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Farmers' perceptions of the use of treated wastewater in agriculture in Chihuahua

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ABSTRACT
Objective: To characterize the farmers of the Tabalaopa-Aldama region in Chihuahua, Mexico, and assess their perceptions regarding the use of treated wastewater (TWW) in agriculture.
Design/methodology/approach: A structured questionnaire was developed and administered to 53 producers from the agricultural sectors of Tabalaopa, Los Leones, and Aldama, in Chihuahua, Mexico. A convenience sampling method was employed for respondent selection, and the data were analyzed using descriptive statistics.
Results: The farmers were primarily engaged in the cultivation of forage crops and pecan trees, utilizing gravity irrigation systems. Irrigation water sources included wells and TWW supplied by the South Wastewater Treatment Plant, which processes domestic wastewater from the city of Chihuahua. Farmers recognized the benefits of using TWW, such as reduced production costs due to lower chemical fertilizer usage and energy savings in water extraction. While 64.2% of farmers expressed interest in using TWW, only 17% indicated willingness to exchange their groundwater concessions.
Study limitations/implications: Although a statistically estimated sample size was considered, the study only covered 21.5% of the total farmer population. Future studies should aim to expand the sample size and enhance data collection through discussion forums and participatory workshops involving relevant stakeholders.
Findings/conclusions: Farmers acknowledge the advantages of TWW and are motivated to use it; however, they are reluctant to trade their groundwater concessions due to the absence of a regulatory legal framework.

Keywords: water; forage crops; profitability; irrigation.

INTRODUCTION

Various factors such as population growth, climate change, increased urbanization, and the overextraction of water for agricultural purposes are exerting growing pressure

on global water resources. It is estimated that by 2050, global water demand will rise by approximately 30% compared to current levels (FAO, 2013). Consequently, the planned reuse of water has emerged as a strategic solution to promote the sustainability of this vital resource. Currently, 20 million hectares are irrigated with treated wastewater (TWW) across 50 countries, accounting for 40% of global food production (Mahfooz *et al.*, 2020). Large-scale water reclamation facilities exist worldwide: Japan operates 1,800 plants, the United States 800, Australia 450, and the European Union 230 projects. In contrast, Latin America has only 50 treatment plants. The principal uses of TWW include agricultural irrigation, urban landscaping, recreational applications, industrial processing and cooling, indirect potable water production, and groundwater recharge (Intriago *et al.*, 2018). In Mexico, several irrigation districts utilize municipal wastewater; the most prominent case is the Tula Valley, where farmers irrigate their fields with wastewater from Mexico City, supplemented by local water sources (FAO, 2013; García-Salazar, 2019). The trend is to increase the use of wastewater as an alternative to control surface and groundwater pollution, enhance water availability, and provide nutrients and fertilizers for crops (Oliveira *et al.*, 2009). Chihuahua ranks as the fifth-largest agricultural state in Mexico, with 1.709 million hectares reported in 2022, representing 5.73% of the national total and encompassing 85,600 agricultural production units (INEGI, 2022). The state leads in the production of apples, cotton, alfalfa, and pecan nuts, and significantly contributes to national maize and bean output (SIAP, 2023). While Chihuahua possesses both surface and groundwater resources, the latter is most extensively exploited (Santos-Hernández *et al.*, 2021). However, aquifer degradation in both quantity and quality is a pressing issue. According to the National Water Commission (CONAGUA, 2018), 58 of the state's 61 aquifers are overdrawn and no longer suitable for further groundwater extraction. Given this scenario, the use of TWW in agriculture presents a viable opportunity to mitigate aquifer overexploitation and secure water supplies for human consumption. This is particularly relevant for the Tabalaopa-Aldama aquifer, which supplies water to the city of Chihuahua. Groundwater from this source is allocated for urban use (78%), agriculture (15%), and industry (7%) (Cervantes *et al.*, 2020). The city of Chihuahua operates two Wastewater Treatment Plants (WWTPs), one of which the southern plant (PTAR-Sur) treats domestic wastewater with an average inflow of 1,200 L s^{-1}. Of this volume, 66.6% is used for agricultural irrigation, 8.3% for greywater applications, and the remainder is discharged into the Chuviscar River (Ochoa-Rivero *et al.*, 2023). As Borja-Bravo *et al.* (2024) emphasize, the optimal utilization of TWW from this plant could yield economic benefits for society, expand the irrigated agricultural area, and increase the water reservoir for human consumption in the city. A key element in leveraging TWW from the PTAR-Sur lies in the participation of farmers from neighboring communities, who stand to benefit directly. However, the adoption of TWW is influenced by the social, economic, and cultural conditions of local populations, as well as by their perceptions of the resource. Therefore, the aim of this study was to characterize the farmers in the Tabalaopa-Aldama region of Chihuahua, Mexico, and to evaluate their perceptions regarding the use of TWW in agriculture. The findings aim to inform the design of public policies related to TWW use, grounded in the realities and perspectives of the stakeholders involved.

