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Adoption of Irrigation Water Contamination Prevention Practices Among Smallholder Farmers in Chile: Integrating the Theory of Planned Behavior and Structural Variables

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Abstract

Irrigation water quality is a crucial factor for agricultural sustainability and food safety, particularly amid climate change, water scarcity, and inadequate rural infrastructure. This study identifies the behavioral and structural factors associated with the adoption of eight water contamination prevention practices among smallholder farmers in central Chile, including irrigation canal cleaning, use of water filters, rainwater collection systems, and irrigation methods that avoid contact between edible crop parts and water. Drawing on the Theory of Planned Behavior (TPB), behavioral constructs were integrated with structural features of production systems to capture both cognitive and contextual drivers of adoption. A survey of 101 farmers in the O'Higgins Region was conducted, and a binary logistic regression model was applied ($n = 96$; AUC = 0.821). Results indicate that adoption was significantly associated with favorable attitudes toward preventive practices (OR = 1.16; $p = 0.014$) and supportive subjective norms (OR = 1.21; $p = 0.037$), while perceived behavioral control showed no significant effect. Among structural factors, the use of modern irrigation technologies was the strongest predictor (OR = 16.55; $p < 0.001$), followed by diversified production systems (OR = 14.55; $p = 0.003$) and the cultivation of fruit trees or vines (OR = 9.00; $p = 0.002$). These findings indicate that attitudinal and normative factors are more consistently associated with adoption when supported by enabling infrastructure and production conditions. They underscore the need for integrated policy approaches that align motivational and material components to promote sustainable water management practices in resource-constrained agricultural contexts.

Keywords: agricultural behavior; Chile; family farming; irrigation water quality; smallholder farmers; sustainable agriculture; technology adoption; Theory of Planned Behavior



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1. Introduction

The escalating climate crisis poses a pressing threat to global food security and sustainable water management. This urgency is further compounded by projected population growth, with estimates reaching approximately 9.7 billion by 2050 and peaking at around 10.4 billion in the 2080s [1]. In this context, agriculture, which currently accounts for approximately 70% of global freshwater withdrawals, is increasingly vulnerable due to both declining water availability and deteriorating water quality [2].

Irrigation water quality is a critical component of agricultural systems, as its degradation can facilitate the introduction of pathogens such as *E. coli*, *Salmonella*, and *Listeria monocytogenes* into the food chain, compromising product safety and public health [3,4]. This situation is particularly acute in rural areas where sanitation infrastructure is insufficient, and extreme weather events further increase the risk of contamination [4].

At the international level, several regulatory frameworks have been established to mitigate microbiological risks in agricultural production. The Codex Alimentarius Commission has issued guidelines for the safe use and reuse of water in food systems [5], and the agri-food industry has adopted protocols such as Hazard Analysis and Critical Control Points (HACCP) [6–9]. However, meeting these standards remains a considerable challenge for small-scale farmers, especially those in low- and middle-income countries, due to economic, technical, and organizational constraints [10].

In Latin America—and particularly in Chile—small-scale agriculture plays a key role in supplying fresh foods to local markets. Yet, it continues to face persistent limitations in infrastructure, technical assistance, financing, and certification mechanisms [3,11,12]. Although significant advances have been made in food safety regulation, specific standards on irrigation water quality for small-scale agricultural systems remain incomplete, hindering effective implementation [13].

Furthermore, there is limited, fragmented information on the pro-environmental behavior of small-scale farmers, including practices and decisions related to water irrigation management and contamination prevention. These behaviors directly affect environmental sustainability and food safety. However, family farmers are often excluded from formal monitoring and evaluation systems, complicating efforts to identify barriers and enabling conditions for the adoption of preventive practices [5–8].

Previous research has explored the adoption of sustainable agricultural technologies by integrating economic, social, and psychological dimensions [14–17]. Among the most frequently applied theoretical frameworks is the Theory of Planned Behavior (TPB), which explains how attitudes, social norms, and perceived behavioral control shape decision-making in agricultural [18–22]. Nonetheless, several authors have questioned TPB's explanatory sufficiency in resource-constrained environments, noting persistent gaps between behavioral intention and actual adoption [21,23]. In particular, the perceived behavioral control (PBC) component has shown inconsistent effects, prompting calls for models that better integrate structural and contextual dimensions [15,24].

Despite this body of evidence, three gaps remain unaddressed in the literature. First, TPB has rarely been applied to the prevention of irrigation water contamination, as distinct from the adoption of irrigation technologies or soil conservation. Second, empirical studies from Latin American smallholder farming contexts remain scarce, limiting the generalizability of existing findings to these settings. Third, few studies simultaneously integrate structural production variables—such as crop type and irrigation method—within a TPB framework, despite evidence that structural constraints systematically mediate the intention–adoption gap [15,20,24].

These gaps are particularly consequential, given that climate change is intensifying contamination risks by concentrating pollutants in reduced water volumes. At the same time, smallholder farmers producing food for national and export markets remain largely excluded from the formal monitoring system [3,6].

This study addresses the following research question: What behavioral and structural factors explain the adoption of irrigation water contamination prevention practices among smallholder farmers in central Chile? To answer this, the TPB framework is applied while incorporating structural variables related to production systems, proposing an inte-

grated approach that examines how socio-behavioral constructs interact with technical and material conditions in rural agricultural contexts.

2. Materials and Methods

2.1. Conceptual and Analytical Framework

Understanding the factors influencing farmers' adoption of sustainable practices is essential for designing effective policies in rural contexts. The Theory of Planned Behavior (TPB), proposed by Ajzen [18], provides a robust analytical framework for examining how beliefs, attitudes, social norms, and perceived behavioral control influence individual decision-making. Its application in agricultural research has enabled scholars to investigate farmers' intentions to adopt innovations and the factors that facilitate or hinder their implementation within real-world production systems.

According to TPB, the intention to perform a behavior depends on three main determinants: (i) attitude toward the behavior, or the individual's positive or negative evaluation of its outcomes; (ii) subjective norms, or perceived social pressure to perform or avoid the behavior; and (iii) perceived behavioral control, which refers to one's perceived capacity and available resources to execute the action.

Each of these components is underpinned by a set of beliefs—behavioral, normative, and control beliefs, respectively—reflecting past experiences, cultural frameworks, social contexts, and structural conditions that influence decision-making [18,19].

