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Adaptations in agricultural water management in arid regions: Modelling farmer behaviour and cooperation on irrigation sustainability in Morocco

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ABSTRACT

Climate change has disrupted weather patterns and heightened drought risks in arid and semi-arid regions, requiring adaptations to crop and irrigation strategies to sustain food production. This study integrates qualitative and quantitative approaches to examine the factors influencing farmers crop and irrigation management decisions, with a focus on groundwater management and drip irrigation adoption. Semi-structured interviews 70 farmers from Al Haouz Basin, Morocco provided insights into motivations for crop and irrigation choices. Inductive coding was used for qualitative responses, and data analysis examined how farm size and tenure influenced decision-making. An integrated modelling approach combining the theory of planned behaviour and structural equation modelling (SEM) was used to interpret drivers of irrigation management strategy. The interviews revealed that 83 % of farmers were concerned about groundwater decline, with 40 % identifying salinity as a major challenge. We found that falling groundwater levels and soil salinization have already impacted yields and raised concerns about further declines, prompting large-scale farmers to transition to more profitable and drought-resilient olive cultivation. Analysis of the SEM showed that attitudes toward drip irrigation efficiency, maintaining groundwater supply, and preventing increases in groundwater salinity influence farmers' intentions regarding their water usage. Additionally, perceived behavioural control played a key role in shaping adoption behaviours, reinforcing the importance of structural and economic factors in decision-making. Land ownership conferred greater long-term perceived control over sustainable water use. However, qualitative findings revealed that cooperation on groundwater management was limited, with many farmers citing a lack of perceived benefits and logistical challenges, highlighting collective action challenges. Complexities related to subsidy applications and land tenure deter drip irrigation adoption, especially among smallholders, constraining climate change resilience. Our study contributes to understanding farmers' coping strategies and presents a foundation from which to develop evidence-based policy reforms enhancing agricultural and water sustainability across arid and semi-arid regions.

1. Introduction

Climate change exacerbates water scarcity in arid and semi-arid regions, posing a major risk to agriculture and food security. Declining and increasingly variable rainfall coupled with rising evapotranspiration drastically strains surface and groundwater resources available for crop irrigation (Dessalegn and Merrey, 2015a). Excessive pumping driven by the expansions of irrigated crop lands has depleted aquifers and heightened agricultural water demand. The declining and less reliable water supply has sharpened competition over limited resources, creating social tensions and governance challenges (Gleeson and Richter, 2018). Implementing shared irrigation infrastructure systems and coordinated management practices is critical but faces notable obstacles.

Studies from sub-Saharan Africa highlight issues like conflict over

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dwindling surface and groundwater resources, deficiencies in system maintenance, and inequitable water distribution as supplies tighten (Meinzen-Dick, 2014; Muchara et al., 2014). In the Middle East and Africa, unregulated well drilling has strained groundwater levels, while farmer associations have struggled to manage deteriorating surface irrigation networks (Garces-Restrepo et al., 2007; Mohammed Rachid Doukkali, 2005). While these studies emphasise the broader challenges of water scarcity, there is limited empirical evidence on the social and behavioural dimensions of water use decisions at the farm level, particularly in arid regions such as Morocco. As climate change exacerbates water scarcity, understanding potential barriers to coordinated irrigation management through irrigation reforms and investments becomes increasingly urgent.

Increasing reliance on groundwater for reliable irrigation due to climate change (Bordbar et al., 2023) combined with unrestrained pumping threatens the long-term sustainability of groundwater resources. Excessive water withdrawals during peak crop demand cause falling groundwater levels and alterations to aquifer hydrogeology over time. Continuous evaporation can also create saline groundwater through evaporite mineral precipitation when arid conditions limit the leaching of accumulated salts (Yechieli and Wood, 2002). Such dynamics currently prevail in arid and semi-arid regions, with over-exploitation and rising salinity (5 dS/m) threatening the sustainability of irrigation resources (Salman and Pek, 2020a). This combination of over-extraction and salinity has been documented as a major threat to sustainable irrigation in arid and semi-arid regions. Yet, the behavioural and socioeconomic drivers underlying these practices remain poorly understood.

The rapid expansion of individual drip irrigation systems incentivizes unsustainable groundwater extraction, progressively depleting aquifers and causing threats to irrigation viability (Meinzen-Dick, 2014). Additionally, as individual groundwater use expands, hidden competition among farmers intensifies, exacerbating water shortages and fuelling social tensions in regions already grappling with limited resources (Dessalegn and Merrey, 2015b). Despite these pressing challenges, many farmers lack awareness of how their individual behaviours collectively contribute to resource depletion, hindering the emergence of effective cooperative solutions. Understanding these dynamics requires integrated analyses that connect farmer behaviour, social norms, and structural barriers to sustainable water management.

With increasing water scarcity and groundwater depletion in arid regions, understanding the drivers of crop choice and irrigation choices is of critical importance. Existing research predominantly adopts an economic rationality perspective, focusing on cost-benefit analyses while often overlooking the broader influences on farmer decision-making, such as social dynamics, cultural norms, and individual perceptions(Wens et al., 2020). The full range of factors influencing farmers' crop and irrigation choices, particularly in the context of environmental and policy pressures, remains poorly understood (Kurukulasuriya and Mendelsohn, 2007). Research shows rising temperatures and shifting precipitation patterns associated with a changing climate in semi-arid regions require adaptations to cropping systems to reduce water demands (Gebrehiwot and Van Der Veen, 2013). Yet, few studies examine how these climate pressures interact with farmer preferences, resource limitations, land tenure constraints, market incentives, and social dynamics to shape land management decisions. Significant knowledge gaps persist regarding how climate beliefs, local knowledge, and social networks influence the adoption of low water-consuming crops and efficient irrigation practices (Teklewold et al., 2013).

Our study addresses these gaps by integrating qualitative and quantitative approaches to examine the drivers of crop and irrigation decision-making, focusing on groundwater use and drip irrigation adoption in arid environments. Our objectives were threefold: (1) to advance conceptual understanding of the motivations, constraints, and social dynamics shaping crop and irrigation management decisions; (2) to explore the barriers preventing collective action among farmers, particularly regarding sustainable groundwater management and (3) to inform policies and practices that can enhance sustainable agriculture in water-limited regions vulnerable to climate disruptions.

