Household water quality in areas irrigated with wastewater in the Mezquital Valley, Mexico

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ABSTRACT

Wastewater for irrigation in low- and middle-income countries can recharge aquifers and potentially contaminate supply sources. The infiltration rate has increased 13-fold in Mexico's Mezquital Valley, the largest agricultural area wastewater-irrigated worldwide, thus we assume that wastewater had contaminated supply sources. Fecal indicator bacteria (FIB) counts were enumerated in household water of two wastewater-irrigated areas, Tula and Tlahuelilpan, and a groundwater irrigated area, Tecozautla. During 2016–2017, household water, wastewater, and groundwater were sampled, analyzing fecal coliforms, fecal enterococci, and *Escherichia coli*, following membrane filtration procedures, and confirming the presence of *E. coli* by polymerase chain reaction. Nearly 50% of household water contained fecal contamination of up to 4.62×10^4 CFU/100 mL. Significant differences between FIB counts in household water from Tula and Tecozautla were observed by Kruskal–Wallis and Dunnett tests. Household water samples from Tula contained highest FIB counts. Wastewater from Tula and Tlahuelilpan contained counts of six orders-of-magnitude of FIB. Counts were high when residual chlorine was <0.2 mg L^{-1} and underwater storage. This research serves as a baseline to observe improvement with a newly installed wastewater treatment plant. Safe irrigation wastewater reuse should be performed under strict surveillance, considering human safety a priority.

Key words | chlorination, fecal indicator bacteria (FIB), household water, Mezquital Valley, storage, wastewater

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HIGHLIGHTS

- Case study of the conditions that prevail in middle-income countries in rural areas where water reuse is a common practice.
- Water for human use and consumption contained fecal indicator bacteria and potentially pathogenic *E. coli* in wastewater-irrigated areas.
- Lack of chlorination and water storage contribute to FIB counts.
- Wastewater treatment can aid in the improvement of water quality for irrigation and positively influence water quality for human use and consumption.
- Processes taking place in the Mezquital Valley are relevant to support modification of the WHO Guidelines for the use of wastewater excreta and greywater.

doi: 10.2166/wh.2020.095

INTRODUCTION

Wastewater is an alternative source for agricultural irrigation and a sustainable solution for water scarcity (Asano 2005; Reznik *et al.* 2019). Agriculture uses 70% of the planet's available drinking water, and the wastewater reuse would aid in reducing water extraction (Nas *et al.* 2020). Since sewage contains different chemical contaminants and microorganisms, it should receive treatment for safe reuse (Asano 2005). In high-income countries, water quality for reuse has been improving, and irrigation is now a controlled practice (Salgot & Folch 2018). However, countries such as China, Mexico, Chile, and Peru still utilize wastewater for agricultural irrigation. In low- and middle-income countries, reuse is not planned, and wastewater can infiltrate through the soil and incidentally contribute to the recharge of aquifers (Foster & Chilton 2004).

There is evidence of wastewater infiltration into aquifers in countries such as Syria, Peru, and Thailand; Mexico is no exception, wastewater contributes to the recharge of aquifers from León, Guanajuato, and the Mezquital Valley, Hidalgo, north of Mexico City (Foster & Chilton 2004; Lesser-Carrillo *et al.* 2011). The Mezquital Valley is the largest agricultural area irrigated with wastewater worldwide. For more than 100 years, nearly 90,000 ha have been irrigated with wastewater from the Mexico City Metropolitan Area (MCMA). Irrigation is performed by flooding, and the infiltration rate has increased 13-fold higher than the natural infiltration (Chávez *et al.* 2011). Wastewater can be incidentally treated during the infiltration process, but the purification capacity of the aquifers is unknown (Jiménez *et al.* 2004). It varies according to geologic materials and the specific conditions *per site* (Lesser-Carrillo *et al.* 2011).

In the Mezquital Valley, the microorganism load in wastewater is very high: up to 10 orders-of-magnitude have been reported (Chávez *et al.* 2011; Fonseca-Salazar *et al.* 2016). Therefore, infiltrated wastewater can potentially contaminate aquifers, which may be used for public supply. Humans can ingest microorganisms and chemicals through the use and consumption of contaminated tap water, and this may become a health problem (Foster & Chilton 2004).

At present, waterborne diseases continue to be a public health concern (Hales 2019), especially in developing countries. Over 59 million cases of gastrointestinal diseases worldwide are caused by groundwater extracted for public use (Murphy *et al.* 2017). In Mexico's Hidalgo State, nearly 29,500 cases of gastrointestinal diseases were reported by the Epidemiological Bulletin between 2015 and mid-2018 (Dirección General de Epidemiología 2018). In the Mezquital Valley, Contreras *et al.* (2017) found that the prevalence of diarrhea in children residing in communities exposed to wastewater was 10%, two-fold higher than in non-exposed communities.

Unfortunately, there is evidence of supply sources contaminated with fecal coliforms (FC), pathogenic bacteria, and parasites, in addition to the contribution of chemical contaminants in the Mezquital Valley (Downs *et al.* 1999; Lesser-Carrillo *et al.* 2011; Fonseca-Salazar *et al.* 2016). Given this evidence, we investigated whether the inhabitants of the Mezquital Valley receive contaminated water, with fecal indicator bacteria (FIB) due to affected supply sources. It is hypothesized that household water from irrigated with wastewater-irrigated areas contains more FIB counts in comparison to areas irrigated with water of better quality. The aim of this research was to quantify FIB in household water in two areas irrigated with wastewater in the Mezquital Valley, Tula and Tlahuelilpan and an area irrigated with groundwater, Tecozautla.