More recent literature has expanded the TPB framework by incorporating additional constructs, including self-efficacy, social identity, place attachment, and institutional trust [25–28]. These extensions aim to strengthen the model's explanatory power, particularly in cases where intention does not necessarily translate into behavior—a phenomenon known as the intention–behavior gap [21,29].

A recurrent critique of TPB concerns its limited integration of structural and material dimensions. As seen in studies by Bechini et al. [15], Eanes and Zhou [20], and Zhang et al. [30], positive attitudes or intentions alone may not lead to adoption when farmers lack infrastructure, technical support, or economic incentives. From this perspective, agricultural behavior cannot be analyzed solely through a psychological lens. Still, it must also consider contextual variables such as land tenure, crop type, access to technology, and participation in farmer networks [31,32].

An essential contribution in this direction is provided by Gütschow et al. [24], who introduced the concept of the “action space”, defined as the effective range of decisions available to farmers given their structural environment. This notion helps explain why even those with good intentions may face barriers that hinder the adoption of sustainable practices.

Building on these insights, Bechini et al. [14,15] proposed a disaggregated operationalization of TPB in agricultural settings to more precisely capture the variability, intensity, and directionality of decision-making processes. Their approach breaks down the model's three core components into products, ranging from belief strength to corresponding evaluations. It adjusts them around a neutral midpoint on a 1-to-5 Likert scale (where 3 represents neutrality). The equations are expressed as follows:

- Attitude = behavioral belief strength $\times$ (outcome evaluation – 3);
- Subjective norms = motivation to comply $\times$ (normative belief – 3);
- Perceived control = control belief strength $\times$ (control power – 3).

This transformation identifies drivers and barriers to behavior: positive values indicate a facilitating influence, whereas negative values reflect an inhibiting one. To qualify as a driver or a barrier, two conditions must be met: the combined score must have an absolute value ≥ 3 , and the underlying belief must have an intensity ≥ 3 on the scale.

The Likert scale ranges from 1 to 5, with 3 representing the neutral value. For example, a belief strength of 4 and an outcome evaluation of 4 yield a score of 4 times (4 minus 3) = 4, indicating a driver. In contrast, a strength of 3 and an evaluation of 2 results in $3 \times (2 - 3) = -3$, indicating a barrier. This procedure enhances the model's interpretive precision by distinguishing between truly motivating factors and those that appear neutral due to ambivalent belief combinations.

This refined operationalization has been successfully applied in dairy systems in northern Italy, where practices such as crop residue incorporation were promoted by positive beliefs and technical support, whereas others, like green manure use, faced economic and social constraints [15]. Its main contribution lies in improving TPB's predictive validity by distinguishing between factors that genuinely drive adoption and those that inhibit it despite high belief intensity.

The present study adopts this methodological procedure to classify the socio-behavioral factors influencing the adoption of irrigation water contamination prevention practices among small-scale farmers in central Chile. In a context characterized by structural limitations and low awareness of contamination risks, the analysis examines how these behavioral constructs interact with production system features—such as crop type and irrigation technology. The integrated conceptual model applied in this study is presented in Figure 1.

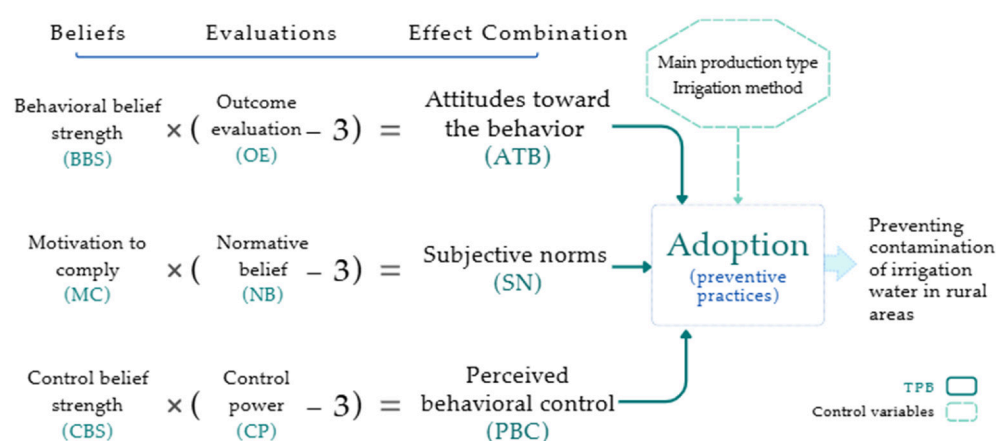


Figure 1. Conceptual Model: TPB and Variables of Production Systems. Note. Prepared by the authors based on the work of Bechini et al. [14,15] and Castillo et al. [33].

2.2. Case Study

This study was conducted in the Libertador General Bernardo O'Higgins Region, one of Chile's main agricultural zones, with a strong specialization in fruit production and a significant presence of small-scale farmers. The region accounts for approximately 20.7% of Chile's national agricultural and forestry value added [34]. It faces considerable challenges related to water sustainability, including microbiological contamination of irrigation water, inadequate environmental oversight, and limited access to suitable technologies [11].

According to the VIII National Agricultural and Forestry Census [35], the region covers 16,387 km² and recorded 9130 agricultural production units (UPAs) across a total surveyed area of 1,137,600 ha. The ten sampled communes account for 3585 UPAs covering 241,228 ha. Fruit trees are the dominant productive activity (45.4% of UPAs), followed by vegetables and annual crops (21.3%) and grapevines (7.0%). Regarding farm size, 50.2% of regional UPAs have less than 10 cultivated hectares, a proportion that ranges from 36.8% to 71.5% across the sampled communes [35]. In the Chilean institutional framework, PRODESAL users are classified as small producers under INDAP Organic Law N° 18910, defined as farmers whose productive assets do not exceed 3500 UF and whose land does

not exceed 12 Basic Irrigation Hectares—a threshold consistent with the farm size profile documented in this census for this area.

Between 2013 and 2022, the region reported 235 food contamination notifications, primarily in fresh fruits and vegetables, according to the Food Safety and Alerts Information Network (RIAL). This figure places O'Higgins among the three most affected regions in Chile [36–38]. These trends highlight the urgent need to address irrigation water quality, particularly in small-scale systems supplying local markets that lack effective risk mitigation strategies.