MATERIALS AND METHODS

Location of the study area

The research was conducted in the agricultural sectors of Tabalaopa, Los Leones, and Aldama, located between the Tabalaopa-Aldama and Aldama-San Diego aquifers within the Chuviscar River basin (Figure 1), in the state of Chihuahua. The central coordinates of the study area are 28° 43’ 52.80” North latitude and 105° 58’ 14.26” West longitude.

Data collection

To collect data, a structured questionnaire was administered to farmers within the study area. The instrument comprised 32 closed- and open-ended questions and was validated through a pilot survey (n=10). The variables included were organized into the following categories: a) Farmer’s personal information; b) Plot characteristics; c) Forage production technology; d) Farmer’s perception of treated water; and e) Production costs.

Sample estimation

A representative sample was estimated using the finite population method, and the size was determined using the following formula:

$$n = \frac{Z^2 Npq}{(N-1)e^2 + Z^2 pq}$$

Where n represents the sample size; N denotes the total population, which corresponds to the number of registered farmers across the three agricultural sectors (247), as reported by local stakeholders; Z is the standard normal distribution value for a 90% confidence level (1.64); p is the estimated proportion of the population exhibiting the phenomenon

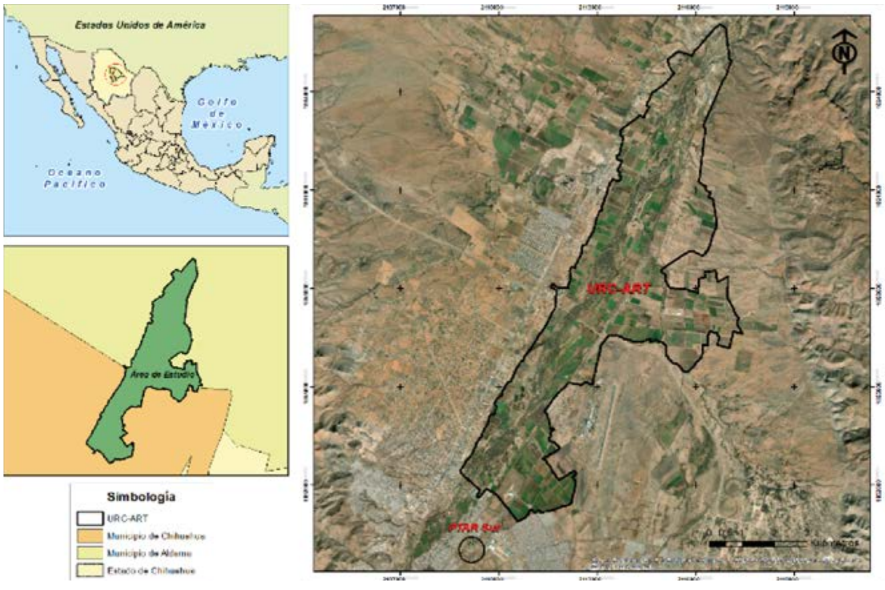

Figure 1. Location of the study area.

under study (0.5); q is the proportion not exhibiting the phenomenon $(1-p)$; and e is the maximum permissible estimation error (10%). Substituting these values into the formula resulted in a sample size of 53 farmers. Respondents were selected using non-probabilistic convenience sampling, as interviews were conducted only with producers who were available and willing to participate.

Data analysis

The data collected from the survey were recorded and coded using Excel 2016 spreadsheets, and subsequently analyzed through descriptive statistics. The profitability of the region's main crops was assessed by first estimating production costs, which were classified as follows:

a) *Variable costs*, including expenses for fertilizers, pesticides, fungicides, herbicides, mechanized and manual labor, and harvesting;
b) *Fixed costs*, which comprised general service expenses.