METHODS

Study site

The Mezquital Valley in Hidalgo is located 100 km north of the MCMA, three irrigation districts compose the Valley: 003 Tula, 100 Alfajayucan y 112 Ajacuba (Chávez *et al.* 2011). Tula, Tlahuelilpan, and Tecozautla were the municipalities (counties) involved in this study. In 2017, operations began in the Atotonilco-Wastewater Treatment Plant (Atotonilco-WWTP), built to treat approximately 23,000 L s^{-1} (60%) of MCMA wastewater to provide treated wastewater

to part of the irrigation districts of the Mezquital Valley (SEMARNAT 2007). The sampling design was based on the Atotonilco-WWTP initiating its operation in 2016; nevertheless, this did not occur until December 2017. Despite this, we distinguished the areas that would receive treated wastewater from those that will not. Tula was irrigated with wastewater at the sampling time and was supposed to receive treated wastewater for irrigation from the Atotonilco-WWTP. Tlahuelilpan municipality was irrigated with wastewater and will not receive water from the Atotonilco-WWTP. Finally, in Tecozautla, groundwater from extraction wells is used for irrigation, located 200 km from the MCMA (Figure 1).

Household selection

We obtained the approvals of the Ethics, Research, and Biosafety Committee of the National Institute of Public Health-Mexico (INSP-México), as well as from the health authority of the State of Hidalgo. This research forms part of a larger epidemiology-based project in which a survey was applied in 880 households, gathering information in the incidence of diarrhea in children under 5 years of age in the Mezquital Valley, where our sampling was based. Households where at least one child under 5 years was recorded with diarrhea and was referred as a case. For each case, a household was identified in the neighboring blocks with a child under 5

