100.0)
2 – Why don't you use the treated wastewater for crop irrigation at your farm?				
– No access to treated wastewater	6 (16.7)	6 (20.0)	0 (0.0)	12 (14.1)
– Expensive	1 (2.8)	0 (0.0)	0 (0.0)	1 (1.2)
– Wastewater treatment plant is not available	5 (13.9)	11 (36.7)	0 (0.0)	16 (18.8)
– For quality reasons	1 (2.8)	1 (3.3)	0 (0.0)	2 (2.4)
– For health reasons	3 (8.3)	0 (0.0)	0 (0.0)	3 (3.5)
– It is not legally permitted	3 (8.3)	0 (0.0)	0 (0.0)	3 (3.5)
Total number of responses	19 (51.4)	18 (48.6)	0 (0.0)	37 (100.0)

Despite sharing a similar climate and geography, the Tunisian group reported a notably lower frequency of river canal utilization for irrigation than their Lebanese and Jordanian counterparts, suggesting potential variations in water management practices across the region ($\chi 2(2) = 17.668$, $p = 0.000$). Kruskal–Wallis H test showed a significantly higher proportion of surveyed Tunisians relied on TWW for irrigation than Lebanese and Jordanians ($\chi^2(2) = 35.264$, $p = 0.000$). For instance, 84.2% of the Tunisians always or often irrigated with TWW (Table S2 – Supplementary material) primarily due to limited water availability (42.1%) but also to protect water resources (21.1%) and enhance production (21.1%) (Table 3). Additionally, the Tunisians occasionally used river streams and rivers (15.8–21.1%) and sometimes resorted to groundwater (15.8%) (Figure S1 – Supplementary material).

In comparison, more than two-thirds of the surveyed Lebanese farms (63.9%) and more than a third of Jordanian growers (46.7%) do not use TWW due to limited access to TWW (16.7 and 20.0%) and the absence of treatment plants (13.9 and 36.7%), respectively. For instance, Jordanian farmers on highlands often use groundwater without access to TWW. Although 26.7% of the Jordanian growers surveyed reported always using TWW, there remains potential for further adoption of this sustainable water source. This is particularly relevant given that the Zarqa river water, which was used by the Jordanian growers in this study, receives TWW.

When asked about their usage of untreated wastewater, most Jordanian growers (96.7%) reported that they never used it. In contrast, a substantial portion of Lebanese (36.1%) and Tunisian (15.8%) growers reported occasional use of untreated wastewater for irrigation. Also, 86.7% of growers in Jordan never used diluted raw sewage or untreated wastewater. However, in Lebanon, 33.3% of growers occasionally use untreated wastewater.

More farms in coastal areas of Lebanon could have used untreated wastewater but were not covered in this work. The agriculture sector and water resources management in Lebanon have been severely impacted by institutionalized corruption, wasted funds for the rehabilitation of wastewater plants, and state dysfunction (Farajalla *et al.* 2015). These issues have resulted in a degraded environment and the widespread use of untreated wastewater, including raw sewage and factory effluents, being released into river streams that are used for irrigation purposes. We may also assume response biases among the Jordanian and Tunisian groups as they may not have responded candidly, considering the legal system in Jordan and Tunisia that strictly prohibits this practice.

As for the rainwater, while it represents an additional source of water for the Lebanese (69.4%) and Jordanians (43.4%), it was the least reported among the Tunisians (21.1%) (Figure S1 – Supplementary material). These findings show that rainfall harvesting was common among Jordanians and Lebanese likely due to the topography helping to harvest the rainfall.

The planning and development of wastewater reuse schemes have recently progressed in Jordan and Tunisia. But driven by the critical water stress level and the country's dependency on agricultural development, Jordan is considered the most advanced country in the region concerning quality control and safety schemes for reuse (ACWUA 2010; Breulmann *et al.* 2020). However, the treatment is mainly at the secondary level in both countries. In Tunisia, 122 WWTP are producing about 300 millions m^3. Approximately 95% of this water is treated at a secondary level to preserve Tunisia's water resources and marine environment (Drechsel & Munir 2018). Additionally, 33 WWTPs in Jordan are operated by the water authority of Jordan (WAJ), treating more than 190 MCM in 2020. More than 95% of the effluent in Jordan is reused in agriculture, mainly in the Jordan Valley, after mixing with rainwater (Dawoud 2017; Breulmann *et al.* 2020).

In contrast, WWT for reuse has not been a priority in Lebanon, given the sufficient natural water resources. Besides, according to the National Analysis of Water Reuse Potential in Irrigation report, governance challenges, limited financial capacities, and lack of a regulatory framework are acute shortfalls in bringing WWT to its full potential in Lebanon. These shortcomings significantly affect the operations, maintenance, and monitoring of water treatment and technical capacity building for staff to generate water quality that meets the standard for reuse (Eid-Sabbagh *et al.* 2022).