To that end, we conducted a set of semi-structured interviews with farmers on crop choices, perceptions of groundwater depletion, drip irrigation adoption, drought adaptation and mitigation strategies, and collective action barriers. We aimed to identify factors shaping on-farm adaptations and reveal leverage points for interventions to support production. We identified emergent themes through inductive coding analysis from the interview responses and translated these to an integrative theoretical modelling approach. By combining the theory of planned behaviour (TPB) and structural equation modelling (SEM), we explored how attitudes, social norms, and perceived control influence intentions to adopt practices (Ajzen, 1991b). SEM enabled us to quantify the relationships between these factors, testing hypothesised pathways and examining the influence of structural constraints such as land tenure and subsidy accessibility (Anderson and Gerbing, 1988).

By modelling the complex interactions influencing farmers' behaviour, we provide evidence-based insights to help agricultural communities adapt to changing climate and water pressures. This systems-level perspective of the climatic, technological, and behavioural aspects of decision-making aims to inform integrated solutions tailored to the climate and socioeconomic realities farmers face.

2. Methodological approach

2.1. Study area

The study area is the irrigated perimeter R3, covering an estimated area of 3800 km^2. It located in Al Haouz plain, situated in the Tensift basin in Morocco, approximately 40 km to the east of Marrakech (Fig. 1). This perimeter includes approximately 310 farmers (Salman and Pek, 2020b). The prevailing climatic conditions are categorized as semi-arid continental. This region experiences considerable fluctuations in both annual and intra-year rainfall, with an average yearly precipitation of 250 mm. The distribution of the irregular rainfall is skewed towards the winter and spring seasons, accounting for approximately 70 % of the total. The potential evapotranspiration (ET_0) is relatively elevated, with the potential to reach up to 1500 mm annually. Winter temperatures tend to dip to an average low of 4°C, while summer temperatures soar to an average high of 37°C. The prevalent soil composition ranges from clay to loam in texture. The Haouz Agricultural Development Regional Office (ORMVAH) is the local agricultural office in charge of the management of irrigation water. It manages the irrigation infrastructure and allocates irrigation from dam water according to the scheduling defined at the beginning of the agricultural campaign. The water allocation is based on the dam water level and negotiations with farmers. Farmers using water from irrigation systems are organized in self-ruled associations called Agricultural Water Users Associations (WUA), which are formal organizations that partially enable them to manage and maintain their irrigation system.

2.2. Survey design and data collection

2.2.1. Questionnaire prototype development

We held interviews with irrigation experts and regional professionals to gain preliminary insights into water management practices and farming conditions in the study region. Drawing on this and previous work (El Fartassi et al., 2023), we developed a questionnaire prototype to elicit information on farmers' crop and irrigation management practices and decision-making. The prototype underwent thorough review by the same irrigation experts and regional professionals to ensure its consistency and adaptability to the agricultural context of Morocco. Their review involved evaluating the clarity of the questions, the appropriateness of the terminology used, and the relevance of each

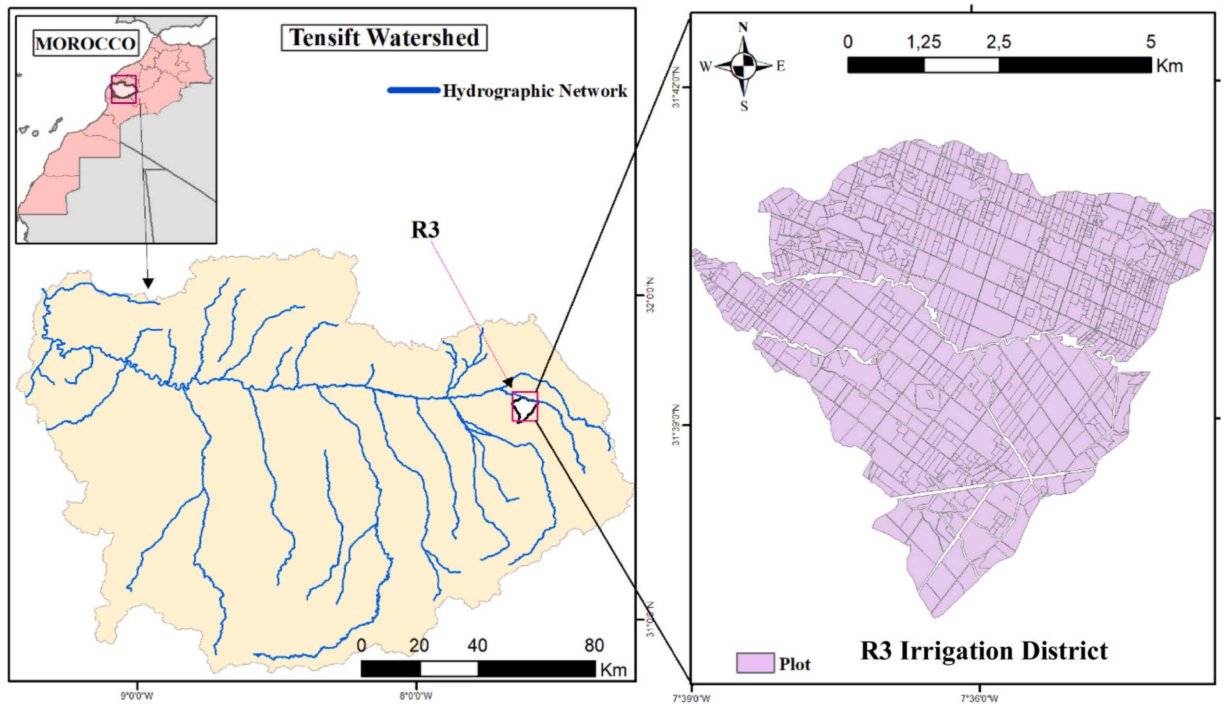

Fig. 1. Location of the study area: R3 perimeter.

question. They provided feedback to help align the questions with the specific challenges faced by farmers in the region, such as issues related to water scarcity, irrigation infrastructure, and crop preferences. This review process was essential for ensuring that the questionnaire was contextually relevant, culturally sensitive, and capable of capturing the nuanced factors influencing farmers' irrigation and crop management decisions. The questionnaire was administered through in-person, oral interviews to accommodate varying literacy levels among respondents. This approach ensured that all questions were fully explained and that responses accurately reflected the farmers' perspectives. The questionnaire was initially developed in English and subsequently translated into Moroccan Arabic, incorporating input from local agricultural experts to ensure cultural and linguistic appropriateness. Before formal data collection, we conducted a pilot test with six farmers to assess the clarity and interpretability of the questions. Feedback from the pilot test informed refinements to the questionnaire, including rephrasing questions to improve comprehension and aligning the structure to better capture the nuances of farmers' responses. Prior to data collection, the questionnaire underwent ethical review and was approved through Cranfield University's online research ethics approval system.