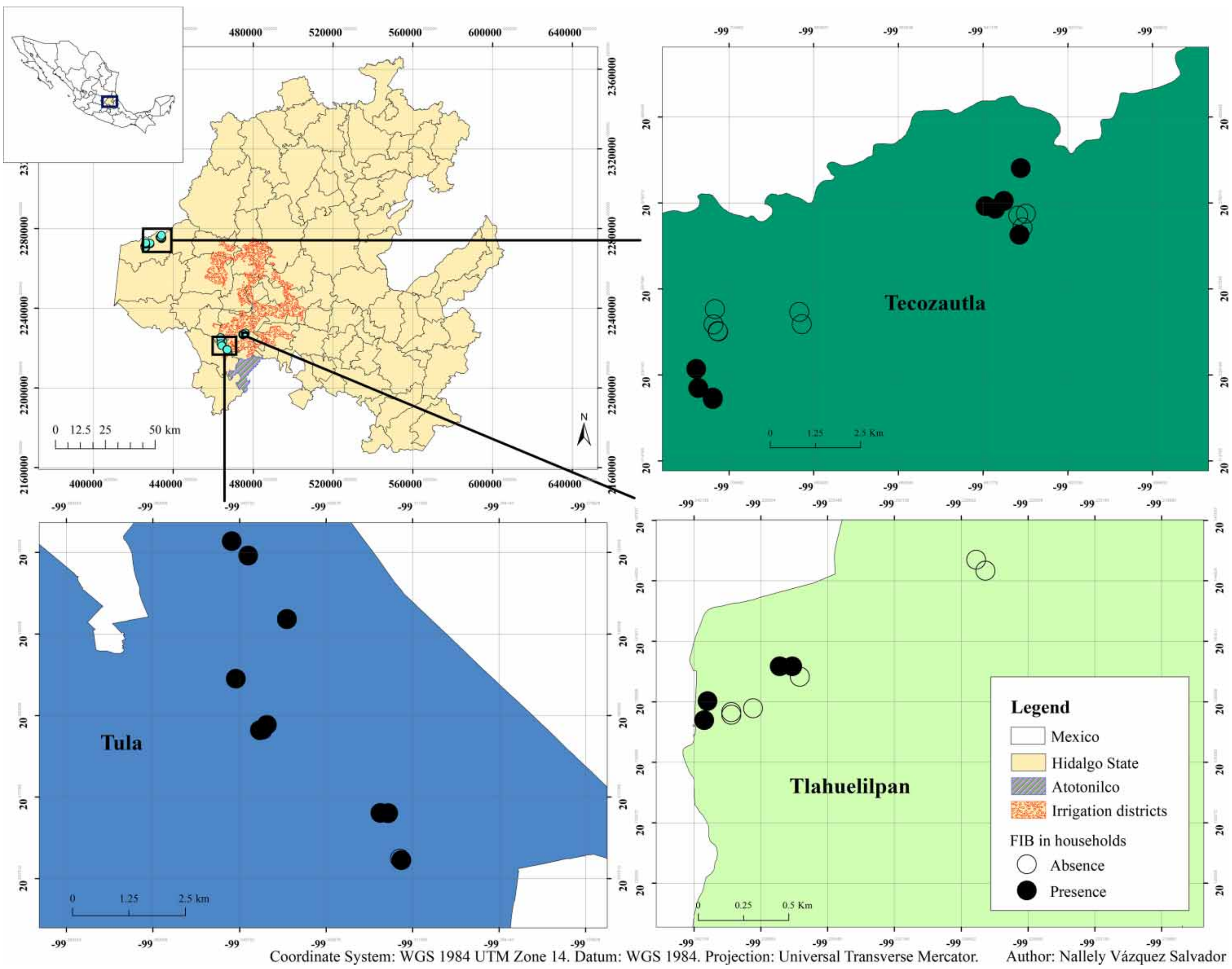


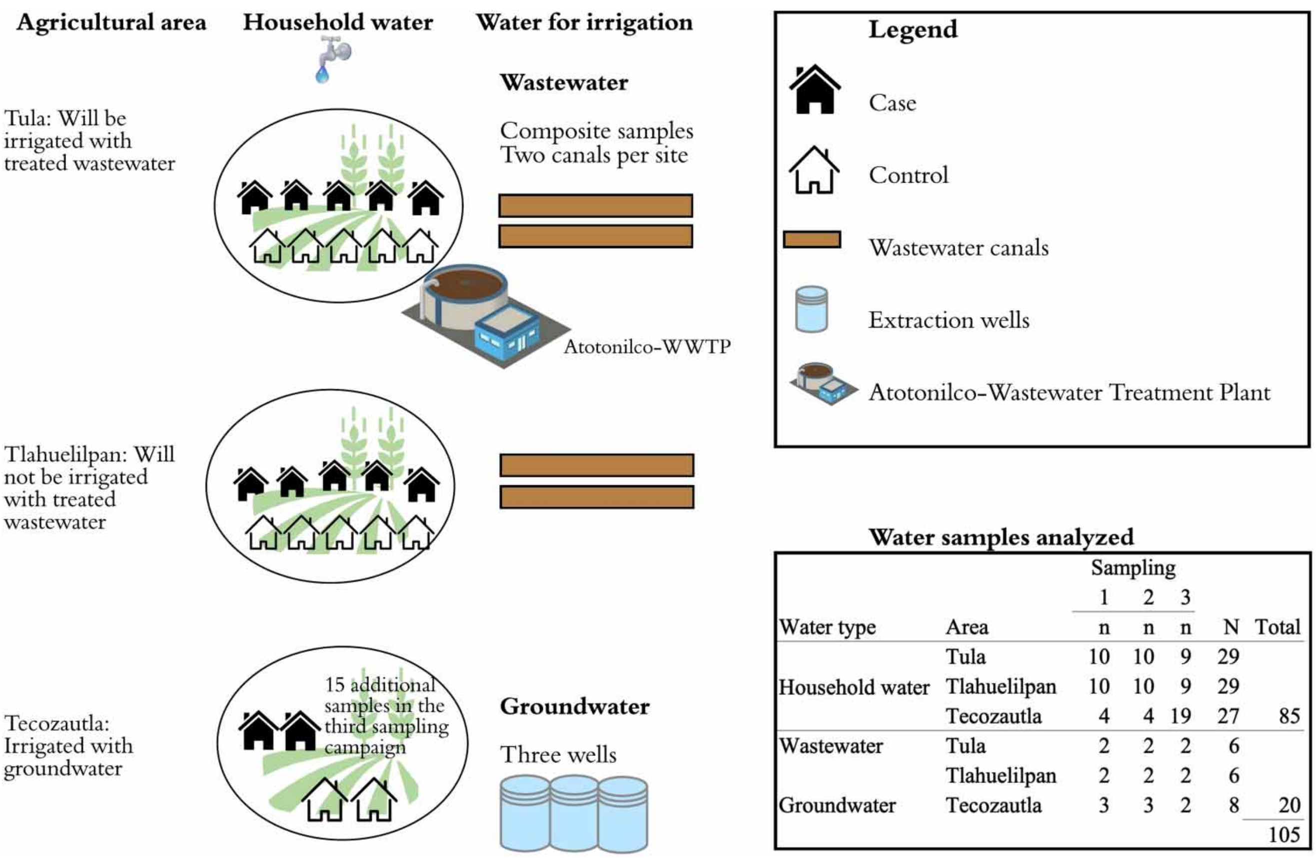
Figure 1 | Counties involved in this study, Tula and Tlahuelilpan irrigated with wastewater and Tecozautla irrigated with groundwater, located in the State of Hidalgo, Mexico.

years of age without diarrhea, this referred to as control. We randomly select a subsample of these households regarding the same number of cases and controls.

Household and irrigation water sampling

Monitoring consisted of three sampling campaigns from November 2016–May 2017, June–July 2017, and October–December 2017. In both Tula and Tlahuelilpan, 10 household water samples were collected during each sampling campaign. Due to a lower proportion of diarrhea in Tecozautla, four household water samples were collected during the first and second campaigns. In the third sampling campaign, we analyzed 15 additional households to increase the sample number. A total of 85 household water samples were taken at the three sampling locations. Irrigation water was collected simultaneously during each sampling event. We monitored wastewater from four irrigation canals; two in Tula and two in Tlahuelilpan. In Tecozautla, groundwater from three different irrigation wells was collected; a total of 20 irrigation water samples were collected (Figure 2).

Samples were collected in sterile polypropylene bottles. In the households, we took 1 L of tap water, and when this was not possible, we collected stored water due to the intermittent water service supply in the zone, better known as *tandeo* (distribution of water by turns). In some cases, there was a hose connected to the tap; therefore, water was taken from the hose, which is the water used within the household. In areas receiving wastewater, we collected 250 mL at three points along each canal and then mixed them to prepare a composite sample. In Tecozautla, we collected 1 L of groundwater directly from the extraction wells. All sites were sampled and analyzed in triplicate. We kept



		Sampling				
		1	2	3		
Water type	Area	n	n	n	N	Total
Household water	Tula	10	10	9	29	
	Tlahuelilpan	10	10	9	29	
	Tecozautla	4	4	19	27	85
Wastewater	Tula	2	2	2	6	
	Tlahuelilpan	2	2	2	6	
Groundwater	Tecozautla	3	3	2	8	20
						105

Figure 2 | Sampling design scheme showing households in each agricultural area. An equal number of cases and controls of diarrhea in children under 5 years of age were taken, and irrigation water was collected simultaneously.

the samples in coolers (4 °C) until their processing in the laboratory (~24 h or less).