The regulations in Lebanon prohibit the use of sewage for irrigating vegetables and some fruit trees (Karaa *et al.* 2005). Nevertheless, some farmers in the current and other studies reported occasional use of diluted and untreated wastewater (Houri & El Jeblawi 2007; Halablab & Holail 2011; Faour-Klingbeil *et al.* 2016b). The limited water availability, compounded with institutional fragmentation and overlapping responsibilities, limits the effective operational management of water resources (Alcon *et al.* 2019) and motivates unlawful practices for higher yields (Mojid *et al.* 2010). For example, reported that when water sources decline in the summer, farmers used private wells for irrigation and diluted sewage to overcome the shortage and produce a higher crop yield (Faour-Klingbeil *et al.* 2016b).

On the other hand, the results showed that incentives and subsidies for wastewater reuse were generally the most minor reported reasons for TWW applications (Table 3). In Jordan, the farmers are committed to paying the amount of 4 piasters/m^3 of TWW to the WAJ within one month of receiving the invoice (Breulmann *et al.* 2020). The low tariffs for the TWW combined with the government's targeted campaigns on the measures taken to ensure the safety of crops irrigated with TWW have eased the health concerns of the residents of the Wadi Musa area in Jordan and encouraged farmers to use it for irrigation purposes (SWIM 2013). There is a divergence in Jordan concerning farmers' payment for TWW taken directly from the WWTPs. Meanwhile, farmers in the Zarqa river have free access to the TWW left discharged into the river. In contrast, the Tunisian government strongly supports WWT and incentivizes its reuse. The national water pricing strategy is adopting very low (almost for free) tariffs to enhance the rate of reuse (DGGREE 2018). However, since 2022, a decree was emitted according to which farmers have to cover the energy pumping cost incurred for irrigation using TWW, which caused some reluctance in areas where alternative water resources are available.

3.3.2. Irrigation method and water quality control

According to the responses obtained, drip irrigation was the most commonly used method for irrigating root and leafy vegetables and fruit trees, accounting for 41.2–45.9% of the total. Furrow irrigation was also used for a variety of crops, primarily fodder and fruit trees, with a range of 7.1–34.1%. Spray irrigation, on the other hand, was the least reported method (3.5–11.8%), particularly for irrigating vegetables that are commonly consumed raw (4.7%) (Figure 2).

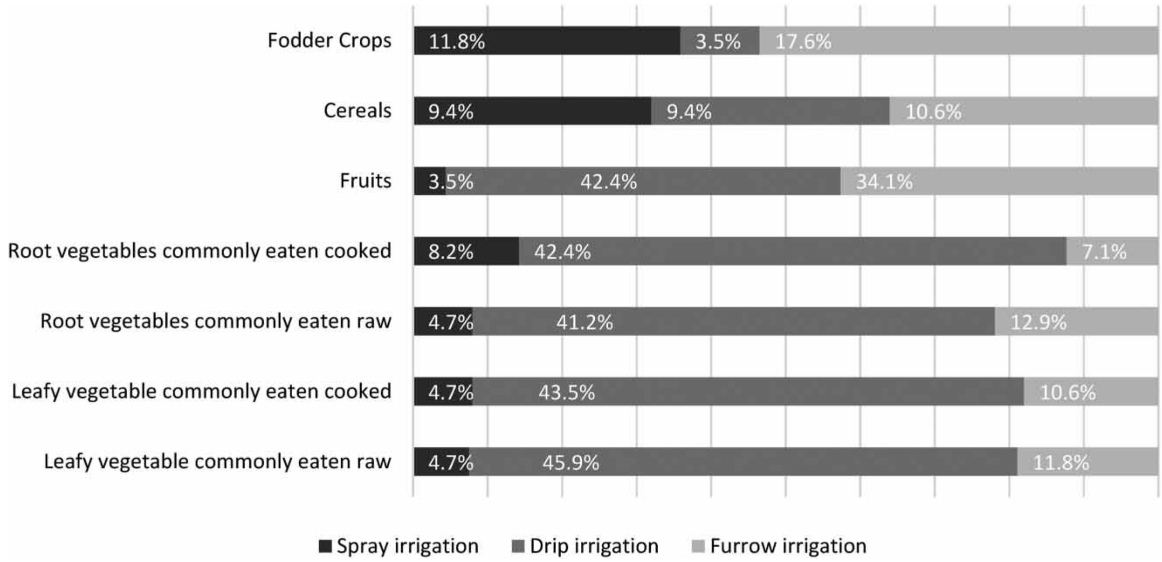


Figure 2 | Irrigation method applied to different crops.

The utilization of drip irrigation in fruit and vegetable farms was notably higher in Jordan, where it was applied in 70–76.7% of such areas. In contrast, Lebanon reports a range of 30.6–41.7%, while Tunisia has usage rates between 0 and 10.5%. In the latter, fruits and vegetables were predominantly irrigated by furrows (10.5–68.4%) (Table S3 – Supplementary material).