Revenues were calculated based on information provided by producers regarding product sale prices and crop yields. Finally, producer profit was estimated as the difference between total revenue and total production cost. The *Return per Peso Invested* (*RPI*) was calculated by dividing gross revenue by production cost (Arenas-Julio *et al.*, 2021).

RESULTS AND DISCUSSION

Socioeconomic characteristics of the surveyed farmers

Among the farmers surveyed, 91% were men and 9% women, with an average age of 59 years. Regarding education, 9% reported having no formal schooling, 38% had completed primary education, 28% secondary education, 9% high school, and 15% held a university degree. On average, the respondents had 37 years of experience in agricultural activities. According to De Freitas and Pinheiro (2013), age, education, and agricultural experience are key factors that shape farmers' productive capacities and skills. These variables are closely linked to the adoption and implementation of technological innovations within production units. Similarly, Mahjoub *et al.* (2022) emphasize that these characteristics influence farmers' knowledge regarding the quality parameters of the water used in their production systems. A total of 56.6% of respondents indicated that agriculture was their sole source of income. Meanwhile, 30.2% combined agriculture with livestock activities; 9.4% reported deriving income from both agriculture and a personal business; and 3.8% combined agriculture with formal employment. These findings reveal a diversified income structure or pluriactivity within the production units. This approach is increasingly recognized as a strategy within family farming, where agricultural and non-agricultural activities are interwoven to meet household needs and ensure social reproduction. Such diversification represents not only a means of financing the operation of production units but also an adaptive strategy in response to ongoing transformations in the agricultural sector (Osorio-García *et al.*, 2015).

Productive characteristics of agricultural production units

On average, the surveyed farmers cultivate 15 hectares. Among them, 85% reported holding ejido land, while 15% operated under private ownership (Table 1). Most respondents utilized gravity irrigation systems, with only 6% employing sprinkler or drip irrigation. These findings reflect the broader reality of rural Mexico, where ejido land tenure remains predominant (Morett-Sánchez & Cosío-Ruiz, 2017). According to Olvera-Salgado *et al.* (2014a), in the state of Chihuahua, ejido tenure is associated with lower levels of technological advancement and fewer development opportunities compared to private ownership. Ejido systems are the largest consumers of water due to their reliance on gravity irrigation and limited technological modernization, which restricts water conservation efforts. In contrast, privately owned land tends to exhibit more favorable economic, social, technological, and environmental conditions.

In the study area, low water use efficiency in agriculture is evident, primarily due to the predominance of gravity irrigation systems Mexico's most widely used method covering 91% of irrigated land, while only 9% employ sprinkler or drip systems (FAO, 2017). Although irrigation modernization has been shown to increase agricultural productivity, economic returns, and water savings (Olvera-Salgado *et al.*, 2014a), several factors influence its adoption. According to García-Salazar *et al.* (2023), the adoption rate of modern irrigation systems is shaped by variables such as electricity prices, the economic value of water (based on crop market value), rainfall, temperature, farm size, aquifer overexploitation, and farmers' educational level. Olvera-Salgado *et al.* (2014b) noted that in Chihuahua,

Table 1. Productive Characteristics of Farmers' Parcels.

Feature		Farmers (n)	Farmers (%)
Land Tenure			
	Ejido	45	85
	Private Property	8	15
Plot Area			
	Seasonal	8	15
	Irrigation	53	100
Irrigation Type			
	Gravity-Flow	47	89
	Sprinkler	3	6
	Drip	3	6
Water supply source			
	Own well	2	4
	Shared well	9	17
	TWW	23	43
	Surface water	4	8
	Collective well + TWW	10	19
	Private well + TWW	3	6
	Collective well + Surface water	2	4

Source: Prepared with information obtained from the survey.

drip irrigation systems are typically used for high-investment crops such as vegetables and are adopted by farmers with higher socioeconomic status. In contrast, gravity irrigation systems are predominant among producers of staple crops with lower socioeconomic status and limited access to technological innovations. Therefore, expanding the use of modern irrigation systems requires integrating farmers' socioeconomic conditions into the design of implementation strategies, considering factors such as plot size, income levels, cropping patterns, and availability of technical assistance (Torres-Moreno *et al.*, 2023; García-Salazar *et al.*, 2023). In the study, 28.3% of surveyed farmers reported using more than one water source for agricultural purposes (Table 1), typically combining well water with Treated Wastewater (TWW). A significant proportion of farmers rely on TWW for cultivation. As noted by Ochoa-Rivero *et al.* (2023), the PTAR-Sur discharges its effluent into the Chuviscar River, and the resulting combined flow supports downstream agricultural activities. Farmers with plots located near the river benefit the most from access to TWW, whereas those with parcels farther away rely primarily on well water.