Physicochemical and bacteria measurements

To describe water quality in all water types, we recorded the following *in situ:* temperature (°C), pH, dissolved oxygen (DO) (mg L^{-1}), electrical conductivity (μS cm^{-1}), total dissolved solids (TDS) (mg L^{-1}), and turbidity (NTU) using a YSI EX02 Multiparameter Water Quality Probe (Yellow Springs, OH).

Other variables, such as location and residual chlorine, were registered for each household. For household water only, we measured residual chlorine using a DR 2800 model Spectrophotometer (Loveland, CO). Residual chlorine records were classified according to Mexican Regulation NOM-127-SSA-1994 (DOF 2000), which established an acceptable interval of 0.2–1.5 mg L^{-1}. Values below this interval were classified as 'do not meet', while values falling within the interval were classified as 'meet'.

In the laboratory, we enumerated the following FIB: FC, fecal enterococci (FE), and *Escherichia coli,* following standard membrane filtration procedures (APHA 2005).

E. coli polymerase chain reaction confirmation

DNA extraction was performed applying the boiling protocol to confirm *E. coli* by polymerase chain reaction (PCR) (Dashti *et al.* 2009). The primers Fw-5′-ATGGAATTTCGCCGATTTTGC-3′ and Rv-5′-ATTGTTTGCCTCCCTGCTGC-3 at 1 mM initial concentration were used to amplify the gene *uidA*, a conserved region of *E. coli* (Heijen & Medema 2006). Amplification conditions were included with an initial activation step at 95 °C for 3 min, 30 denaturation cycles at 95 °C for 30 s, annealing at 60 °C for 30 s, extension at 72 °C for 30 s, and final elongation at 72 °C for 5 min. Amplicon size was 200 base pairs.

Statistical analysis

A Kruskal–Wallis test to observe differences of FIB counts between areas was applied. Later, we performed a *post hoc* test (Dunnett test) to recognize these areas. The paired comparisons performed were the following: Tula versus Tecozautla and Tlahuelilpan versus Tecozautla. We also ran paired comparisons between FIB counts in stored water versus non-stored water (tap water or from a hose connected to the tap) by the Mann–Whitney *U* test. All statistical results were significant at an α of <0.05. All analyses were carried out in RStudio program suite ver. 1.2.5001 statistical software.

RESULTS

Physicochemical parameters

Physicochemical parameters measured in household water samples showed average values of 18.7 °C for temperature, a pH of 7.4, and DO of 6.7 mg L^{-1}. EC, TDS, and turbidity were higher in Tula, presenting average values of 1,790.8 μS cm^{-1}, 1,333.4 mg L^{-1}, and 15.9 NTU. In Tlahuelilpan, EC and TDS were also elevated (1,673.4 μS cm^{-1} and 1,273 mg L^{-1}), while in Tecozautla, mean values of 1,288.2 μS cm^{-1} and 913.6 mg L^{-1} were recorded for EC and TDS, respectively.

For wastewater, mean values for temperature, pH, and DO of 17.6 °C, 7.6, and 2.1 mg L^{-1} were recorded, respectively. Values for EC and TDS were similar to those of household water (1,430 μS cm^{-1} and 1,103.5 mg L^{-1}), while turbidity was 86.4 NTU.

In groundwater, temperature, pH, and DO were higher than in other water types, presenting mean values of 21.4 °C, 8.1, and 7 mg L^{-1}, unlike the pattern observed in household and wastewater, which demonstrated lower average values of EC and TDS (670.9 μS cm^{-1} and 468.2 mg L^{-1}).

Residual chlorine in household water was measured between 0 and 0.96 mg L^{-1}. Lowest values of chlorination were observed in Tula, while in Tlahuelilpan, highest concentrations were recorded. Media values of 0.05, 0.25, and 0.17 mg L^{-1} for Tula, Tlahuelilpan, and Tecozautla, respectively, were measured. According to the NOM-127-SSA-1994-based classification, 'do not meet' (residual chlorine <0.2 mg L^{-1}) and 'meet' (between 0.2 and 1.5 mg L^{-1}), 27 household water samples from Tula do not comply with the NOM and only two samples fell within the recommended range. In Tlahuelilpan, 15 household water samples do not meet and 14 meet the regulation, while in Tecozautla, 20 samples do not meet and 7 met the

regulation. FIB counts were higher when residual chlorine was below 0.2 mg L^{-1} (Figure 3).

FIB and *E. coli* PCR

Overall, the household water analyzed from the three areas involved contained fecal contamination; 46, 35, and 38% of the samples were positive for FC, FE, and *E. coli*.

The presence of *E. coli* was confirmed in 82% of the positive household water samples by molecular methods. In the case of wastewater and groundwater, *E. coli* was confirmed in 100% of the positive samples.