Furthermore, drip and surface irrigation schemes were the most used in the Middle Governorates in Jordan, while sprinkler irrigation schemes were used at As-Samra WWTPs, although not allowed according to JS 893 (Breulmann *et al.* 2020). Our results aligned with a recent study which showed that Lebanese farmers (34.6%) prefer to use drip irrigation systems over other options such as sprinkle (22.5%), surface and pressurized irrigation (15.3%), and surface irrigation (14.9%) (Jaafar & Kharroubi 2021). These findings indicate a strong preference for drip irrigation systems among Lebanese farmers.

Less than half of the surveyed growers actively monitored the quality and safety of their irrigation water. Specifically, microbiological tests were performed by 32.9% of the growers, while 37.6% conducted chemical tests and 29.4% carried out turbidity tests (Table 4). When asked about the frequency of tests conducted, less than a third, 29.4, 27.1, and 22.4%, performed microbiological, chemical, and physical tests once a year, respectively. In comparison, only a few reported bi-annual tests (4.7, 8.2, 9.4%) or more than twice a year (3.5, 4.7, 2.4%), respectively.

A Kruskal–Wallis *H* test confirmed a statistically significant difference in monitoring the quality of water used in irrigation by microbiological, chemical, and physical tests between the different countries, $\chi^2(2) = 5.228$, $p = 0.053$. The mean rank was 44.35, 38.81, and 38.76 for Lebanon, 47.42, 56.75, and 54.5 for Jordan and 29.24, 32.74, and 33.47 for Tunisia ($p < 0.05$). Furthermore, the proportion of Jordanian growers who tested

Table 4 | The reported analytical tests for monitoring irrigation water quality

Total sample size ($N = 85$)	Country Lebanon N (%)	Jordan N (%)	Tunisia N (%)	Total N (%)
Monitoring the quality of irrigation water				
Microbiological tests				
Yes	$13^{a,b}$ (36.1)	13^{a} (43.3)	2^{b} (10.5)	28 (32.9)
No	$23^{a,b}$ (63.9)	17^{a} (56.7)	17^{b} (89.5)	57 (67.1)
Chemical tests				
Yes	10^{a} (27.8)	21^{b} (70.0)	1^{a} (5.3)	32 (37.6)
No	26^{a} (72.2)	9^{b} (30.0)	18^{a} (94.7)	53 (62.4)
Physical (turbidity) tests				
Yes	7^{a} (19.4)	17^{b} (56.7)	1^{a} (5.3)	25 (29.4)
No	29^{a} (80.6)	13^{b} (43.3)	18^{a} (94.7)	60 (70.6)

Values in the same row not sharing the same subscript are significantly different at $p < 0.05$.

their irrigation water quality was significantly higher than that of Lebanese and Tunisian growers ($p < 0.05$). Of the three countries, Tunisian growers monitored water quality the least which could be explained by the fact that TWW quality monitoring according to national regulations, i.e., the standards of reuse in agriculture NT 106.03 (1989) lies primarily with the regional water authorities.

Monitoring the irrigation water quality is essential for ensuring the safety of crops that are often consumed raw. This is particularly important since leafy vegetables and fruits, which account for 48.2 and 52.9% of crops grown by farmers in this study (Table S1 – Supplementary material), are highly susceptible to contamination. Although the drip irrigation system was widely used for crops cultivation in the three countries (Table S3 – Supplementary material), pathogens, such as *E. coli* O157:H7 and O145, could still be transmitted through contaminated water and may even be internalized through root uptake leading to foodborne disease outbreaks (Gelting & Baloch 2013).

Figure 2 shows that surface water and inadequately treated wastewater were used in certain growing areas in Jordan and Lebanon, which poses a significant risk of contaminating vegetable crops (Gerba & Choi 2006; Faour-Klingbeil *et al.* 2016b; Perez-Mercado *et al.* 2018; Rodrigues *et al.* 2020). For example, recent studies have detected faecal coliforms and *E. coli* in water samples collected from 14 rivers in Lebanon, with concentrations exceeding the permissible limit. Moreover, 45% of the *E. coli* isolates were found to be multiple-drug-resistant (Dagher *et al.* 2021). Similarly, Faour-Klingbeil *et al.* (2016b) showed that Lebanon's irrigation water and post-harvest washing contributed to the pathogenic contamination of leafy greens and radishes. The authors found that 60% of the *E. coli* isolated from fresh produce irrigated by river streams, diluted sewage, and washed in ponds with river water exhibited multiple-drug resistance (Faour-Klingbeil *et al.* 2016a).

Additionally, the groundwater quality, a predominantly used water source in Lebanon and to a lesser extent by the Jordanian growers, is increasingly shown to be prone to deterioration due to salinization and contamination with hazardous pollutants as a result of exploitation and intensive agriculture, mainly in arid and semi-arid areas (Purnama & Marfai 2012; Bartzas *et al.* 2015; Hartmann *et al.* 2021; Hasan *et al.* 2021). Hence, it is prudent to maintain periodical controls on water quality to minimize and reduce the contamination of crops.