Crop Profitability

Table 2 presents the crops identified by farmers as the most important in the region. The predominance of forage crops is attributed to the strong presence of livestock farming. Regarding pecan production, plantations have significantly expanded over the past decade in the municipalities of Chihuahua and Delicias. Between 2014 and 2023, both harvested area and production increased at an average annual growth rate of 12.6% and 11.2%, respectively (SIAP, 2023).

According to the results shown in Table 3, pecan was the most profitable crop, yielding a return of $1.86 for every peso invested equivalent to a profitability rate of 186%. These findings are consistent with those reported by López *et al.* (2011), who noted that pecan cultivation offers high profitability when managed under medium-level technology,

Table 2. Cultivated Area and Yield of Main Crops.

Crop	Variable	Unit of measurement	Average values
Alfalfa	Average Area	ha	7.5
	Yield	Bales ha^{-1}	261
Oatmeal	Average Area	ha	18.6
	Yield	Bales ha^{-1}	143
Corn	Average Area	ha	4.8
	Yield	t ha^{-1}	30.3
Ryegrass	Average Area	ha	9
	Yield	Bales ha^{-1}	277
Sorghum	Average Area	ha	5.6
	Yield	Bales ha^{-1}	400
Walnut	Average Area	ha	7.5
	Yield	t ha^{-1}	1.6

Source: Prepared with information obtained from the survey.

Table 3. Crop profitability.

Crops	Production Costs	Gross Income	Revenue	GPI*
	$ ha^{-1}			
Alfalfa	13,969	20,855	6,886	1.49
Oatmeal	9,385	11,400	2,015	1.21
Corn	18,063	24,267	6,204	1.34
Ryegrass	10,080	27,750	17,670	2.75
Sorghum	11,800	24,000	12,200	2.03
Walnut	39,692	113,411	73,719	2.86

GPI=Gain per Peso Invested.
Source: Prepared with information obtained from the survey.

making it a viable and low-risk option. This, combined with the high market value of pecans, explains the expansion of plantations and production in the study region.

Other crops such as ryegrass, sorghum, alfalfa, maize, and oats showed lower profitability compared to pecans. However, they remain widely cultivated due to their lower investment requirements and their role as essential feed inputs for livestock production. These crops support the sale of live calves, carcass meat, and milk (Quintana & Solís, 2023).

Farmers' perceptions of the impact of drought in recent years

Farmers reported that the droughts experienced in recent years have significantly affected their agricultural activity. For 47.2% of them, the main issue identified was a decrease in crop yields. This situation affects forage availability, forcing livestock-owning farmers to purchase it at high prices, in addition to suffering animal losses or resorting to selling their livestock. The consequences on their livelihoods, livestock productivity, crop yields, and the availability of irrigation water have led farmers to seek alternative sources of income or, in some cases, to abandon agriculture for other types of work (Alotaibi *et al.*, 2020). A total of 45.3% of farmers stated that they had not taken any measures to address the drought periods of recent years, while 54.7% reported that they had implemented actions such as reducing the number of irrigations, switching from gravity to sprinkler irrigation systems, extracting more water from their wells, constructing countercurrent embankments, reducing the cultivated area, and drawing supplementary irrigation from the river. Among all respondents, 73.6% expressed concern that their water source could be depleted. The main causal factors they perceived were droughts that affect aquifer recharge, the depletion of wells, and the population growth of the city of Chihuahua, which leads to increased domestic water consumption. Meanwhile, 26.4% believed their water sources were not at risk of depletion, assuming that water availability remains sufficient.