2.2.2. *Survey structure*

The questionnaire comprised five sections. Section one captured farm characteristics like cultivated area, irrigation sources, irrigation systems, cropping patterns, and rotations. Section two examined farmers' perceptions of groundwater issues and satisfaction with surface water allocation. Section three assessed farmers' views on drip irrigation adoption, drought adaptation strategies, and coping with water shortages. Section four focused on information sources used for irrigation decisions, barriers to collective action, and successes in collaborative irrigation practices. Finally, section five recorded farm size and tenure type. Full details of the interview questions are given in Table S1, Appendix B, supplementary material.

2.2.3. *Survey deployment*

The survey was conducted between December 2021 and May 2022, over a period of approximately five months. Given low literacy rates and limited technology access among the farming population in rural areas of Morocco, we conducted in-person interviews to administer the questionnaire. During these interviews, the questionnaire was completed through an oral discussion to accommodate varying literacy levels. In the initial stage, local agricultural office representatives joined the interviews to build trust and gain farmer support, a strategy that can aid survey participation among hesitant communities (Tindana et al., 2007). We surveyed 70 farmers, with each interview taking between 30 min to one hour.

2.2.4. *Sampling technique*

The selection of farmers was conducted using the Latin Hypercube Sampling (cLHS) approach to ensure that the sample was representative of the study area and of sufficient size for structural equation modelling (Iacobucci, 2010; Wolf et al., 2013). The sample size of 70 farmers was deemed sufficient for our analysis due to the use of Diagonally Weighted Least Squares (DWLS) estimation, which is specifically designed for models with ordinal data and smaller sample sizes. The cLHS method is particularly suited for capturing variability across multiple factors in smaller sample sizes, making it appropriate for the study area. To maximize representativeness, the sampling strategy accounted for key factors such as farm size, irrigation sources, and geographic distribution. Farms were stratified by size into small (<5 ha), medium (5–20 ha), and large (>20 ha) categories to reflect differences in agricultural practices and resource access. Additionally, farmers were selected to represent a range of irrigation systems, including those relying on groundwater, dam water, and surface water, thereby capturing diverse water management strategies in the region. Geographic distribution was also considered to ensure spatial heterogeneity was adequately represented. This included differences in soil types and access to infrastructure across the basin. Soil samples were collected during farmer interviews as part of a wider study.

2.3. *Methods of analysis*

2.3.1. *Descriptive analysis*

The data were analysed using R (R Core Team, 2022) and GenStat

(VSN International, 2023) software. We first assessed if crop preferences and cropping patterns varied significantly according to farm size and tenure type using a Pearson χ^2 test. To categorize farm size, we divided the farms into three groups based on area: small farms were less than 5 ha, medium farms ranged from 5 to 20 ha, and large farms were greater than 20 ha. This classification is commonly used in Morocco (Toumi, 2008). For tenure type, we classified farms as either fully owned by the farmer, partially or fully tenanted, or a combination of owned and tenanted land.

For the qualitative data on factors influencing crop management practices, perceived benefits/disbenefits of irrigation systems, and willingness to cooperate, we used an inductive coding approach to identify themes emerging from responses. It involved reading the raw qualitative data, assigning descriptive codes to segments of text, and then grouping these codes into broader categories and themes that emerge from the data itself. A single researcher manually performed the coding process to ensure consistency in approach and interpretation. The researcher carefully documented the coding framework and thematic structure during the process to maintain transparency and traceability. Regular discussions with other team members were held to review the emerging themes and validate the findings, helping to ensure that the coded data accurately represented the farmers' responses. Subsequently, we assessed whether the willingness to cooperate significantly varied with farm size and tenure type by performing a χ^2 permutation test.

2.3.2. *Theoretical framework and hypotheses testing*

The Theory of Planned Behaviour (TPB) is a theoretical framework for understanding the motivations behind behaviours (Conner and Armitage, 1998). TPB posits intentions as the proximal predictor of actions based on three drivers: attitudes, subjective norms, and Perceived Behavioural Control (PBC) (Fig. 2) (Ajzen, 1991a). Attitudes reflect favourable or unfavourable assessments about performing the behaviour (Ajzen, 1991a). Subjective norms encompass perceived social pressures relating to important others' expectations and norms (Rivis and Sheeran, 2003). PBC signifies perceived capacity to execute the behaviour (Ajzen, 2002).

The hypotheses were derived through an iterative process that integrated the qualitative data collected through interviews with the constructs of the TPB. The qualitative interviews provided a dataset, revealing key factors influencing farmers' decision-making regarding groundwater use and the adoption of drip irrigation technology. Emerging themes such as farmers' perceptions of groundwater depletion, attitudes toward drip irrigation efficiency, and the influence of social networks were systematically coded and categorised. These themes were then mapped onto the core TPB constructs (attitude, subjective norms and PCB) to formulate hypotheses about how these factors shape farmers' intentions for both groundwater use (G) and drip irrigation adoption (I) (G.H1-G.H3, I.H1-I.H3) and that farmers with stronger intentions to adopt drip irrigation were more likely to implement this practice, forming the basis for I.H4. The survey data was subsequently used to operationalise these latent variables, quantifying each TPB concept through structured questionnaire responses and enabling statistical validation through Structural Equation Modelling (SEM).

Based on the TPB, the following hypotheses were formulated regarding factors influencing farmers' groundwater use (G) intentions and Drip irrigation (I) adoption.

G.H1-G.H3. Farmers' social norms, attitude, and PBC positively influence their intention to use groundwater.

I.H1-I.H3. Farmers' social norms, attitude, and PBC positively influence their intention to adopt drip irrigation technology.**I.H4.** Farmers' intention to adopt drip irrigation positively influences actual adoption behaviour.

2.3.3. *Structural equation modelling analysis*

Structural equation modelling (SEM) is a statistical technique that estimates relationships between multiple variables simultaneously. It allows modelling of complex interactions between observed and latent (unobserved) variables (Anderson and Gerbing, 1988). Combined with theory, SEM is a powerful approach to understanding human intentions and behaviours. For example, it has been applied with the TPB across agricultural contexts to understand farmers' adoption intentions. SEM can estimate the relationships between attitudes, social norms, perceived control, intentions and behaviours. Related studies have used SEM with TPB to understand water-saving agriculture adoption, (Wang et al., 2023), the effect of water availability on crop revenue (Zewdie et al., 2019) and the adoption of low-carbon technology (Yang et al., 2022).