The frequency of conducting turbidity tests was found to be significantly lower in Lebanon (19.4%) and Tunisia (5.3%) compared to Jordan (56.7%) (Table 4). The results in Lebanon were not surprising, considering the unformalized use of conventional resources and limited reuse applications. Of those who controlled water quality, 31.5% relied on trained staff for water sampling and 28.9% on local authorities' inspectors, with the latter reported mainly by the Jordanian growers (39.1%), whereas 30.4 and 61.5% of Lebanese and Jordanian growers stated they collect water samples. On the other hand, this study revealed that a high proportion of the surveyed growers in Tunisia, of whom a great majority applied TWW for crops, did not test the microbiological, chemical, and physical properties of the water used (Table 4).

These results reveal that water quality monitoring is not well established in the agricultural practices of the sampled areas. This is a concerning finding, given the pressing issue of water scarcity, which may necessitate an expansion of water reuse practices. In the United States, for example, TWW reuse has been applied to a wide range of crops, such as wheat, grain, barley, vegetables, fruits, and nuts, in response to the acute shortage of water availability (Rock *et al.* 2019).

These testing rates and the general disregard to water quality monitoring may have significant implications for risk management and public health especially as wastewater collection and treatment processes in these countries and the region as a whole are facing challenges (Eid-Sabbagh *et al.* 2022). Consequently, given that advanced technologies are generally not common, the existing WWTPs capacities might be strained by the high load of industrial pollutants, e.g., pharmaceuticals and antibiotic residues, and dioxins. This situation may lead to generating secondary treatment effluents which serve as a main source of persistent micropollutants in the environment (Breulmann *et al.* 2019), eventually permeating the food chain. Hence, whether the practice of water reuse remains limited in scope or expands, it is crucial to prioritize improving WWT infrastructure and enhancing water quality monitoring practices as a critical measure for compliance with international standards and to mitigate risks associated with using reclaimed water in agricultural production.

3.3.3. The growers' knowledge and access to information on water reuse

More than two-thirds (69.4%) of the surveyed growers stated not having access to information from their local authorities on the safe reuse of wastewater for irrigation. This was primarily observed among the Lebanese growers (83.3%) but unexpectedly reported by the Jordanians (66.7%) and Tunisians (47.4%). Based on the new Master Plan REUSE 2050, the national regulations will be revised in the upcoming years to include various categories based on the fit-for-purpose approach and will cover several categories of TWW quality (BRLi 2023).

Also, in Lebanon, decision No. 8/1 dated March 2001 exists on wastewater standards to cover wastewater discharge to the sea, surface water, and sewerage systems. However, standards for reusing treated effluents have not been laid down, and there are no specified requirements concerning sampling methods, locations, and frequency of analyses (Karaa *et al.* 2005).

Along the same line, most of the growers (87.1%) did not know about any regulations on wastewater reuse. Surprisingly, less than half of the surveyed growers in Tunisia (42.1%) reported awareness of applicable laws compared to only 5.6 and 3.3% of the Lebanese and Jordanian growers, respectively, which suggests a lack of effective public–private communication and accessibility to regulatory guidance. Moreover, it was concerning that very few ($n = 4$) stated the specific rules or guidelines, e.g., Sanitary and Phytosanitary (SPS) measures, crop restrictions for wastewater reuse, and national standards for reuse in agriculture NT106.03.

In addition, more than half of the growers were unaware that pathogens (60.0%), the COVID-19 virus (63.5%), pesticides (55.3%), and pharmaceuticals (54.1%) could be transmitted to food via TWW. The level of limited knowledge was notably higher among Tunisian growers (86.7, 83.3, 86.7, and 83.3%, respectively) compared to their Lebanese and Jordanian counterparts, with a statistically significant difference ($p < 0.05$) (Figure 3).

Pathogens such as *Salmonella* spp., *E. coli* intestinal nematodes, and *Legionella* spp. were identified in high quantities, especially if disinfection or advanced filtration treatment such as membranes are not part of the treatment (Ofori *et al.* 2021). Moreover, enteric viruses had been identified in the effluent of secondary TWW for irrigation (Von Sperling & de Lemos Chernicharo 2005; Symonds *et al.* 2014). Similarly, Mahjoub *et al.* (2009) and Al-Mashaqbeh *et al.* (2020) found various endocrine disrupter and pharmaceutical compounds including antibiotics in effluents. In Jordan, the authors showed that As-Samra WWTP could not completely remove the pharmaceuticals and personal care products from wastewater; therefore, some of these compounds were transmitted to vegetables, such as parsley, irrigated by TWW (National Academy of Science 2016). Today, using reclaimed water for all types of vegetable crops, whether raw or cooked, is still prohibited. Therefore, the main crops irrigated with TWW are fruit trees (citrus, grapes, olives, peaches, pears, apples, pomegranates, etc.), fodder (alfalfa, sorghum, berseem, etc.), industrial crops (sugarbeet), and cereals (Breulmann *et al.* 2020).