The target population consisted of smallholder farmers participating in the Local Development Program (PRODESAL), implemented by the Agricultural Development Institute (INDAP) under Chile's Ministry of Agriculture (MINAGRI). This program provides technical assistance, production incentives, and public–private linkages. As of 2023, PRODESAL served 8243 users in the O'Higgins Region, representing 11.4% of the national total [39].

The study was carried out in ten municipalities selected for their productive diversity and engagement with local PRODESAL teams: San Vicente, Doñihue, Rengo, Malloa, Quinta de Tilcoco, Coinco, Coltauco, Olivar, Chimbarongo, and Placilla. Participant selection followed a purposive sampling strategy. Inclusion criteria were: (1) active registration in the PRODESAL program at the time of the survey; (2) engagement in agricultural production activities during the 2023–2024 growing season; and (3) availability during field visits coordinated by PRODESAL technical advisors. Farmers were excluded if they had not been active in agricultural production during the reference period or if they were unavailable during scheduled fieldwork dates. This sampling strategy was adopted given the absence of a complete and accessible sampling frame for smallholder farmers in the region, and because PRODESAL constitutes the primary institutional channel through which this population can be systematically reached. The authors acknowledge that this design introduces potential selection bias, as PRODESAL users have greater access to technical support and institutional resources than non-participating farmers, potentially leading to an overestimation of adoption levels. This limitation is discussed in Section 5. A total of 101 valid observations were collected. The geographic distribution of the sampled municipalities within the O'Higgins Region is shown in Figure 2.



Figure 2. Map of the O'Higgins Region and Selected Municipalities. Note. Adapted from INDAP, O'Higgins Region (<https://www.indap.gob.cl/ohiggins>) (accessed on 16 July 2026).

2.3. Data Collection

A structured survey instrument, validated by subject-matter experts, was designed and divided into five sections: (1) socio-demographic and productive characteristics; (2) sources and uses of irrigation water; (3) management practices and contamination prevention measures; (4) behavioral variables based on the Theory of Planned Behavior (TPB); and (5) dimensions related to social capital.

The survey was conducted in person in January 2024, during meetings coordinated by PRODESAL technical advisors. The field team consisted of the lead researcher and four trained enumerators. Data was collected using digital forms (Google Forms, Google LLC, Mountain View, CA, USA) and automatically uploaded to a centralized database. All participants gave informed consent before their participation.

2.4. Sample Characterization

The final sample consisted of 101 farmers (63 men and 38 women; 62.4% and 37.6%, respectively). The sample is predominantly mature: 49.5% were aged 45–59 years, and 46.5% were aged 60 years or older. This profile is consistent with the regional pattern documented by the VIII National Agricultural and Forestry Census, according to which the average age of producers in the O'Higgins Region is 60.4 years, with 79.1% of the farming population aged 50 or above [35], reflecting the advanced aging of family agriculture in central Chile. In terms of formal education, 42.0% had completed primary schooling or less, 30.0% had completed secondary education, and 11.0% had technical or university-level training. The majority (60.4%) reported more than 21 years of farming experience. Regarding productive characteristics, the primary activity was vegetables and annual crops (51.5%), followed by fruit trees and vines (28.7%), diversified production (15.8%), and livestock or other activities (4.0%). Farm size was predominantly small: 76.8% of respondents cultivated less than 0.5 ha, and only 3.2% reported more than 5 ha, consistent with the small producer profile established under INDAP Organic Law N°18910 and with the farm structure of the sampled communes, where between 36.8% and 71.5% of UPAs have less than 10 cultivated hectares [35]. The main irrigation method was surface irrigation (68.0%), followed by drip or sprinkler systems (22.0%) and mixed approaches (7.0%). Irrigation canals or ditches were the primary water source for 81.2% of respondents.

Regarding household income, 76.2% reported monthly earnings below CLP 460,000 (approximately USD 500), reflecting the subsistence and semi-subsistence nature of the farming units in the sample. In terms of social capital, 51.5% belonged to a water users' organization, while 40.6% reported no organizational affiliation. All participants were active PRODESAL users at the time of the survey. The logistic regression model was estimated on a final sample of $n = 96$ after excluding five observations with missing values for the irrigation method variable (category 91).

2.5. Data Analysis

Initial data screening was conducted in Stata (version 15; StataCorp LLC, College Station, TX, USA). All subsequent analyses were performed in R (version 4.5.1; R Core Team, Vienna, Austria) via RStudio (version 2026.06.0+242 "Blue Plumbago"; Posit Software, PBC, Boston, MA, USA), using the psych, GPArotation, and nFactors packages for exploratory factor analysis; lavaan and semPlot for confirmatory factor analysis; car [40] for variance inflation factors; pROC for the area under the ROC curve; ResourceSelection for the Hosmer–Lemeshow test; and margins for marginal effects.

2.5.1. Empirical Model

A binary logistic regression model was estimated to assess the influence of cognitive and structural factors on the adoption of practices to prevent contamination of irrigation water. The dependent variable Y_i takes the value 1 if the farmer i adopted at least one preventive practice, and 0 otherwise. The model is expressed as follows:

$$\ln\left(\frac{P(Y = 1 | X)}{1 - P(Y = 1 | X)}\right) = \beta_0 + \beta_1 \text{Prod}_i + \beta_2 \text{IMethod}_i + \sum_{\alpha} \beta_{\alpha} Z_{\alpha i}$$

where Y_i represents the probability that the farmer i adopts at least one preventive measure to avoid irrigation water contamination. The variables are defined as follows:

- Prod_i denotes the type of production system (vegetables, fruit trees, diversified production, livestock);
- IMethod_i refers to the irrigation method (gravity or technified);
- $Z_{\alpha i}$ is a vector of socio-behavioral variables derived from TPB, operationalized following the methodology of Bechini et al. [14,15].

To assess potential multicollinearity among the independent variables, Generalized Variance Inflation Factors (GVIFs) were computed for all predictors in the final model, following Fox and Weisberg [40]. All GVIF values were well below the conventional threshold of 5: production system type (2.06), irrigation method (1.82), Attitude Toward Behavior (1.59), Perceived Behavioral Control (1.44), and Subjective Norms (1.22). These results confirm the absence of problematic multicollinearity and support the robustness of the coefficient estimates.

2.5.2. Variable Operationalization

The independent variables were classified into two main categories. The first comprised structural characteristics of the production system—such as primary crop type and irrigation method—measured using closed-ended multiple-choice questions. The second category encompassed socio-behavioral dimensions, consisting of 17 items adapted from studies based on the Theory of Planned Behavior (TPB) [14,15], measured on a five-point Likert scale.