Farmers' knowledge of TWW

Farmers' knowledge of treated wastewater (TWW) is extensive, partly because some currently use this type of water and those who do not are aware of its benefits. A total of 64.2% of respondents expressed interest in using TWW for their crops, and the reasons for doing so included reduced production costs, savings in fertilizer use and electricity for water extraction, and greater water availability. This result is consistent with findings among farmers in countries such as Tunisia and Pakistan, who stated that TWW has a positive impact on agricultural crops, as this type of water provides nutrients to plants and reduces fertilizer use (Akhtar *et al.*, 2018; Mahjoub *et al.*, 2022). Likewise, in Iran, the main drivers for using TWW in agriculture were water scarcity, increased crop yields, reduced production costs, difficulty in accessing freshwater, freshwater savings, and improved soil fertility (Maleksaeidi *et al.*, 2018).

The main advantage observed by farmers when using TWW for irrigation focused on the reduction of production costs, since wastewater contains significant amounts of beneficial nutrients such as N, P, and K, and micronutrients like Fe and Zn, which can promote plant growth and yield, thus reducing the demand for chemical fertilizers (Pereira *et al.*, 2012; Jung *et al.*, 2014). Therefore, the careful use of TWW can reduce fertilizer application and, consequently, lower both production and environmental costs (Turlej and Banás, 2018). A total of 22.6% of farmers expressed willingness to exchange their well water for TWW for agricultural use. However, 13.2% stated they would not exchange well water for TWW because they operate recreational centers (spas) and need to maintain their wells for water supply. The remaining 64.2% chose not to answer the question. The low response regarding willingness to exchange well water for TWW was due to the fact that producers were not aware of any proposal specifying the conditions under which the exchange would occur. In addition, at that time, no governance framework existed for the use and availability of this resource, creating an atmosphere of uncertainty and insecurity that made it difficult for them to make a decision regarding the exchange of well water for TWW. Finally, farmers were asked whether they would be willing to exchange their clean water concession for a TWW concession for agricultural use. In this regard, 56.6% chose not to answer. The farmers who expressed willingness to make the exchange (17%) stated that they would do so because they were aware of the advantages of TWW, as it would ensure water availability for their crops and allow them to continue their economic activities. They also considered that this would benefit the city's population, which is continuously growing and requires increasing volumes of potable water. On the other hand, 26.4% were not willing to make the exchange because they were uncertain whether TWW would be sufficient to irrigate their cultivated area, which would affect their production. They also mentioned that giving up their well water concession would reduce the value of their land. Among those who would not exchange their concession, 57.1% stated that they did not have a well to exchange. The opinions expressed by farmers reflect their interest in using TWW for their crops; however, there is no clear willingness to negotiate an exchange of this resource for their groundwater extraction concessions. In reality, the farmers who currently use TWW do so because the resource is available and located near their plots. However, there is no regulatory legal framework governing the use of TWW. In this sense, to enable proper and efficient use, changes must be made in the traditional structures of water resource allocation, requiring investment in infrastructure, the establishment of water and soil quality standards, regulatory frameworks, and institutional mandates.

CONCLUSIONS

Farmers in the agricultural region of Tabalaopa-Aldama, in Chihuahua, are primarily engaged in the cultivation of forage crops and pecan, using gravity irrigation systems. Within their production units, the main sources of irrigation water are wells and treated wastewater (TWW) from the PTAR-Sur, which recycles domestic water from the city of Chihuahua. Farmers are aware of the agricultural advantages offered by the use of TWW, particularly in terms of reduced production costs due to lower fertilizer use and savings on electricity for groundwater extraction. While 64.2% of farmers expressed interest in using TWW, only 17% were willing to exchange their groundwater concessions for TWW. To promote the safe reuse of TWW in the region, institutions and stakeholders must ensure a systematic, reliable, high-quality, and timely supply. Public policies concerning the use of TWW should focus on regulating treated water quality, establishing usage standards, and fostering research and development in water treatment technologies, crop technology packages using TWW irrigation, and frequent soil quality monitoring to ensure the sustainability of agricultural systems.

When designing public policies, it is essential to consider the existing knowledge gap regarding reuse and water quality parameters. Therefore, farmers and consumers must be educated and made aware through periodic training campaigns about the benefits and risks associated with TWW. At the governmental level, it is crucial to promote economic incentives and financing mechanisms for water reuse projects. Additionally, the establishment of a legal and regulatory framework to facilitate the management and distribution of TWW is of utmost importance.

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