Our results highlighted a lack of awareness and knowledge among farmers in the studied countries regarding wastewater reuse practices and associated risks. This could be attributed to the absence of dedicated local organizations entities and public–academic partnerships focused on providing education and extension support to farmers. Some efforts were being made at the technical and utility levels. For instance, the Arab Countries

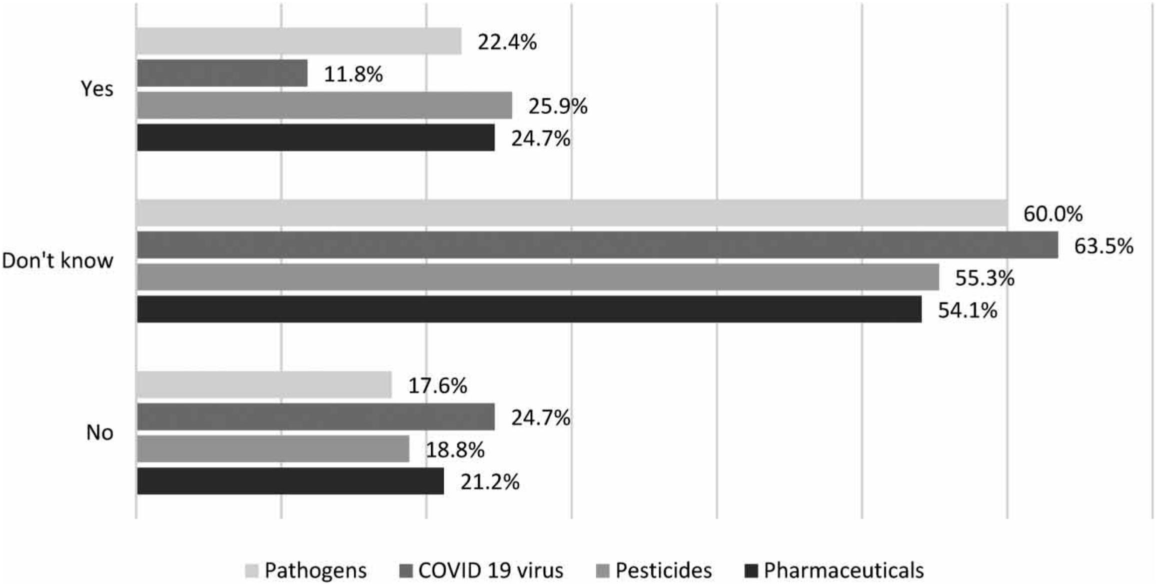


Figure 3 | The growers' opinion on the transmission of pollutants to crops via treated wastewater reuse.

Water Utilities Association (ACWUA) has taken active measures to enhance the training and skills of technical experts and engineers involved in the management of water and wastewater utilities. Yet, the sustainability of these programs relies on adequate funding and the emphasis of these initiatives has been primarily directed towards technical professionals, with relatively less attention given to the agricultural sector, particularly the farmers.

On the other hand, the WHO has undertaken the development of the Sanitation Safety Planning manual, specifically designed to facilitate the safe utilization and disposal of wastewater, greywater, and excreta (WHO 2015). This manual serves as a valuable resource, offering clear and sequential guidance to entities responsible for managing wastewater, including its reuse. A key aspect of this guidance is aligning practices with the guidelines established in 2006. However, so far, there have not been endeavours to put into practice the recommended measures due to the scientific and technical expertise needed in this domain. Hence, enhancing partnerships among stakeholders is vital, along with the necessity of developing local agencies or institutions dedicated to empowering and educating all actors in the agricultural setting.

3.4. The growers' trust and their attitudes toward wastewater reuse for irrigation

According to most of the growers surveyed, water scarcity is increasingly becoming a concern for agricultural production (Figure 4). However, a lower proportion of Lebanese growers (63.9%) agreed with this statement compared to the majority of Jordanian (96.7%) and Tunisian (89.5%) growers (see Table S4 in the Supplementary material). In addition, only 54.1 and 50.6% of all growers agreed that using TWW is a crucial option to overcome water scarcity and enhance yield production, respectively (Figure 4). On a scale of 1 (disagree) to 3 (agree), Tunisian growers agreed significantly more with those statements, with mean scores of 2.79 ± 0.63 and 2.74 ± 0.65. In contrast, Lebanese (2.31 ± 0.75 and 1.97 ± 0.77) and Jordanian growers (2.30 ± 0.65 and 2.37 ± 0.81) had lower mean scores ($p < 0.05$). This indicates a higher proportion of Tunisian growers (89.5 and 84.2%) agreed with the statements than Lebanese (47.2 and 27.8%) and Jordanians (40.0 and 56.7%), respectively.

Only 40% believed the water quality used for irrigation is safe and does not present health risks to consumers. Meanwhile, 30.6% are uncertain about the safety of the water. Despite this, the majority of growers agree on the importance of regularly checking the water quality, as reflected in a score of 2.84 ± 0.508 (Table 5). Other studies also showed that health concerns were not raised among farmers using direct or indirect wastewater and sometimes accepted the risks due to the economic advantage of TWW applications (Carr *et al.* 2011).