Composite indicators were constructed for each TPB dimension by integrating belief strength and evaluation/perception components, following the procedure described in Section 2.1.

The assignment of items to each TPB subcomponent followed both theoretical and empirical criteria. Item selection was guided by an iterative process involving four model specifications that tested alternative operationalizations of each construct (see Appendix A). For Motivation to Comply (MTC), items capturing the disposition to seek and use technical information were retained, as institutional extension agents (PRODESAL/INDAP technical advisors) constitute the primary normative referent in this context—an adaptation consistent with applications of TPB in extension-based agricultural systems [14,15]. The model specification incorporating these items produced the best fit among the alternatives tested (AIC = 106.4; AUC = 0.821). For Control Belief Strength (CBS), items encompassing both cognitive barriers and regulatory constraints were included, reflecting Ajzen's [18] broad definition of control beliefs as perceptions of internal and external factors that facilitate or inhibit the behavior, and consistent with extensions of this construct to regulated production contexts [20,41]. Control Power (CP) was operationalized with a single item due to sample size constraints; this limitation is acknowledged in Section 5.

To validate the internal consistency of the items and reduce dimensionality, both Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) were performed.

These were complemented by additional validation techniques, as summarized in Table 1. The specific assignment of items to each TPB component is detailed in Table 2, while a comprehensive description of the EFA and CFA procedures is provided in Appendix A.

Table 1. Summary of statistical methods used for item validation and factor structure assessment.

Method	Description
Extraction	Maximum Likelihood and Principal Components
Rotations	Orthogonal (Varimax) and Oblique (Oblimin)
Adequacy tests	RMSEA, CFI, TLI, Cronbach's Alpha, McDonald's Omega
Bootstrap	Factorial stability in small samples

Table 2. Assignment of survey items to TPB constructs and components.

TPB Construct	TPB Component	Item Description	Question Evaluated
Attitude Toward Behavior (ATB)	Behavioral belief strength (BBS)	Importance of maintaining clean water	How important is it for you to keep irrigation water free of contaminants?
		Concern about contamination	How concerned are you about possible irrigation water contamination in your area?
		Water quality and crop health	Using better-quality water improves plant health and growth.
	Outcome evaluation (OE)	Changing practices could affect current production	Changing my water quality practices could affect my current production.
Subjective Norms (SN)	Motivation to comply (MTC)	Technological resources for information	I have the necessary tools to access water-quality information.
		Online resources	I use online resources to learn about agricultural topics.
		Technical advice	I seek advice from agricultural experts or technicians when facing problems.
	Normative belief (NB)	Community recommendations	How willing are you to follow the community's recommendations for water care?
		Neighbors' opinions	How much influence do your neighbors' opinions have on your water quality decisions?
Perceived Behavioral Control (PBC)	Control belief strength (CBS)	Lack of knowledge	A lack of knowledge makes it challenging to implement effective water safety measures.
		Insufficient labor	I lack additional labor to implement water quality measures.
		Exclusionary regulations	Regulations on water access are overly strict and fail to adequately address the needs of small farmers.
		Complex permits	Obtaining product certification permits can be a slow and complicated process.
	Control power (CP)	Impact of institutional programs	Support programs have had a positive impact on my agricultural activities.

Source: Own elaboration based on survey instrument and TPB structure.

The dependent variable was constructed following the methodology proposed by Bechini et al. [14,15]. Farmers were classified as “adopters” if they reported implementing at least one preventive measure against irrigation water contamination. The specific

practices—such as the use of water filters or clarifiers, and the installation of water-related signage—were identified through Exploratory Factor Analysis. A detailed explanation of the EFA procedure used to validate this construct is provided in Appendix B.

3. Results

3.1. Descriptive Statistics

The final analytical sample comprised 96 small-scale farmers, after excluding 5 cases with missing values in one or more model variables; the initial sample comprised 101 participants. Of these, 34.4% ($n = 33$) were classified as adopters—farmers who had implemented at least one irrigation water pollution prevention practice—while 65.6% ($n = 63$) were non-adopters.

Table 3 presents the comparisons of means and proportions between adopters and non-adopters, based on the TPB constructs and production system characteristics.

Table 3. Baseline Descriptive Statistics.

Variable	Total Sample ($n = 96$)	Non-Adopters (SD)	Adopters (SD)	W	<i>p</i> -Value
TPB Variables					
ATB *	2.33 (7.1)	1.25 (6.97)	4.49 (6.95)	743	*
BBS	4.62 (0.57)	4.67 (0.49)	4.60 (0.59)	1072	
OE	3.49 (1.47)	3.25 (1.45)	3.94 (1.43)	746	*
SN	1.34 (3.23)	1.00 (3.33)	1.99 (2.97)	894	
MTC	3.19 (1.0)	3.13 (1.03)	3.31 (0.95)	932	
NB	3.42 (1.0)	3.30 (1.09)	3.64 (0.85)	886	
PBC	2.03 (3.41)	2.91 (4.62)	3.44 (4.42)	940	
CBS	3.99 (0.66)	3.80 (0.74)	4.08 (0.76)	866	
CP	3.47 (0.79)	3.67 (1.17)	3.76 (1.05)	932	
Production System Variables					
Vegetables/annual crops	(52.1%)	(61.90)	(33.33)	—	*
Fruit trees, vines/nuts	(29.2%)	(22.22)	(42.42)	—	*
Diversified production	(15.6%)	(12.70)	(21.21)	—	*
Livestock production	(3.1%)	(3.17)	(3.03)	—	*
Gravity irrigation	(69.8%)	(79.37)	(51.52)	—	**
Irrigation technology	(30.2%)	(20.63)	(48.48)	—	**

Note. Means (standard deviations) are reported for continuous variables; frequencies (percentages) for categorical variables. Continuous variables were analyzed using the Wilcoxon rank-sum test; the W statistic reported in the table corresponds to the rank-sum statistic returned by this test. Categorical variables were analyzed using Chi-squared or Fisher's exact tests. For production system type, the *p*-value (0.042) corresponds to a single Chi-squared test comparing the overall distribution across categories between adopters and non-adopters. For irrigation method, the *p*-value (0.010) corresponds to a single Chi-squared test. The final sample ($n = 96$) differs from the initial sample ($n = 101$) due to the exclusion of cases with missing values in one or more model variables. Significance levels: ** $p < 0.05$, * $p < 0.1$.