In our study, we applied SEM combined with TPB to model groundwater use and drip irrigation adoption **(Table A1).** This enables estimation of how the TPB factors as well as other variables in our conceptual framework relate to and influence farmers' groundwater and technology use. While the intention to extract groundwater does not necessarily mean a farmer will adopt drip irrigation, choosing to install drip irrigation systems requires securing access to groundwater. So while the relationship between groundwater usage intentions and drip irrigation adoption may be asymmetric, these two factors are closely linked, as reliable groundwater access is essential for supporting drip system installation. Therefore, the formulated model serves to explore both intentions.

Our SEM analysis of farmers' intention to use groundwater and drip irrigation adoption behaviour consisted of four primary components:

1) Model specification: We first developed a theoretical model representing the 4 hypothesized relationships between variables in our framework (described in 2.3.2). This was based on the TPB and previous literature on technology adoption in agriculture. We hypothesized that attitudes, subjective norms, and PBC would positively predict farmers' intentions to use groundwater and adopt drip irrigation.
2) Measurement Model: We specified a measurement model relating latent variables (attitudes, subjective norms, PBC, intention and behaviour) to their observed indicators from the survey data (Appendix A). For example, attitudes towards groundwater use were measured through survey questions on groundwater salinity, groundwater supply and drip irrigation efficiency.
3) Regression Model: We created a regression model with pathways between latent variables according to our research hypotheses. For

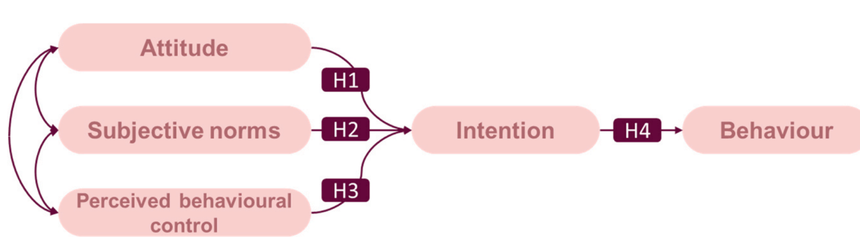

Fig. 2. Conceptual framework of the Theory of Planned Behaviour.

instance, we modelled a pathway from PBC to the intention to adopt drip irrigation.

4) Structural Model: We combined the measurement and regression models to create an overall structural model representing the relationships between latent constructs. We also allowed the residual variances between the latent variable of attitude, subjective norms, and PBC to be correlated to account for commonalities not captured by our survey. We used this structural model to assess our theoretical framework.

We fitted the SEM models using the *lavaan* package in R statistical software. We allowed for freely estimated correlations between observed variables and latent variables.

To interpret the SEM results and assess model fit, we examined fit indices. For overall fit, we looked at the x^2 test, Root Mean Square Error of Approximation (RMSEA), Comparative Fit Index (CFI), and Standardized Root Mean Square Residual (SRMR). We also assessed the R^2 values for each dependent variable to evaluate the percent of variance explained by the model. Standardized path coefficients were examined to compare the magnitude of effects between constructs. We checked the convergent validity to ensure the latent variables represented distinct underlying constructs and that the model accurately represented our theoretical framework. Convergent validity was verified by examining the factor loadings of indicators on their respective constructs. We calculated Kuder-Richardson Formula KR-20 value to assess the internal consistency reliability of binary variables. The normality assumption was checked using the Shapiro-Wilk Normality Test.

For the SEM analysis, we used diagonally weighted least squares (DWLS) estimation along with non-linear optimization through the Nelder-Mead algorithm.

3. Results

3.1. Descriptive statistics

The participants were predominantly male (98.57 %, n = 69), with only one female. This gender distribution is reflective of broader farming demographics in the region, where male farm ownership and decision-making dominate. Recent data suggest that female landholders in Morocco represent less than 7 % of all landholders, and female-headed farms remain rare in the Al Haouz Basin. Women own only 2.5 % of utilised agricultural land in Morocco, and although female-headed households represent approximately 16 % of the national total, women are predominantly involved as unpaid family labourers rather than as landowners or independent farm operators (USAID, 2018).

Farmers with access to dam-driven irrigation were members of local Water User Associations (WUAs); 41.43 % of the total farmers were WUA members. The participants included farm owners (67.14 %, n = 47) and renters (32.86 %, n = 23). Farm sizes fell into three categories: small (<5 ha; 18.57 %), medium (5–20 ha; 37.14 %), and large (>20 ha; 44.29 %). We did not find a significant interaction between farm tenure and farm size.

3.2. Crop choice

Of the farmers interviewed, 57 out of 70 were cultivating olive trees. Cereals, horticultural crops, forage, and pulses were grown by 50, 32, 30 and 25 farmers, respectively. The permutation test for the association between crops and farm size showed evidence that crop choice depends on the farm size (**p = 0.008**). Large-scale farmers tended to cultivate more olive trees compared to small- and medium-scale farmers (Table S1**)**. At the province scale, cereals remain the dominant crop, covering over 60 % of cultivated land, while olive trees represent around 22–23 %. However, more recent figures specific to the Al Haouz region report that olive trees cover 124,200 ha, accounting for 85 % of the tree crop area and 64 % of total cultivated land (ORMVAH, 2021). Our sample reflects this shift, with 81 % of farmers cultivating olives. The high prevalence of olive cultivation in our sample is therefore broadly consistent with regional cropping trends.

Monoculture was adopted by 40 % of participants (n = 28), while 17 % practised intercropping. Notably, 43 % (n = 30) engaged in both cropping approaches. We found no significant association between farm size and cropping pattern.

The survey highlighted a shift away from cereals. The most frequently cited factor was drought susceptibility (6/14 responses), impacting cereal yields. Consequently, cereals are being replaced by olive trees (5/14 responses) which were perceived as more drought (3/14 responses) and salinity (1/14 responses) tolerant. Drip irrigation adoption, which is better suited to perennial crops, has also propelled this transition (1/14 responses), and poor cereals marketability (1/14 responses) was also mentioned.

While certain farmers have transitioned to olive production or horticulture (2/14 responses), the survey showed that multiple agronomic and economic factors limit the feasibility of horticultural crops for many farmers. Recurrent drought was a major issue (12/32 responses), along with concerns that tree canopies limit yields of intercropped horticulture (5/32 responses). Complex management demand posed additional challenges (3/32 responses), while expensive inputs added financial burden (2/32 responses). Limited market demand also undermined profitability (4/32 responses). Declining soil fertility affected cultivation as well (4/32 responses). Storage difficulties further compounded the challenges (1/32 responses).