Fewer Lebanese (30.6 and 38.9%) and Tunisian growers (36.8 and 26.3%) believed that TWW affects the quality of the products and discourages buyers, respectively, than the Jordanians (73.7%). However, the latter scored significantly higher (2.57 ± 0.774) than their Lebanese and Tunisian counterparts ($p < 0.05$), indicating a higher level of concern toward consumer rejection of crops irrigated with TWW

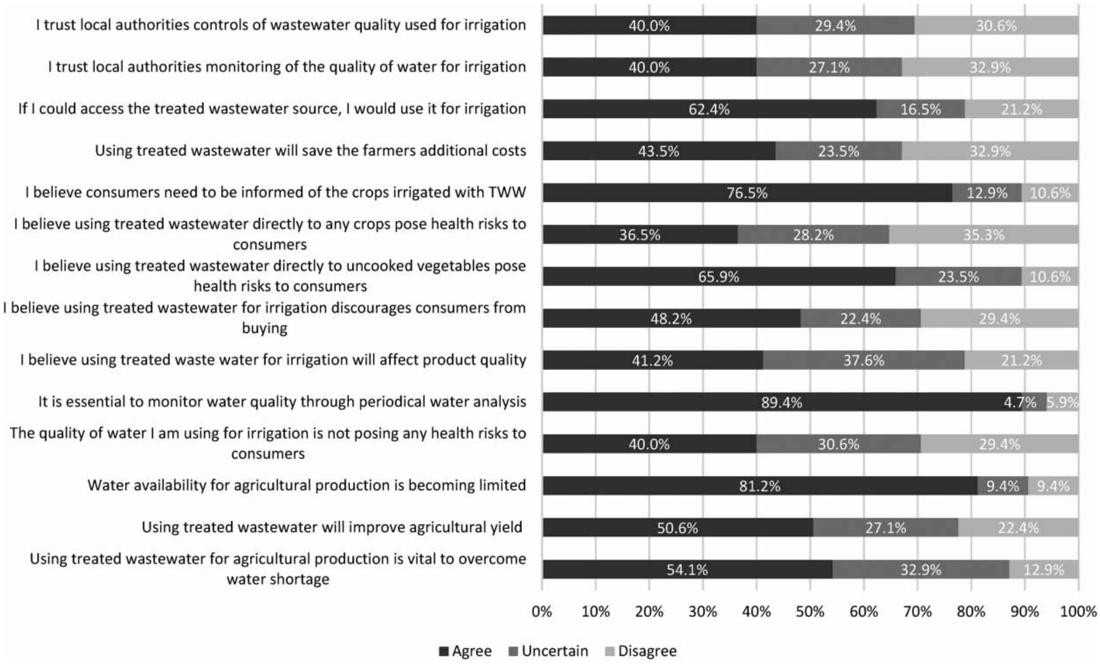


Figure 4 | The growers' attitudes towards treated wastewater reuse.

Table 5 | Mean scores of growers' expressing trust and attitudes toward wastewater reuse

	Country			
Statements	**Lebanon Mean* ± S.D.**	**Jordan Mean* ± S.D.**	**Tunisia Mean* ± S.D.**	**Total Mean* ± S.D.**
Using treated wastewater for agricultural production is vital to overcoming water shortages	2.31^{a} ± 0.75	2.30^{b} ± 0.65	2.79$^{a, b}$ ± 0.63	2.41 ± 0.71
Using treated wastewater will improve agricultural yield	1.97^{a} ± 0.77	2.37 ± 0.81	2.74^{a} ± 0.65	2.28 ± 0.81
Water availability for agricultural production is becoming limited	2.44$^{a, b}$ ± 0.81	2.93^{a} ± 0.36	2.89^{b} ± 0.31	2.72 ± 0.63
The quality of water I am using for irrigation is not posing any health risks to consumers	2.06 ± 0.83	2.30 ± 0.79	1.89 ± 0.87	2.11 ± 0.83
It is essential to monitor water quality through periodical water analysis	2.72 ± 0.61	2.93 ± 0.36	2.89 ± 0.46	2.84 ± 0.51
I believe using treated wastewater for irrigation will affect product quality	2.14 ± 0.68	2.40 ± 0.77	2.00 ± 0.88	2.20 ± 0.77
I believe using treated wastewater for irrigation discourages consumers from buying	2.11 ± 0.82	2.57^{a} ± 0.77	1.74^{a} ± 0.87	2.19 ± 0.87
I believe using treated wastewater directly on vegetables often eaten raw poses health risks to consumers	2.31^{a} ± 0.71	2.73^{a} ± 0.64	2.74 ± 0.56	2.55 ± 0.68
I believe using treated wastewater directly on any crops poses health risks to consumers	2.19^{a} ± 0.75	1.67^{a} ± 0.88	2.21 ± 0.85	2.01 ± 0.85
I believe consumers need to be informed of the crops irrigated with TWW	2.53 ± 0.69	2.87 ± 0.51	2.58 ± 0.77	2.66 ± 0.66
Using treated wastewater will save the farmers additional costs	2.31^{a} ± 0.75	2.13 ± 0.90	1.68^{a} ± 0.95	2.11 ± 0.87
If I could access the treated wastewater source, I would use it for irrigation	2.14^{a} ± 0.90	2.50 ± 0.73	2.79^{a} ± 0.63	2.41 ± 0.82
I trust local authorities monitoring of the quality of water for irrigation	1.64^{a} ± 0.76	2.63$^{a, b}$ ± 0.76	2.00^{b} ± 0.67	2.07 ± 0.86
I trust local authorities' controls of wastewater quality used for irrigation	1.61^{a} ± 0.73	2.73$^{a, b}$ ± 0.64	2.00^{b} ± 0.67	2.09 ± 0.84