Household water FIB: comparisons among areas

The Kruskal–Wallis test revealed significant differences in FIB among the three areas (p-value$^a = 1.43 \times 10^{-10}$, 2.65×10^{-5}, and 4.48×10^{-8} for FC, FE, and *E. coli*, respectively). The Dunnett test was also performed and showed that Tula behaves differently from Tecozautla, presenting higher FIB counts and a p-value$^b = 0.01$, 0.0006, and 0.005 for FC, FE, and *E. coli*, respectively. In contrast, this pattern was not observed in the comparison between Tlahuelilpan versus Tecozautla (p-value$^b = 0.99$, 0.98, and 0.99 for FC, FE, and *E. coli*, respectively); fecal contamination in both areas was similar, despite irrigation practices with groundwater in Tecozautla (Table 1).

For all areas, the FIB group with the majority of counts was FC followed by *E. coli* and, at a lesser proportion, FE (Figure 3). Minimal values for all FIB groups were zero or not detected (<1 CFU/100 mL), while maximal FIB counts were between one or two orders-of-magnitude. Highest FIB counts were in households located in Tula followed by Tecozautla, and lowest contaminations were found in households from Tlahuelilpan (Figures 1 and 4).

The Mann–Whitney U test suggested high counts of FIB when the water is stored, and exhibited a decrease of FIB in tap or hose water, with significant differences observed for the three FIB groups. For FC, p-values $= 1.66 \times 10^{-6}$ and 8.34×10^{-5} were estimated for the paired comparisons: stored water versus tap water, and store water versus hose connected to the tap. For FE, p-values $= 5.58 \times 10^{-5}$ and 8.73×10^{-5} were computed, while for *E. coli*, p-values $= 1.59 \times 10^{-5}$ and 4.66×10^{-6} were calculated for stored water versus tap water as well as for stored water versus hose water, respectively.

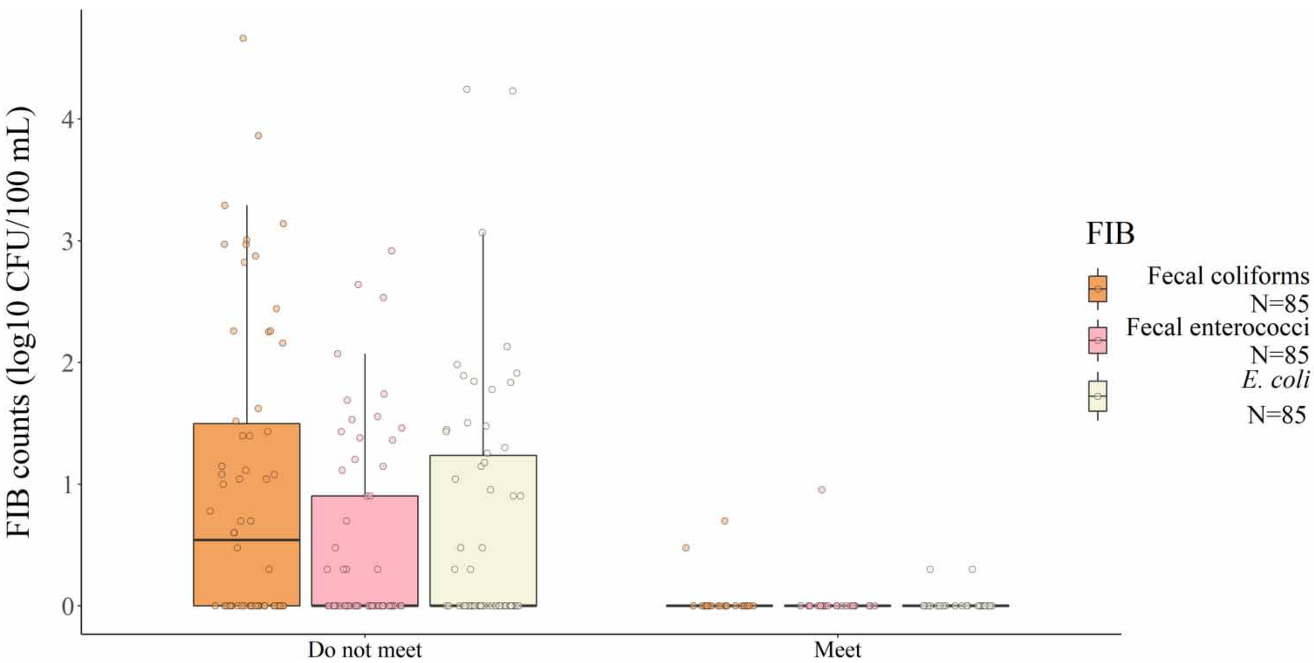


Figure 3 | FIB counts according to the comparison of residual chlorine with NOM-127-SSA-1994 (DOF 2000). Meet: 0.2–1.5 mg L^{-1}; Do not meet: below 0.2 mg L^{-1}.

Table 1 | Parameters for FIB counts reported in Colony Forming Units per 100 mL in household water samples

Variables	Area	N	GM (CFU/100 mL)	Min	Max	SD	p-value[a]	p-value[b]
FC	Tula	29	**19.4**	ND	**4.6×10^4**	**467.8**	1.43×10^{-10}	0.01
	Tlahuelilpan	29	1.9	ND	277.1	6.1		0.99
	Tecozautla	27	4.3	ND	750.8	22.8		
FE	Tula	29	**4.5**	ND	**825.6**	**7.0**	2.65×10^{-5}	0.0006
	Tlahuelilpan	29	1.4	ND	34.4	1.9		0.98
	Tecozautla	27	2	ND	54.8	1.4		
E. coli	Tula	29	**7.4**	ND	**1.7×10^4**	**350.9**	4.48×10^{-8}	0.005
	Tlahuelilpan	29	1.3	ND	78.3	0.76		0.99
	Tecozautla	27	3.5	ND	82.3	4.7		

Note: GM, geometric mean; SD, standard deviation; ND, not detected.
Bold values represent significant differences.
Detection limit <1 Colony Forming Unit (CFU).
[a]*p*-value obtained by Kruskal-Wallis test for the comparison between areas.
[b]*p*-value obtained by Dunett-test for paired comparisons.