Significant associations were identified between adoption and characteristics of the production system. The use of irrigation technologies was higher among adopters (48.5%) compared to non-adopters (20.6%), with a statistically significant difference ($p = 0.010$). Similarly, productive diversification was positively associated with adoption ($p = 0.042$). In contrast, the cultivation of vegetables and annual crops was more prevalent among non-adopters, with a marginally significant difference ($p = 0.042$).

Regarding the combined TPB constructs, a statistically significant difference was observed for ATB. Farmers in the adopter group displayed significantly more favorable attitudes toward preventive practices than non-adopters ($p = 0.021$). This result derives from the interaction between BBS and OE, as defined by Bechini et al. [14,15]. Within this construct, the OE subcomponent was also positive; adopters reported greater perceived benefits from implementing preventive practices ($p = 0.019$).

In contrast, SN and PBC did not differ significantly between groups ($p > 0.05$). Nonetheless, the SN component showed a positive trend, suggesting a potentially relevant influence of social expectations, though it did not reach statistical significance and warrants further qualitative examination.

These results suggest that the adoption of irrigation water contamination prevention practices among small-scale farmers is better explained when socio-behavioral dimensions derived from the TPB are analyzed alongside structural characteristics, such as crop type and irrigation technology. The descriptive findings reveal distinct structural and attitudinal patterns between adopters and non-adopters, indicating that favorable perceptions of environmental and productive benefits are associated with a higher likelihood of adopting preventive measures.

3.2. Model Results

Table 4 presents the results of the binary logistic regression model estimated using the combined TPB constructs and structural variables. The model demonstrated good overall fit, with McFadden's pseudo R^2 (0.268), Nagelkerke's pseudo R^2 (0.403), and Cox & Snell's pseudo R^2 (0.292), suggesting that the model explains between 27% and 40% of the variation in the likelihood of adoption according to different pseudo R^2 metrics.

Table 4. Logistic Regression Model Estimation.

Variable	β Logit	Std. Error	p -Value	Odds Ratio	95% CI (Low)	95% CI (High)	Marginal Effect	Sig.
Intercept	−3.617	0.783	0.000	0.027	0.006	0.125	—	***
ATB	0.151	0.062	0.014	1.163	1.031	1.312	0.023	*
SN	0.188	0.090	0.037	1.207	1.011	1.441	0.029	*
PBC	−0.077	0.088	0.384	0.926	0.778	1.101	−0.012	
Diversified production	2.678	0.894	0.003	14.552	2.524	83.900	0.414	**
Fruit trees, vines, or nuts	2.197	0.706	0.002	8.999	2.258	35.870	0.330	**
Livestock production	0.660	1.553	0.671	1.936	0.092	40.610	0.082	
Irrigation technology	2.806	0.725	0.000	16.548	4.000	68.467	0.443	***

Note. Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Odds Ratios (OR) indicate the change in odds of adoption for a one-unit increase in the predictor. Marginal effects represent the average marginal effect (AME) on the predicted probability of adoption. Vegetables/annual crops are the reference category for production system type; gravity irrigation is the reference category for irrigation method.

The Hosmer–Lemeshow goodness-of-fit test ($p = 0.348$) confirms that the model is well calibrated, while the area under the ROC curve ($AUC = 0.821$) indicates strong explanatory and discriminative capacity (Table 5).

Table 5. Model Fit Indices.

Fit Index	Model Value
Pseudo R^2 (McFadden)	0.268
Pseudo R^2 (Nagelkerke)	0.403
Pseudo R^2 (Cox & Snell)	0.292
Hosmer–Lemeshow p -value	0.348
AUC	0.821

Note. Fit indices for the binary logistic regression model estimated using combined TPB constructs and structural variables.

The combined TPB constructs produced mixed results. ATB—defined as the product of behavioral belief strength (BBS) and outcome evaluation (OE)—was positively and significantly associated with adoption ($\beta = 0.151$; odds ratio = 1.16; $p < 0.05$). This indicates

that farmers who perceive clear benefits from preventive practices are more likely to implement them.

SN, which combines MTC and NB, also showed a positive and significant relationship ($\beta = 0.188$; odds ratio = 1.21; $p < 0.05$), highlighting the influence of social and community expectations on shaping farmers' decisions.

In contrast, PBC, which combines CBS and CP, did not exhibit a statistically significant effect ($p > 0.05$), suggesting that perceived individual capacity or access to resources does not play a decisive role in adoption among this sample. This aligns with international findings indicating that the effect of control perceptions may depend on contextual or conditional factors.

Regarding structural variables, three production-system characteristics showed significant positive associations with adoption. Farmers using modern irrigation technologies, such as drip or sprinkler systems ($\beta = 2.806$; odds ratio = 16.55), were substantially more likely to adopt preventive practices than those relying on gravity irrigation. The marginal effect of irrigation technology (0.443) indicates that, holding other variables constant, the probability of adoption increases by approximately 44 percentage points for farmers using technified irrigation systems. This is the largest marginal effect in the model, highlighting the key role of access to irrigation technologies in enabling the implementation of preventive practices.

Producers operating diversified production systems ($\beta = 2.678$; odds ratio = 14.55) exhibited higher adoption rates, possibly reflecting greater exposure to varied management practices and a heightened awareness of environmental risks. Similarly, those cultivating fruit trees, vines, or nuts ($\beta = 2.197$; odds ratio = 9.00) showed a greater propensity to adopt preventive measures, likely due to the higher quality standards and stricter management requirements associated with these value chains. By contrast, livestock producers did not show a significant association with adoption ($p = 0.671$), which may be attributable to their small representation in the sample (3%).

In sum, these results suggest that the adoption of irrigation water contamination prevention practices is influenced by an interaction between attitudinal factors, as modeled by the TPB, and structural characteristics of the production system, particularly crop type and irrigation technology. This supports the study's conceptual premise that behavioral intentions are more likely to be translated into concrete actions when reinforced by favorable structural and technical conditions.

4. Discussion

This study examined the factors influencing the adoption of irrigation water contamination prevention practices among small-scale farmers in central Chile—a context marked by increasing water scarcity and food safety challenges in fruit and vegetable production. By integrating the Theory of Planned Behavior [18] with structural variables of the production system, the analysis contributes to a more contextualized understanding of pro-environmental behavior.