The survey disclosed drivers of intercropping abandonment, mainly the inhibitory canopy cover effect (7/11 responses) and persistent drought (4/11 responses).

3.3. Drought management

Most farmers (59/70) reported being impacted by water shortages. Key consequences included increased use of electricity/gas for groundwater pumping (36/59). The energy consumption contributes to a costly production (23/59), consequently impacting profitability as noted by (11/59). Furthermore, farmers also spoke of reducing the area they farmed (27/59) and commented that yields were lower (23/59).

In response to these challenges, limited adaptation strategies have been employed. Notably, 26 out of 59 respondents had chosen to deepen existing wells and boreholes, while 8 out of 59 had resorted to digging new wells. When asked about strategies they would have adopted to lessen the effect of water shortages a majority (48 out of 59 responses) lacked contingency plans. Of the farmers not impacted by water shortages, 4 out of 11 had not developed a pre-emptive coping strategy. Conversely, 3 out of 11 respondents had begun adopting drought-tolerant crops.

3.4. Cooperation

Farmers expressed a low propensity to cooperate with farmers to mitigate water scarcity (37/70). Another 12 were hesitant but open to cooperation contingently. We found no significant differences between the willingness to cooperate and farm size and tenure.

Key deterrents were perceived lack of benefits (29/37) and reluctance to experiment with new crops (3/37), as the currently cultivated crops are perceived to be the most suited for the local conditions of the region. Another factor was simultaneous irrigation needs regardless of crops (2/37) during drought periods. Furthermore, apprehension towards constraints imposed by growing similar crops was voiced by one farmer, while another mentioned the need for governmental oversight and farming associations for effective collaboration.

Among those who indicated a tentative willingness to engage in collaborative practices, three respondents highlighted limited water availability as a critical consideration. The perception that the existing crop selection was optimal for the region was reiterated by two farmers, indicating the significance of established agricultural practices. Notably, aspects like government oversight, simultaneous irrigation during droughts, tenure dynamics, and contract terms were mentioned.

In summary, results revealed modest openness to collaborative water conservation, constrained by agronomic beliefs, coordination challenges, and institutional limitations.

3.5. Irrigation sources and technology

Groundwater was the predominant irrigation source used (66 participants), followed by dam water (28 participants), surface water (6 participants), and rainfed systems (1 participant). Some farmers reported access to multiple sources. We found no significant differences in irrigation sources based on farm size.

The majority of participants (86 %, n = 60) reported groundwater-related issues. Lowering of the water table was the most frequently cited problem (83 %, n = 50). Salinity also emerged as a major challenge (40 %, n = 24). Additionally, 15 % (n = 9) expressed concern about wells drying up. In contrast, 14 % (n = 10) reported no groundwater issues.

The χ^2 permutation test revealed significant differences in perceived salinity presence based on farm size (p = 0.04). However, laboratory soil analysis showed no significant differences in salinity among farm sizes. Both large-scale and medium-scale farmers expressed salinity concerns **(**Table S2**).**

Among surveyed farmers, 47 used gravity irrigation and 31 used drip irrigation; some had access to both systems. The permutation test showed evidence of significant differences between the irrigation systems across farms of different sizes (**p = 0.006**). Large-scale farmers were more likely to adopt drip irrigation systems compared to other categories **(**Table S3**).**

The qualitative survey results highlighted the perceived key benefits and challenges associated with adopting drip irrigation. The main advantages were water savings (n = 21), automation (n = 6), and environmental sustainability (n = 4). However, clogged drippers were a major concern (n = 6).

While some farmers have adopted drip irrigation, others persist with gravity irrigation. The survey identified factors influencing sustained gravity irrigation use. Major barriers were land tenure restrictions (n = 14), insufficient investment capacity (n = 10), and low adoption rates among neighbours (n = 10), highlighting economic and social influences. Additional obstacles were complex subsidy application procedures (n = 8) and limited subsidy awareness (n = 8). Other relevant factors were farm size suitability (n = 6), crop profiles (n = 4), investment constraints (n = 4), inadequate private water access (n = 3) and lack of technical assistance (n = 2).

The qualitative themes identified through inductive coding played a critical role in informing the development of the SEM model by providing the foundation for the selection of latent variables and their observed indicators. Themes such as farmers' attitudes toward drip irrigation efficiency, concerns over groundwater depletion and salinity, and perceptions of social norms related to government policies and community practices were directly mapped to the constructs of the TPB. For example, concerns about salinity and groundwater supply were used to operationalise the Attitude latent variable, while themes related to social influence, such as neighbours' satisfaction with drip irrigation, informed the Social Norms construct.

The qualitative analysis also revealed structural constraints, such as land tenure and farm size, which were incorporated into the model as explanatory variables that influence farmers' PBC. These insights ensured that the SEM model accurately reflected the behavioural, social, and structural factors influencing farmers' decision-making. By linking qualitative themes to the latent constructs, the mixed-methods approach allowed for a deeper exploration of how behavioural intentions are shaped and translated into irrigation practices.

In our SEM, we analysed the complex interrelationships between several factors influencing groundwater use and drip irrigation adoption. The KR-20 value of 0.72 indicates an acceptable level of internal consistency, suggesting the variables reliably measured the intended construct (Kuder and Richardson, 1937). The χ^2 test for the user model produced a non-significant p-value of 0.819, indicating a good fit. The chi-square test statistic resulted in a non-significant p-value of 0.865. This suggests the model does not significantly differ from the baseline model, indicating a good model fit. The CFI of 1.000 and TLI of 1.056 denote a very good model fit. The RMSEA of < 0.001 further indicates excellent fit, and its 90 % confidence interval of 0.001–0.054 and non-significant p-value confirm the RMSEA falls within acceptable limits. The SRMR of 0.084 can be considered satisfactory for SEM models. Overall, the fit indices unanimously indicate an excellent data-model fit.

The covariance value between the latent constructs of social norms and attitude was estimated at 0.057, with a standardised estimate of 1.000 (P = 0.001), indicating that as social norms increase, attitude tends to become more favourable. The covariance value between social norms and PBC was 0.044 with a standardised estimate of 0.669 (P = 0.002). The positive estimate similarly indicates that higher social norms are associated with PBC. The covariance between attitude and PBC was 0.101, with a standardised estimate of 0.968 (P = 0.002). The positive value reveals that as attitude becomes more favourable, PBC increases.