Mean values in the same row with the same superscript letter are significantly different ($p < 0.05$).
*Mean score of attitudes on a 3-Likert scale: 1 'Disagree', 2 'Uncertain', 3 'Agree'.

(Table 5), likely due to past experience with Saudi Arabia ban on the Jordanian fruits and vegetables irrigated with TWW.

Furthermore, more than two-thirds (65.9%) of the growers believed that using TWW on crops that are eaten raw poses health risks to consumers; thus, they thought that consumers should be informed of this application (76.5%), but 23.5% were unsure (Figure 4). But their risk perception was found to be almost two times less (36.5%) when TWW would be applied to crops other than those eaten raw. Overall, the Lebanese had the lowest risk perception related to the use of TWW on vegetables commonly eaten raw ($2.31 \pm .0.710$) compared to the Jordanians (2.73 ± 0.640) and Tunisians (2.74 ± 0.562) (Table 5).

However, the Somers' *d* test showed that growers' willingness to use TWW was not influenced by their perception of health risks related to its application on crops ($p > 0.05$). In Lebanon, untreated wastewater is a prevalent solution, but its users are not aware of its potential side effects on human health and crop production (Karaa *et al.* 2005). Faour-Klingbeil (2017) showed that some farmers using polluted water for irrigation overlooked the risk of introducing hazards to fresh produce. Common quotes from farmers were: '*I know it's polluted with nitrates and other chemicals*', '*using sewage does not harm*',' *lettuce gives higher volume with sewage use*', and '*Sewage gives better volume and reduces the use of fertilizers*'. Education, religion, risk exposure, economic benefits (Carr *et al.* 2011), and income (Abu Madi *et al.* 2003; Mojid *et al.* 2010; Braadbaart & Alaerts 2011) are factors influencing farmers' perceptions and willingness to use TWW.

Approximately 62.4% of those surveyed expressed willingness to use TWW when it is accessible. Notably, Tunisian growers demonstrated the highest level of agreement, followed by Jordanians. The Tunisians showed a positive attitude with a significantly high mean score (2.79 ± 0.63) compared to the Jordanians (2.50 ± 0.73) and Lebanese (2.14 ± 0.90) ($p < 0.05$) (Table 5). The study's findings align with Braadbaart & Alaerts (2011) research on Jordanian and Tunisian farmers' willingness to use reclaimed wastewater. These results also underscore the variations in perceptions and acceptance across the countries in the MENA region, which may be attributed to differences in the regulatory, cultural and legal frameworks as well as the level of trust established between stakeholders.

Only 40% of the surveyed growers showed a favourable attitude towards water quality control by local authorities. However, Jordanian growers had substantially higher trust in their local authorities' monitoring of water and wastewater quality (2.63 ± 0.76 and 2.73 ± 0.64) compared to Tunisian growers (2.00 ± 0.67 and 2.00 ± 0.67) and Lebanese growers, who displayed the lowest level of trust (1.64 ± 0.76 and 1.61 ± 0.73) ($p < 0.05$) (Table 5). These results align with the recent studies of Faour-Klingbeil *et al.* (2021, 2022) that found the low levels of trust in local authorities' risk management to be prevalent among the Tunisian and Lebanese surveyed sample compared to Jordanians.

The analysis showed a significantly positive association between the growers' desire to use TWW if they have access to it and their attitudes toward using TWW as a solution to water shortage ($d = 0.656$, $p = 0.000$), for improving agricultural yield ($d = 0.518$, $p = 0.000$), and for compensating for the limited availability of water for production ($d = 0.741$, $p = 0.000$). But this association was not affected by the growers' trust in local authorities ($p > 0.05$). Surprisingly, this correlation was not influenced by the growers' trust in local authorities ($p > 0.05$). These findings imply that increasing awareness among growers about the benefits of TWW and its availability could enhance water reuse applications by 52–74% and that other factors, such as social, cultural, or economic ones, may contribute to the variations in TWW reuse among the surveyed individuals. For instance, 43.5% of the growers considered TWW to have cost-reduction benefits. But this view was not shared by a significantly higher proportion of Tunisian growers who disagreed (1.68 ± 0.946) compared to their Lebanese (2.31 ± 0.75) and Jordanian counterparts (2.13 ± 0.90) (Table 5). It was reported that, in Lebanon, farmers are willing to pay ($\$0.258/m^3$) to secure the water supply (Alcon *et al.* 2014, 2019). But they prefer to pay more for water-saving measures ($\$0.035/m^3$ for drip irrigation and $\$0.025/m^3$ for extension services) than groundwater and surface water metering ($\$0.0034/m^3$) (Alcon *et al.* 2019). Further research is needed to investigate the influence of demographic and economic factors on growers' attitudes towards TWW, which were not included in this study but may shed more light on the feasibility and sustainability of this practice.