From a socio-behavioral perspective, Attitude Toward Behavior (ATB) emerged as a significant and robust predictor of adoption, validating its operationalization as proposed by Bechini et al. [14,15]. These results align with extensive evidence showing that favorable attitudes—grounded in perceived environmental and productive benefits—are among the most consistent drivers of sustainable practice adoption [15,19,28,42]. Across diverse contexts, farmers who value the ecological or productivity gains of a practice are more willing to adopt it, even when immediate economic incentives are limited. Similarly, Lanza Castillo et al. [33] found that positive attitudes, reinforced by institutional trust, significantly

influence the intention to adopt pressurized irrigation technologies, underscoring the role of perceptions and trust in shaping environmental action.

Nevertheless, the literature also shows that attitudes can take divergent directions. Alotaibi and Kassem [25] documented cases in Saudi Arabia in which the use of treated wastewater or smart meters was perceived as externally imposed, leading to negative attitudes and resistance. Likewise, Shahangian et al. [23], applying the Health Belief Model (HBM), argued that positive attitudes require “cues to action” and a credible institutional environment to translate into behavior. These findings indicate that favorable attitudes are not spontaneous but are socially and institutionally constructed through reinforcement, communication, and experience.

In this sense, the present study reinforces the notion that positive attitudes toward sustainability catalyze adoption when supported by effective extension services, technical assistance, and institutional narratives that clarify benefits and reduce uncertainty. As the concept of “action space” [24] proposes, individual beliefs operate within material and normative constraints. Therefore, public policies that strengthen positive perceptions and reduce perceived risks can transform attitudes into effective behavioral change, driving transitions toward more sustainable agricultural systems.

From a self-critical perspective, it is worth noting that the predominance of ATB in this study may be partly explained by the sample composition. PRODESAL users have been systematically exposed to technical training and food safety communication through institutional programs, which may have reinforced favorable attitudes toward preventive practices independently of their actual adoption. This raises the possibility that the observed ATB effect partially reflects institutionally shaped perceptions rather than autonomous attitudinal formation. Future studies comparing PRODESAL users with non-participating farmers would allow for a more robust assessment of the independent contribution of attitudes to adoption behavior.

The role of subjective norms in this study was positive but weaker than that of attitudes. This pattern reflects mixed findings in the literature. Bechini et al. [15] note that Subjective Norms (SN) often exert limited influence unless the sources of normative pressure—such as advisors, peers, or institutions—are perceived as legitimate and trustworthy. Similarly, Meijer et al. [43] and Zeweld et al. [28] found that membership in farmer networks or cooperatives enhances information exchange, legitimizes sustainable practices, and increases the likelihood of adoption. Baah et al. [42] further differentiate between injunctive norms (approval from significant others) and descriptive norms (observing others’ behavior), showing that only injunctive norms have a significant influence in agricultural contexts.

A notable finding that warrants explicit attention is the apparent discrepancy between the descriptive and regression analyses for SN. In the descriptive comparison between adopters and non-adopters, SN did not show a statistically significant difference between groups ($p = 0.259$). However, in the logistic regression model, SN emerged as a significant predictor of adoption ($OR = 1.21$; $p = 0.037$). This discrepancy is not contradictory but reflects a methodological distinction: the descriptive analysis examines SN in isolation, whereas the regression model controls attitudes, perceived behavioral control, and structural variables. Once these factors are held constant, SN’s independent contribution to adoption becomes statistically detectable. This pattern is consistent with findings from Bechini et al. [15], who note that normative influences tend to emerge more clearly in multivariate models that control for confounding behavioral and structural factors. It suggests that in contexts of institutional extension, normative pressure from technical advisors operates as an independent behavioral lever, distinct from and complementary to attitudinal drivers.

This evidence underscores that explicit validation by peers, community leaders, or technical advisors may be more influential than observing others' actions. In some rural contexts, social norms can even outweigh individual attitudes in predicting behavior [44,45], as farmers respond strongly to moral obligations or collective expectations [46]. This dynamic is particularly relevant in Chile and other Latin American settings, where community-based programs play a central role in agricultural extension. Lanza Castillo et al. [33] also show that institutional trust and participation in local organizations reinforce perceived subjective norms regarding irrigation technologies.

Consequently, policies that strengthen community trust networks and local leadership can amplify the positive influence of subjective norms. Strategies such as collective training sessions, local communication campaigns, and the engagement of recognized advisors can generate normative legitimacy, accelerating the diffusion of preventive practices. Adoption, therefore, should be understood not as an individual cost–benefit calculation but as a socially mediated process shaped by community endorsement and institutional credibility.

In contrast, Perceived Behavioral Control (PBC) did not show significant effects in descriptive or regression analyses. This result is consistent with a broad body of evidence showing that PBC in agricultural contexts is frequently non-significant or conditional, particularly when structural barriers—such as limited infrastructure, restricted credit access, or complex regulatory procedures—constrain farmers' actual capacity to act [14,15,21,23,43,46–53]. In the present study, the non-significance of PBC likely reflects the structural realities of smallholder farming in central Chile: farmers may perceive their capacity to adopt preventive practices as limited not by personal capability but by the material and institutional constraints of their production environment. As Gütschow et al. [24] argue, individual agency is defined not solely by cognition but by the “action space” available to each farmer. This space in this sample is constrained by infrastructural deficits, limited financing, and uncertain regulatory pathways.

From a critical standpoint, the non-significance of PBC in this study may also be partly attributed to limitations in its operationalization. As acknowledged in Section 2.5.2. Control Power (CP) was measured using a single item, which limits the construct's ability to capture the multidimensionality of perceived control capacity. Additionally, the items assigned to Control Belief Strength (CBS) integrate cognitive, institutional, and regulatory barriers into a single dimension—an approach theoretically grounded in Ajzen's [18] broad definition of control beliefs but potentially insufficient to distinguish between the differential effects of internal capability perceptions and external structural constraints. Future research with larger samples should incorporate validated multi-item scales for each PBC subcomponent to more precisely identify which dimensions of perceived control are relevant in smallholder water management contexts.