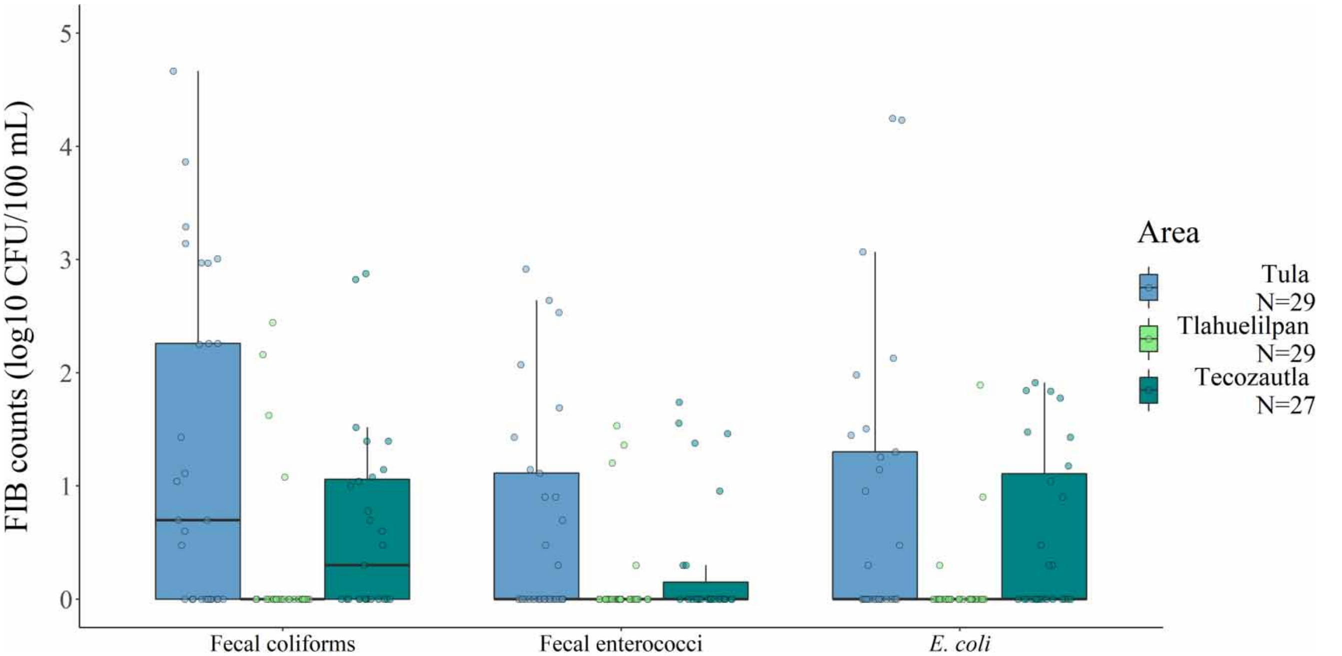


Figure 4 | Boxplot indicating FIB count per area, individual results are shown with points. *N* per area is detailed. It observed that household water samples from Tula contained the highest FIB counts.

Irrigation water comparisons

In general, we found geometric means in wastewater of 3.63×10^6, 1.56×10^5, and 3.02×10^6 CFU/100 mL for FC, FE, and *E. coli*, respectively. The specific values for wastewater analyzed in Tula and Tlahuelilpan are reported in Table 2. For groundwater, we found geometric means of 1.2, 1.2, and 1.3 CFU/100 mL for FC, FE, and *E. coli*, respectively. Due to this apparent difference between wastewater and groundwater, we did not perform a statistical test between these types of water. We contrasted only the areas irrigated with wastewater by means of the Kruskal–Wallis test and observed that these bacterial counts were not significantly different, in that they fall within the same orders-of-magnitude (Table 2).

Table 2 | Parameters for FIB counts reported in Colony Forming Units per 100 mL in water for irrigation

Variables	Area	*N*	GM	Min	Max	SD	*p*-value
			(CFU/100 mL)				
FC	Tula	6	3.9×10^6	4.1×10^4	2.4×10^7	1.4×10^6	0.28
	Tlahuelilpan	6	3.4×10^6	6.5×10^5	1.6×10^7	1.6×10^6	
	Tecozautla	8	1.2	ND	3.1	0.3	
FE	Tula	6	1.4×10^5	2.2×10^4	1.5×10^6	8.9×10^4	0.71
	Tlahuelilpan	6	1.7×10^5	2.6×10^4	6.2×10^5	7.1×10^4	
	Tecozautla	8	1.2	ND	3.7	0.6	
E. coli	Tula	6	3.5×10^6	3.9×10^4	2.2×10^7	2.8×10^6	0.48
	Tlahuelilpan	6	2.6×10^6	4.8×10^5	1.6×10^7	1.1×10^6	
	Tecozautla	8	1.3	ND	19.5	5.9	

Note: GM, geometric mean; SD, standard deviation; ND, not detected.
Detection limit, <1 Colony Forming Unit (CFU).