In the regression analysis, the coefficients for attitude and PBC predicting intention were 0.896 and 0.725, respectively. The positive values indicate that more favourable attitudes and greater perceived control are associated with higher intentions. The negative coefficient of −0.745 for social norms may reflect mediation rather than a direct negative relationship, given the strong positive covariances found between social norms and other constructs. Finally, intention significantly and positively predicted behaviour ($p < 0.001$). This suggests that every one-unit increase in intention is associated with an expected 0.985 increase in the behaviour.

4. Discussion

The results of our study provide valuable insights into various aspects of evolving crop choices, irrigation, and drought management.

4.1. Shifts in crop choices under drought pressure

We found that large-scale farmers were interested in olive tree cultivation, which is driven by economic and environmental factors. Economically, olive trees offer higher profitability and scalability compared to other crops. The relatively lower maintenance costs and steady demand provide a consistent revenue stream that is well-suited to large farmers' capacity for long-term investment (Papachatzis et al., 2012). Environmentally, olive trees are perceived as more drought- and salinity-tolerant compared to cereals. These characteristics, along with the adoption of drip irrigation, which is better suited to perennial crops, make olive cultivation an attractive and sustainable option in drought-prone and saline regions (Morgado et al., 2022).

Our study also identified the increasing challenges related to the cultivation of horticultural and cereal crops. The high input costs, limited market demand, and declining soil fertility were reported to undermine the profitability of these crops and threaten the farmers' economic stability and income diversification. Furthermore, intercropping horticultural or cereal crops with olive trees can be inhibited by the shading effect of the tree canopy and the complex agroforestry management required, as noted by (Temani et al., 2021). The decline in cereals and horticulture may have unintended consequences across economic, agricultural, and environmental domains. The reduced on-farm diversity could negatively impact soil health and biodiversity over time through loss of crop rotations (Morgado et al., 2022).

The transition from cereal and horticultural crops towards intensive

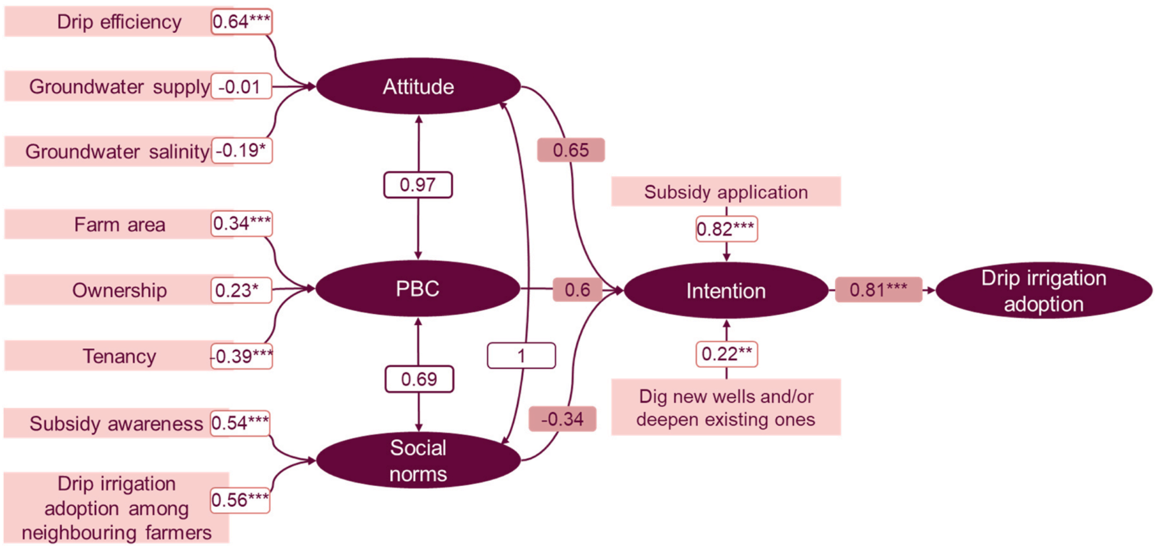

Fig. 3. Structural equation model fitted to data relating to farmers' intention to deepen existing wells and/or dig new ones, and the adoption of drip irrigation. Round nodes represent latent variables, and rectangular nodes are measured variables. Double-headed arrows indicate covariances. Directional arrows linking latent to observed variables show the loadings for each indicator of the latent variable. Causal links between latent variables are indicated by directional arrows. Path coefficients are standardized. *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

olive cultivation reflects the adaptability of farmers in responding to evolving market conditions and environmental constraints. This shift can boost productivity but reduces on-farm diversity, highlighting the need to support sustainable and economically viable practices. Thus, there is a need for further research and policy considerations to support and promote sustainable and economically viable agricultural practices, especially in regions where environmental challenges are a prevalent concern. Integrated solutions like drought-resistant crop varieties (Kaya and Ugurlar, 2023), technical support (Pitt, 2021), market access (Hossain et al., 2022), and sustainable land and water resource management (Gathala et al., 2021) warrant consideration.

4.2. Groundwater use

Groundwater is a widely used irrigation source in the Al Haouz Basin due to its accessibility, particularly compared to surface water, which is less reliable. However, extensive overexploitation has resulted in significant depletion, prompting government-imposed restrictions on the drilling of new wells. Our participants overwhelmingly (83 %) expressed concerns over falling water tables, which they indicated have reduced farming productivity and crop yields over time. Specifically, farmers reported that declining water availability during critical stages of cropping season has led to lower yields. This aligns with research showing groundwater depletion decreases agricultural outputs in arid regions (Mkilima, 2023; Silatsa and Kebede, 2023). Around 15 % of respondents reported wells drying up, directly limiting water availability for crops. Some participants did not encounter these issues due to variations in local hydrogeological conditions.

An apparent discrepancy emerged between perceived salinity presence across farm scales, based on farmer self-reports, and measured soil salinity from laboratory analysis. While large-scale and medium-scale farmers reported greater concerns about soil salinity (40 %), laboratory analysis of soil samples did not find significant differences in salinity levels between farm sizes. The self-reported salinity perceptions may reflect greater awareness and concern among larger farms rather than objective differences in soil properties. This heightened awareness among large-scale farmers could stem from their access to technical advice and greater exposure to market pressures, which necessitate better yield predictability and resource management. In contrast, smaller farms may underestimate salinity risks due to limited resources for soil testing or a lack of technical support. This perception-reality gap has important implications for agricultural decision-making and resource allocation. Participants who manage large farms may be more attuned to potential productivity losses from salinity, prompting cautious attention to early-stage soil degradation. This preventive approach aligns with findings that early intervention in soil salinity management is more cost-effective than remediation of severely affected soils (Qadir et al., 2019). Higher salinity damages soil health and crops, further reducing yields (Mkilima, 2023). The accumulation of salt can also impair water quality and restrict its usability for irrigation (Mkilima, 2023). Understanding this disconnect between perceived and measured salinity levels is crucial for agricultural extension services and policymakers, as it influences how farmers engage with soil management recommendations and adopt sustainable practices. Addressing this discrepancy through tailored awareness campaigns and equitable access to soil testing services could ensure that farmers of all scales make informed decisions and implement timely interventions to mitigate salinity risks.