Beyond behavioral constructs, the results confirm that structural characteristics of production systems strongly influence the adoption of preventive practices. Three variables were particularly relevant: the use of modern irrigation technologies, productive diversification, and the cultivation of fruit trees, vines, or nuts. First, irrigation technologies were the most robust predictor in the model ($OR = 16.55$; $p < 0.001$), confirming the importance of infrastructure as a facilitator of sustainable management. Access to efficient irrigation systems not only improves water use efficiency but also reduces operational barriers, encourages innovation, and connects farmers to training and organizational networks. Second, productive diversification showed a positive association with adoption ($OR = 14.55$; 471 ; $p = 0.003$), suggesting that farmers with more diverse production systems, whether by crop type or complementary activities, tend to exhibit greater flexibility, resilience, and openness to learning, consistent with the findings by Mwambi et al. [31] and Rezaei et al. [21].

Finally, farmers cultivating fruit trees and vines were more likely to adopt preventive practices ($OR = 9.00$; $p = 0.002$). This pattern can be explained by the higher commercial value of these crops, which incentivize investment in quality and safety, as well as their greater sensitivity to water contamination and environmental stress [30,33,41,54].

It is important to acknowledge, however, that these three structural predictors are not equivalent in their cost–benefit profiles or in their feasibility of adoption. The use of modern irrigation technologies typically requires substantial capital investment, access to financing, and technical installation support, making it accessible primarily to farmers who have already benefited from public subsidy programs or institutional credit. In contrast, the association of diversified production systems and fruit tree cultivation with higher adoption rates may partly reflect selection dynamics rather than causal adoption pathways: farmers who cultivate higher-value crops or manage diverse production systems may already operate under greater market pressure, quality standards, and institutional monitoring—all of which independently incentivize preventive practice adoption regardless of behavioral intent. This heterogeneity in the cost–benefit structures of the three predictors should be considered when interpreting the magnitude and direction of their effects and underscores the need for future research to examine these structural variables separately rather than treating them as a homogeneous category of adoption drivers.

Together, these results reinforce that the adoption of pro-environmental practices cannot be understood solely in terms of individual cognition. It emerges from a dynamic interaction between beliefs, social validation, and structural opportunities [50,51]. Integrating these contextual dimensions enhances TPB’s explanatory capacity by capturing the actual action space in which farmers operate.

From a critical reflection on the study’s own findings, several tensions deserve acknowledgment. First, the simultaneous significance of ATB and SN, alongside the non-significance of PBC, suggests that, in this population, the pathway to adoption runs primarily through persuasion and social validation rather than reinforcement of personal capability. This pattern is consistent with PRODESAL’s institutional model, which emphasizes technical advice and community engagement over individual skill development. This design may inadvertently suppress PBC’s role as a behavioral lever. Second, the strong predictive power of structural variables relative to behavioral constructs raises a question that this study cannot fully resolve: to what extent does infrastructure shape attitudes and norms, rather than being merely a parallel predictor? Cross-sectional designs are inherently limited in their ability to address this directionality. Third, the concentration of PRODESAL users—a population with above-average institutional support—likely produces an upward bias in both adoption rates and attitudinal scores, limiting the generalizability of the findings to the broader smallholder farming population. These tensions do not undermine the study’s contributions but point toward a richer research agenda in which longitudinal designs, broader sampling strategies, and more granular operationalizations of PBC can provide a more complete account of behavioral adoption dynamics in resource-constrained agricultural contexts.

5. Conclusions

This study examined the behavioral and structural determinants of the adoption of irrigation water contamination prevention practices among smallholder farmers in the O’Higgins Region of central Chile ($n = 96$; $AUC = 0.821$). The findings reveal a multidimensional adoption process in which cognitive, normative, and structural factors operate jointly rather than independently.

Among behavioral predictors, Attitude Toward Behavior (ATB) was the only TPB construct that emerged as consistently significant ($OR = 1.16$; $p = 0.014$), indicating that

farmers with more favorable evaluations of the benefits of preventive water management are significantly more likely to adopt such practices. Subjective Norms (SN) also showed a significant positive effect in the multivariate model ($OR = 1.21$; $p = 0.037$), though this effect was not detectable in descriptive comparisons between adopters and non-adopters—a pattern consistent with the suppression of normative influences by confounding behavioral and structural variables. Perceived Behavioral Control (PBC), in contrast, showed no significant effect, likely reflecting structural constraints in the production environment rather than a lack of individual capability. Together, these results suggest that in this population, the pathway to adoption runs primarily through attitudinal and normative channels, while perceived control is constrained by material and institutional barriers beyond individual agency.

Among structural predictors, irrigation technology emerged as the strongest driver of adoption ($OR = 16.55$; $p < 0.001$), followed by diversified production systems ($OR = 14.55$; $p = 0.003$) and the cultivation of fruit trees or vines ($OR = 9.00$; $p = 0.002$). These effects considerably exceed those of the behavioral constructs, underscoring that infrastructure and production system characteristics are a more proximate determinant of adoption than attitudinal or normative factors in this context. A favorable attitude is a necessary but insufficient condition for adoption unless accompanied by enabling structural conditions.

These findings carry direct implications for policy design. Interventions targeting adoption should combine two complementary strategies: (1) awareness campaigns and technical training programs that strengthen positive attitudes and normative legitimacy through local advisory systems and community networks; and (2) structural investments—particularly subsidies for irrigation technology modernization and streamlined certification procedures—that reduce the material barriers constraining perceived and actual behavioral control. Given that irrigation technology adoption showed an odds ratio nearly 14 times that of attitudinal predictors, infrastructure interventions are likely to yield greater adoption gains per unit of public investment than communication-focused strategies alone. However, the present study does not provide empirical evidence on the cost-effectiveness, feasibility, or scalability of specific policy instruments. The recommendations above should therefore be interpreted as research-informed hypotheses rather than prescriptions, and their implementation viability requires dedicated evaluation in diverse institutional and budgetary contexts.

This study has several limitations that should inform the interpretation of its findings. The relatively small sample ($n = 96$, of which 33 were adopters) and its concentration in a single high-productivity region restrict statistical power and limit generalizability to other agricultural settings. The recruitment of participants exclusively through PRODESAL introduces selection bias toward farmers with above-average access to technical support and institutional resources, likely leading to an overestimation of adoption levels and the strength of behavioral predictors compared with the broader smallholder farming population. The reliance on self-reported data may further introduce social desirability bias, particularly for practices that are institutionally encouraged. The cross-sectional design prevents causal inference and leaves unresolved the question of whether positive attitudes and normative perceptions preceded or followed adoption. Finally, operationalizing Control Power as a single item limits the construct's ability to capture the multidimensional nature of perceived behavioral control.