4. LIMITATIONS OF THE STUDY

There are two limitations in this study. Firstly, the findings cannot be generalized to the entire population of growers in Lebanon, Jordan, and Tunisia. This is because a fraction of the population may have limited access to online survey tools, coupled with the study's reliance on self-reported data, which could be susceptible to respondents' biases. At the same time, limited funds hindered the researchers from reaching a larger sample size or cover more remote areas in this study. While this survey did not capture the perspectives of growers in other geographical regions, especially those in remote areas with limited access to water and TWW, it has addressed a knowledge gap by shedding light on prevailing trends in farmers' attitudes and practices. These beliefs and practices could be present elsewhere and may have implications for mitigating risks associated with TWW use.

Secondly, the demographic composition of the surveyed participants primarily consisting of landowners and person in charge may also influence the representativeness of the study's findings, as it predominantly captures the perspectives of landowners and those in decision-making roles. This could result in an overrepresentation of a certain segment of the agricultural community as landowners may hold a distinct set of motivations, priorities, and decision-making processes compared to employed farmers. They might also possess a greater sense of investment in the long-term sustainability, influencing their openness to practices like wastewater reuse that could impact soil health and productivity over time. Moreover, their financial stake may prompt them to adopt more conservative approaches to protect their land assets. Conversely, employed farmers, who may have a different interest, could exhibit varying attitudes influenced by their perceptions and reasons such as job security.

Despite these limitations, the data in this study can be valuable for stakeholders involved in WWT planning and operations and for future large-scale research in the region. Besides, unrepresentative samples may still be useful for additional research and the generation of new hypotheses (Rothman *et al.* 2013).

It is recommended that future research focuses on a more diverse participant pool and on incorporating an observational assessment approach for a comprehensive understanding of the food safety risks associated with wastewater reuse in agriculture.

5. CONCLUSION

The accessibility and availability of TWW with advanced technologies are effective solutions for generating safe and fit-for-purpose water quality. However, its widespread applications for crop irrigation may pose significant challenges to food safety unless complemented with good governance.

In conclusion, the results of our study showed that groundwater is a commonly used source of irrigation, with TWW playing a significant role. However, despite the potential benefits of utilizing TWW for agricultural purposes, the current results underscore the need for growers' education and awareness regarding the regulatory and health-related aspects of water reuse. Addressing these knowledge gaps and promoting accessibility to TWW resources are necessary to pave the way for effective water management in the agricultural sector.

This work also highlighted the inadequacy of water quality control tests conducted in the surveyed areas, underscoring the urgent need for implementing robust data collection and analysis systems to monitor water quality indicators and contaminants to ensure the safety of water sources. Establishing this practice is a requisite and key to compliance with international standards and mitigating risks associated with using reclaimed water in agricultural production. It is especially crucial, given the pressing issue of water scarcity, the limited efficiency of WWT technologies and the anticipated expansion of water reuse in the region.

On the other hand, our study suggests significant differences in attitudes and perceptions of growers towards TWW across the countries in the MENA region; hence, the need for region-specific approaches to address the challenges surrounding the adoption of reclaimed wastewater in agriculture. By recognizing the unique attitudes and perceptions of growers towards TWW across the MENA region, policymakers and stakeholders can better promote safe and sustainable use while mitigating potential risks.

WWT plants in small MENA communities are unlikely to adopt advanced treatment technologies in the near future, and many pollutants will remain in recycled water used for agriculture or domestic use. The WHO guidelines provide a flexible risk assessment and management approach. However, its adoption comes down to governments' capabilities to integrate the quantitative microbiological risk assessment and commitment to promoting protective measures along the food chain for pathogen reduction and a robust surveillance system. For this, a radical transformation of farmers' behaviours and awareness is crucial to mitigate the risks of inadequate use and shortfalls in applied controls. The provision of resources, access to technical support, and extension programs should come in tandem as knowledge acquisition tools to enhance the growers' awareness of the risks of TWW reuse and their capacities to reinforce appropriate water and food safety measures.

To bridge these gaps, the establishment of a local association or society dedicated to educating, training, and fostering connections among farmers across the Arab region is crucial. This entity could serve to familiarize farmers with the latest WHO guidelines for wastewater reuse, ensuring they remain well-informed and up to date with the most current practices and recommendations. This would contribute significantly to promoting the safe and effective utilization of wastewater in agriculture, aligning with the principles outlined in the WHO's comprehensive manual.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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