Globally, the depletion of groundwater resources in arid and semi-arid regions demonstrates an urgent need for careful management. Policies that regulate groundwater extraction through quotas or withdrawal limits should be paired with mechanisms to ensure equitable distribution across farm sizes. For example, establishing a tiered quota system based on farm size could promote fairness while reducing over-extraction by large farms. Social norms and networks of farming stakeholders (farmers, retailers, agronomists, authorities) can also emerge as key to sustainably managing resources. Their social capital enables collaborative action among institutions preserving groundwater.

Through our SEM analysis, we found that groundwater scarcity does not substantially impact attitudes. Unexpectedly, common concerns over salinity negatively affect attitudes without corresponding usage reductions. This suggests farmers remain attracted to groundwater, due to subsidy incentives for drip irrigation and the increased productivity it enables. This finding aligns with (Boularbah et al., 2019) and (Kuper et al., 2018) that in collective irrigation systems where water resources are scarce and unpredictable, there is tendency towards groundwater overexploitation.

In our study, we investigated whether different land tenure types —specifically ownership and tenancy— influence PBC and, subsequently, resource extraction decisions. Our findings suggest tenure impacts the intention to use groundwater and adopt drip irrigation. The contrasts between ownership and tenancy models become evident when considering how farmers make specific actions and investments under each framework. Ownership cultivates greater perceived control and stewardship, leading to more sustainable groundwater and irrigation practices, while tenancy constrains perceived control and focuses extraction decisions on short-term yields. This echoes (Sugden, 2014) observation that insecure tenure and high rents deter tenant farmers from drilling wells. Given potentially shorter land use, tenants may prioritize extracting from shallower, existing wells over costly new drilling. These investment discrepancies highlight how tenure shapes resource management strategies with significant sustainability implications. To address these challenges, policies should aim to reduce tenure insecurity by promoting long-term tenancy agreements that incentivise sustainable investments (Goris et al., 2024; Lovo, 2016). Additionally, integrating tenancy terms that encourage shared responsibility for irrigation infrastructure and resource conservation between landlords and tenants could align short-term and long-term interests (Li et al., 2021).

4.3. Drip irrigation

The lowering of the water table highlights the pressing need for sustainable water management practices. In this respect, drip irrigation promotion has garnered attention (El Gueddari, 2004). (Kuper et al., 2018) highlight the pivotal role of groundwater in enabling expanded drip irrigation, within the sociocultural contexts of state subsidies and farmers' willingness to adopt the technology. Within this socio-economic landscape, (Kuper et al., 2018) describe a dual paradox - despite efficiency, drip irrigation exerts added pressure on groundwater. We note that without reliable access to water sources, particularly groundwater through wells, farmers are unable to install drip irrigation systems. This dependency on well access creates a significant barrier to the adoption of drip irrigation, especially in areas where groundwater resources are limited or where there are restrictions on water abstractions. As (Molle and Tanouti, 2017) note, government incentives aimed at encouraging drip irrigation adoption for increased productivity and water savings have inadvertently led to increased groundwater extraction. This phenomenon can indeed be interpreted as an example of Jevon's Paradox, where improvements in technological efficiency lead to greater, rather than reduced, resource consumption. In this case, while drip irrigation is more water-efficient at the field scale, the resulting increases in productivity and profitability often incentivise farmers to expand irrigated areas or intensify production, thereby offsetting any potential water savings (Kuper et al., 2018). This policy contradiction highlights the complexity of achieving resource conservation through technological innovation alone. It highlights the need for complementary governance measures, such as limits on groundwater extraction or incentives for conserving water, to ensure that efficiency gains translate into sustainable resource use rather than exacerbating resource depletion. This interconnection points to the need for policies that not only promote efficient irrigation technologies but also address equitable access to water resources and sustainable groundwater management. As (Foster and Garduño, 2013a) argue, effective groundwater governance requires an integrated approach that balances technological innovation with resource conservation and social equity.

We found a positive association between "Social norms" and "Attitude". Whilst we acknowledge that this association is not necessarily causal, societal and peer influences can strongly shape perceptions of this technology. As social norms shift, attitudes also change, potentially impacting willingness to adopt drip irrigation. Similarly, we observed a positive covariance between "Social norms" and "PBC". Social norms can help strengthen confidence in installing drip irrigation. Consequently, changes in social norms can boost farmers' perceived control, making them more likely to translate their intentions into actual behaviour.

Our results reveal large-scale farmers' significant inclination towards drip irrigation. This traces back to the 1980s in Morocco when companies provided free installation, leading to substantial yield increases and expansion of the technology (Benouniche et al., 2014). Noticing this shift, the government developed keen interest in drip irrigation, with many large landholders successfully securing subsidies to acquire equipment. In this context, government incentives aimed to encourage adoption for increased productivity, income and water savings, with subsidies found to alleviate financial barriers (Heumesser et al., 2012). However, despite a 100 % subsidy for smallholders, perceived obstacles around lengthy procedures still hinder uptake by this group. Furthermore, interviewed farmers emphasized land tenure barriers, with landowners showing higher adoption rates than tenants. This divergence could stem from shorter tenant time horizons on land or complex financing procedures deterring subsidy leveraging. While further investigation is needed, preliminary results indicate land tenure systems could interact with institutional contexts to shape technology adoption. Thus, policies may falter without assessing land issues and clarifying how programs could better accommodate all producers. Policymakers should consider developing tailored support mechanisms for tenant farmers, such as streamlined subsidy application processes or loan guarantees that account for their limited land tenure horizons. Additionally, public-private partnerships could be established to provide access to shared drip irrigation infrastructure, which would reduce the financial burden on tenant farmers while promoting sustainable irrigation practices. Introducing incentives for landowners to encourage tenant participation in water-saving technologies, such as tax reductions or grants, could further enhance adoption rates. However, technology adoption alone is insufficient to prevent overextraction. These incentives should be coupled with robust water allocation limits, monitoring systems, and graduated penalties for exceeding usage thresholds.