Future research should address these limitations by: (i) replicating this study in regions with different water stress levels, institutional capacities, and production profiles to assess the transferability of these findings; (ii) applying longitudinal designs that allow tracking of behavioral change over time and assessment of the direction of causality between attitudes, norms, and adoption; (iii) incorporating mixed-methods approaches

to capture farmers' perceptions, social dynamics, and the mechanisms through which structural factors shape behavioral determinants; (iv) evaluating the environmental and public health outcomes of adoption at the watershed level; and (v) exploring the integration of complementary frameworks—such as UTAUT, the Health Belief Model [23], or the action space approach [24]—to better account for the interaction between structural constraints and individual behavioral capacity.

In conclusion, advancing sustainable water management in smallholder agricultural systems requires coordinated public action that simultaneously strengthens individual motivation, legitimizes collective norms, and removes structural barriers to adoption. The evidence from this study suggests that structural interventions, especially the modernization of irrigation technology, may offer higher-leverage policy entry points than communication-focused strategies alone, though this hypothesis requires empirical validation through impact evaluation studies. Only by addressing these interconnected layers can public policy promote resilient and scalable behavioral change that safeguards both food safety and environmental sustainability in rural Chile.

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Appendix A. Exploratory and Confirmatory Factor Analysis for TPB Construct Validation

Appendix A details the exploratory and confirmatory factor analyses (EFA and CFA) performed to operationalize the Theory of Planned Behavior (TPB) constructs.

Appendix A.1. Exploratory Factor Analysis Iterations for Relevant Item Selection

Table A1. Exploratory Factor Analysis (EFA) iterations.

	EFA1	EFA1a	EFA2	EFA2a	EFA3	EFA3a	EFA4	EFA5	EFA5a
EFA Type	No predefined	Refined	3 factors	Refined	ML	PA	Bootstrap: No predefined	Bootstrap: 3 factors	Bootstrap: 3 factors
TPB Items evaluated	All (37)	Refined (16)	All (37)	Refined (15)	All (37)	All (37)	All (37)	All (37)	Refined (11)
Reliability	$\alpha = 0.81$, $\omega = 0.94$	$\alpha = 0.77$, $\omega = 0.94$	$\alpha = 0.81$, $\omega = 0.93$	$\alpha = 0.81$, $\omega = 0.93$	$\alpha = 0.81$, $\omega = 0.87$	...	...	...	$\alpha = 0.59$, $\omega = 0.76$
χ^2 (>0.05)	632.09	92.68	823.98	90.03	804.72	823.87	1289.75	1433.07	41.01

Table A1. *Cont.*

	EFA1	EFA1a	EFA2	EFA2a	EFA3	EFA3a	EFA4	EFA5	EFA5a
TLI (≥ 0.90)	0.77	0.97	0.62	0.88	0.65	0.62	0.38	0.35	0.83
RMSEA (≤ 0.08)	0.05	0.03	0.07	0.06	0.07	0.07	0.12	0.13	0.07
RMSEA 90% C.I.	0.041–0.066	0–0.065	0.059–0.079	...	...	...	...	...	0–0.206
RMSR (≤ 0.08)	0.06	0.04	0.08	0.05	0.08	0.08	0.09	0.10	0.06
BIC	−1629.05	−298.76	−1745.70	−200.73	−1764.97	−1745.81	−1123.36	−1136.61	−74.37

Note. Cronbach's Alpha (α), McDonald's Omega (ω), and Chi-square (χ^2) are reported. EFAs with the best fit were further evaluated using CFA.

Appendix A.2. Confirmatory Factor Analysis Iterations

Table A2. Confirmatory Factor Analysis: Fit Indices.

Fix Index	Recommended Value	CFA Model (EFA1a)	CFA Model (EFA2a)
Chi-Square	<3	245.776	102.950
Degrees of Freedom (df)	–	155.000	62.000
<i>p</i> -Value	$p > 0.05$	0.000	0.001
Comparative Fit Index (CFI)	>0.95	0.844	0.891
Tucker–Lewis Index (TLI)	>0.95	0.809	0.863
Root Mean Square Error of Approximation (RMSEA)	<0.08	0.077	0.081
Standardized Root Mean Square Residual (SRMR)	<0.08	0.085	0.079

Note. CFI and TLI values close to 1 indicate better model fit. RMSEA and SRMR values below 0.08 are considered acceptable thresholds.

Appendix B. Dependent Variable Construction: Item Selection via Exploratory Factor Analysis

Appendix B presents the analysis used to construct the dependent variable, including polychoric correlations and factor loadings for item selection.

Appendix B.1. Correlation Matrix for the Dependent Variable

Table A3. Correlation matrix among dependent variables.

	Septic Tank Away from Water Sources	Irrigation Canal Cleaning	Waste Bins Present	Water Protection Warning Signs	Rainwater Collection Drum	Water Filter or Clarifier	Plastic Mulch Cover	Irrigation Avoids Edible Parts
Septic tank away from water sources	1.000							
Irrigation canal cleaning	−0.552	1.000						
Waste bins present	0.108	0.114	1.000					
Water protection warning signs	0.103	0.596	0.753	1.000				
Rainwater collection drum	0.850	−0.178	−0.055	0.265	1.000			
Water filter or clarifier	−0.003	0.673	−0.094	0.502	0.338	1.000		
Plastic mulch cover	0.034	−0.248	0.165	−0.094	−0.201	0.100	1.000	
Irrigation avoids edible parts	0.164	0.110	−0.030	0.014	0.044	0.027	0.137	1.000

Note. Polychoric correlation matrix among the binary or ordinal variables used to define the dependent variable through EFA.

Appendix B.2. Factor Loadings After Varimax Rotation

Table A4. Exploratory Factor Loadings (Varimax Rotation).

Variable	Factor 1
The septic tank is located away from water sources that may come into contact with crops	0.18
Periodically cleans the irrigation canals	0.18
There are garbage bins for waste and refuse generated in the field and at home	0.07
Warning signs or notices are present in my area for water protection	0.59
Uses a drum or other container to collect rainwater for decanting	0.33
Using a water filter or clarifier	0.53
Uses plastic mulch under the crop	−0.05
Irrigation is done in a way that the water does not come into contact with the edible part	0.04

Note. Factor loadings from the rotated solution were used to select indicators of preventive practice adoption.

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