DISCUSSION

Clean water and sanitation are part of the 2030 Agenda for Sustainable Development. We gathered evidence that, in the agricultural area studied where wastewater is used for irrigation, there is no guarantee of access to clean water although the latter comprises a sustainable development goal and a human right for living under safe environmental conditions (United Nations 2015).

Physicochemical parameters for household water can be compared with Lesser-Carrillo *et al.* (2011), who measured TDS from supply sources showing similar values. In both studies, the Maximum Permissible Limits (MPL) of NOM-127-SSA1-1994 (DOF 2000) for TDS are exceeded (MPL = 1,000 mg L^{-1}). Other parameters included in this regulation are pH and turbidity; in our study, pH was 7.4, which met the MPL (between 6.5 and 8.5), which is similar to that reported by Lesser-Carrillo *et al.* (2011). Turbidity in Tula was 15 NTU, above the MPL of 5 NTU. Temperature and EC were also similar to those reported by Lesser-Carrillo *et al.* (2011) (18.7 °C, and values greater than 1,000 μS cm^{-1}), but these are not included in NOM-127-SSA1-1994. Some of these parameters evidence the degradation of supply sources and household water.

According to the limits established by Mexican Official Regulation NOM-127-SSA1-1994 (DOF 2000), FC or *E. coli* must be absent in water for human use and consumption; however, we found 46 and 38% of household water samples with these indicators. In a previous study in the area serving for pilot sampling, the results demonstrated other percentages of contamination in household water, including 25% of samples positive for FC and 8% of samples positive for *E. coli* (Contreras *et al.* 2017). Therefore, we can state that the water presented poor quality if we consider FIB, as well as confirmed potentially pathogenic *E. coli.* This outcome supports the idea that at least one-quarter of the water for human use and consumption in low- and middle-income households may be contaminated by fecal material, a proportion that is in agreement with the suggested level of Bain *et al.* (2014), a topic of inequity and environmental justice.

Household water quality is worse in Tula compared with Tlahuelilpan and Tecozautla (Figure 4). This result was consistent with our hypothesis that household water from areas irrigated with wastewater contained higher FIB counts, an issue that must be considered in areas with wastewater reuse for irrigation worldwide. However, the FIB load was similar in Tlahuelilpan and Tecozautla irrigated with wastewater and groundwater, respectively (Table 1). The similar pattern between these latter areas demonstrates that fecal contamination is common in the entire region, an issue to be considered by the Ministry of Health authorities. These data confirm that the influence of infiltrated wastewater flowing into the aquifer, which is well documented (Downs *et al.* 1999; Foster & Chilton 2004; Lesser-Carrillo *et al.* 2011), represents a threat to the inhabitants of the Mezquital Valley. The Mexican Regulation focuses on contaminants in wastewater discharged into national

water bodies (NOM-001-SEMARNAT-1996, DOF 1997), and a limit of 1,000 FC/100 mL is considered. FC loads of >1,000 CFU/100 mL were found and reported in this study (Table 2), supporting evidence that the Mezquital Valley aquifer received discharges of these above the allowed limits, which exerts a negative impact on recharge and water quality for irrigation. The Atotonilco-WWTP operation will change the conditions of the irrigation water, but it will take a long time to observe its benefits in irrigated soils and aquifers, which means an improvement in livelihoods among the farmers in the Mezquital Valley. This research serves a baseline for observing such an improvement.

Currently, wastewater for irrigation is not safe: bacterial counts were very high, above 7 logs of FC and *E. coli*, and between four and six orders-of-magnitude for FE (Table 2). During the pilot sampling for irrigation wastewater, geometric means of CFU/100 mL of 1.13×10^7, 7.65×10^5, and 2×10^6 for FC, FE, and *E. coli* were enumerated, while geometric mean counts of groundwater for irrigation were FC = 2.63, FE = 1.57, and *E. coli* = 6.44 CFU/100 mL, as reported in the pilot sampling (Contreras *et al.* 2017). Counts were similar in the pilot study as well as in the reported sampling campaigns. Our findings support what has been reported in other studies, in which very high values of FIB have been observed (Chávez *et al.* 2011; Fonseca-Salazar *et al.* 2016). According to World Organization Health (WHO) recommendations, wastewater for irrigation must be below 1,000 *E. coli* per 100 mL (WHO 2006), thus representing a threat for the inhabitants of the Mezquital Valley.

Due to that household water samples were collected at the point of use, it is difficult to follow the source of contamination, and the comparison was not sufficient among areas that irrigate with different types of water. Therefore, we consider that the fecal contamination that occurred in household water can be multifactorial.

Of the three areas, household water quality was worst in Tula. Currently, it should be irrigated with treated water from the Atotonilco-WWTP. However, the Plant was not operating when sampling was carried out, and irrigation was still performed with wastewater. Exposure to wastewater could be affecting household water quality, along with the lack of chlorination. In addition, it is necessary to consider that Tula is the most urbanized of the three areas and it is immersed within an industrial area with a petrochemical plant and several cement industries. It is probable that there is a negative influence on water quality and a worse environmental health state due to a higher number of inhabitants (109,093 inhabitants versus 37,674 in Tecozautla; INEGI 2015) because a higher amount of local sewage is generated.

In contrast, water quality did not present a significant difference between Tlahuelilpan and Tecozautla, in contrast with our initial prediction. This pattern has been already found and was reported by Falkenberg and collaborators (2018), who also worked in agricultural areas irrigated with different water types (wastewater, surface water, and groundwater as control). These authors did not find a significant difference in *E. coli* counts in any of the areas. Tlahuelilpan and Tecozautla are more agriculturally oriented than Tula. The number of inhabitants is lower in Tlahuelilpan than in Tecozautla (19,389; INEGI 2015), which we suggest contributes to the better water quality recorded in Tlahuelilpan. Additionally, our records indicated higher concentrations of chlorine, which could influence the reduction of microorganism counts.

Tecozautla is a rural area that has more limited health and sanitation services and, in general, more precarious conditions. Its inhabitants ingest the household water, a situation representing a risk since it is contaminated with fecal material and *E. coli*. The inhabitants from Tula and Tlahuelilpan consume bottled water, of unknown origin and quality; therefore, it would be necessary to evaluate the level of fecal contamination in the bottled water.

According to our field data, low levels of residual chlorine were recorded in household water, chlorine is the local primary disinfection treatment for water supplied for human use and consumption. In Mexico, NOM-127-SSA1-1994 establishes a concentration between 0.2 and 1.5 mg L^{-1} as an acceptable interval for residual chlorine in household water (DOF 2000). Unfortunately, we found lower levels of residual chlorine in household water samples (Min–Max: 0–0.96 and a mean of 0.14 mg L^{-1}). We think that the high bacterial counts recorded in household water occurred due to the lack of chlorination (Figure 3). It is possible that there is not an appropriate system of disinfection in any of the study areas. Thus, bacteria and other

microorganisms are not eliminated and can be ingested by the inhabitants of these areas.

Another factor that exerted an effect on water quality was storage, which is associated with intermittent water service. The three areas present a non-continuous (intermittent) water distribution service (denominated *tandeo*), and a partial supply of water occurs in low- and middle-income countries, as described by Brown *et al.* (2013). Storage is a procedure that persons require when the water supply is limited; water is stored during variable periods and, in general, under non-controlled conditions (uncovered storage recipients); as a consequence, bacterial regrowth can occur (Falkenberg *et al.* 2018).

The presence of animals is important in the study areas because nearly 80% of households have pets or farm animals, which can contribute to fecal contamination. According to Gerba (2015), the FC load is different in animal feces, for example, ducks can excrete up to 3.3×10^7 CFU/g feces. On the other hand, a high proportion of solid wastes (garbage) on the floor of households (75%) and surroundings at the time of our visit was observed, an indicator of deficient cleanliness. Clean hands were observed in 86% of persons who gave us access to their household. Falkenberg *et al.* (2018) attributed a mitigation effect to good practices of hygiene and good hand-washing behavior because of their function as barriers that control waterborne diseases. The authors suggest that hands comprise a contamination pathway due to their contact with water. Therefore, hand washing and hygiene are fundamental.

CONCLUSION

General conditions that do not guarantee safe water and sanitation were observed, including not meeting NOM-127-SSA1-1994, insufficient chlorination levels, intermittent water service, and poor intrahousehold water-management practices. Appropriate provision from supply sources, adequate disinfection of drinking water, and better sanitation measures, along with integrative programs on sanitation and hygiene as well as community education, would be strategies for reducing the consequences of contaminated water. These proposals would aid in improving water quality in the studied areas and are strategies that would enhance water and living conditions by reducing waterborne diseases. A definite recommendation lies in the enhancement of the chlorination system and the avoidance of a shortage of water supply or storage under controlled conditions. In the household, individuals should cover recipients in case of water storage and disinfect this water before human consumption.

Moreover, we strongly recommend improving wastewater quality prior to its reuse in the Mezquital Valley, which receives inadequate water quality. This situation may improve over time through the operation of the Atotonilco-WWTP in the State of Hidalgo, a process that should be monitored to follow the changing conditions. As noted, improvement should be observed over time. Our prediction is that improvement will not be observed immediately, in that there is an accumulation of organic matter, microorganisms, and chemicals in the soil, in sediments, and in the irrigation canals, as well as in the different soil layers through which the water infiltrates. Finally, it is necessary to know the risk for humans because water contains high bacterial densities and the potential presence of pathogens. A real improvement of water quality, discharge control, and safe reuse oriented toward risk reduction, in addition to the previously mentioned elements, will guarantee access to safe water and access to sanitation services and hygiene. This should represent an improvement in the area that could contribute toward Sustainable Development Goal number 6 when reusing wastewater for irrigation and related to clean water use in the area. The Mezquital Valley is a reference place for water reuse practices related to public health issues, due to its dimensions and period of water reuse can be considered as a natural laboratory. The environmental health conditions in the Mezquital Valley represent a topic of interest for the World Health Organization for its update of the Guidelines for the Safe Use of Wastewater, Excreta, and Greywater from 2006, in that water reuse is and will become a common practice worldwide.

ACKNOWLEDGEMENTS

We thank Posgrado en Ciencias Biológicas of the Universidad Nacional Autónoma de México (UNAM) for

the development of the postgraduate studies of NV-S in its program. We appreciate grant number 449352 awarded by Consejo Nacional de Ciencia y Tecnología to support the graduate studies of NV-S. Finally, we thank the persons and authorities of Hidalgo State for the permits and facilities to carry out this study.

FUNDING

Financial support for the study design, data collection, and field work was provided by Project 'Prevalencia de enfermedades gastrointestinales y presencia de multidrogoresistencia en comunidades expuestas al reúso de agua residual en el Valle del Mezquital, Hidalgo' (PCNPN2014-14-247779), PI Dr Horacio Riojas-Rodríguez, Instituto Nacional de Salud Pública, México.

DATA AVAILABILITY STATEMENT

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

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First received 2 April 2020; accepted in revised form 22 October 2020. Available online 10 November 2020