Our analysis reveals key dynamics influencing groundwater usage intention and drip irrigation adoption behaviours. Of the three theoretical drivers of intention, we find attitude exerts the strongest positive relationship in both contexts — more favourable attitudes are associated with heightened intention to use groundwater and adopt drip irrigation. PBC also positively predicts intention. Strategies improving attitude and PBC can effectively strengthen intentions to act. The negative "social norms" coefficient in regression may appear counterintuitive. However, it suggests the direct impact of social norms on intention may be weaker relative to attitude and PBC. Although social norms may not directly increase intention, their influence is offset by the positive relationships they have with "attitude" and "PBC." Interventions should reinforce positive attitudes and perceived control while considering the more indirect role of social norms.

The robust positive relationship between intention and behaviour reaffirms intention's role as a key predictor of actual adoption. Influencing intention is critical for driving engagement with drip irrigation. Farm size underscores the contextual relevance of drip irrigation choices within diverse agricultural landscape. Limited private water access helps explain gravity-flow prevalence (Ameur et al., 2013), while lack of technical assistance further reinforces this choice (Benouniche et al., 2014).

The challenges posed by the limited replenishment of groundwater accentuate the importance of water source availability, which is critical for the sustained operation of drip irrigation. However, the reality of drip irrigation's sustainability impact is complex, rather than saving water, drip irrigation adoption is associated with unintended consequences like higher crop densities, shifts to water-intensive crops, and reuse of water that was supposedly saved through drip irrigation to expand cultivated areas (Molle and Tanouti, 2017; Sraïri, 2021). These factors collectively increase water consumption versus conserving water. A paradox emerges when governments promote drip irrigation while limiting groundwater use, considering drip irrigation a pump-based irrigation technology.

4.4. Cooperation

Farmers have adapted to water shortages by deepening existing wells and drilling new ones, reflecting urgent efforts to secure supply amidst recurring droughts. Our study revealed limited contingency plans for building resilience in drought-prone regions, indicating a lack of proactive preparation and insights into groundwater levels (Laraichi and Hammani, 2018). Our findings of low willingness to cooperate on groundwater-driven irrigation align with previous findings. As (Meinzen-Dick, 2014) and (Mukherji and Shah, 2005) note, groundwater lacks the visible and institutional infrastructure that facilitates cooperation, unlike surface water irrigation systems. The invisibility of groundwater and lack of transparent monitoring enable individualistic pumping behaviours. Farmers respond to water shortages by increasing their pumping rate, creating a self-reinforcing cycle similar to the "tragedy of the commons."

However, collective action is possible, as (Shah et al., 2007) discuss, pointing to successful community-based initiatives in India and Mexico. For example, in India, groundwater user associations have been established where farmers collectively agree on groundwater extraction limits, share monitoring responsibilities, and regulate well use to prevent overexploitation. Similarly, in Mexico, community-level groundwater management programs involve local groups setting rules for groundwater extraction and collectively investing in water-saving technologies. These initiatives demonstrate that even in the absence of formal infrastructure, effective community organization, trust-building, and locally crafted rules can enable successful collective management of groundwater resources. Our study reinforces that despite less intuitive cooperation for groundwater, social collaboration remains essential for sustainability, requiring comparable trust, communication, and understanding as surface water. Also, implementing community-led groundwater monitoring systems, supported by regional authorities, could encourage transparency and accountability. These systems can help farmers better understand aquifer conditions and align extraction with sustainable limits.

In contrast to some studies where smallholders show greater cooperation openness (Meinzen-Dick, 2014; Shah et al., 2007), our finding that farm size did not impact willingness indicates this reluctance crosses scales. However, other research similarly found no farm size-cooperation association (Kerr et al., 2002). This suggests that while farm size may play a contextual role, cooperation cannot be attributed to large versus small-scale agricultural systems.

Incentives and institutional structures are crucial for enabling collective action, as (Foster and Garduño, 2013b) emphasize. Government initiatives can establish ground rules and support local stakeholders in devising equitable governance plans. To encourage cooperative action, policies should establish or strengthen WUAs by providing funding, training, and technical support for community-led monitoring systems. WUAs could play a critical role in setting extraction limits, promoting resource-sharing agreements, and increasing transparency. Pilot programs demonstrating the benefits of cooperative irrigation practices could also help build trust among farmers and foster collaboration. Our work reinforces that enhancing resilience requires social ingenuity alongside technical solutions. Sustainable groundwater irrigation depends on facilitating communication, building trust, and aligning individual and collective interests.

4.5. Challenges of constructing an integrative modelling framework to understand farmers' decision-making

The integrated modelling framework developed in this paper provides a methodological approach for elucidating the multidimensional drivers shaping farmers' decision-making processes. While centred on irrigation technology adoption and water resource usage in a specific regional context, the conceptual scaffolding of qualitative investigation, theory-driven hypothesis modelling, and statistical relationship testing has cross-disciplinary relevance. These components offer a transferable template for constructing integrative explanations of decision-making phenomena in diverse contexts.

Specifically, initial qualitative interviewing allows inductive identification of key attitudes, norms and perceived behavioural beliefs directly from farmer experiences, contextualizing their decisions. Translating these concepts into behavioural theory constructs enables hypothesis formulation regarding relationship dynamics. Integrating this conceptual model with structural equation modelling quantifies influence strengths through statistical testing procedures generalizable beyond the study setting.

Our analytical approach enabled a comprehensive understanding of the complex drivers influencing farmers' decisions, whilst also posing integrative challenges. For instance, while thematic coding exposed perceived obstacles around technology adoption, SEM analysis quantified the relative influence of factors like attitude and PBC. However, effectively harmonising the different data types proved challenging, requiring meticulous integration to ensure compatibility. Moreover, the indirect effects between variables emerged as more intricate than originally hypothesised. Still, the integrated framework provided multidimensional insights into farmers' decision-making processes.

Beyond analytical challenges, we encountered practical field difficulties during data collection. Some farmers were unavailable on-site at the time of the survey, or their farm locations were difficult to access, which occasionally required selecting nearby alternatives to maintain efficiency. Additionally, only one farmer refused to participate, highlighting a generally high level of cooperation among respondents. Despite these logistical challenges, we managed to preserve the sample's representativeness by maintaining diversity across farm sizes, locations, and irrigation practices.

5. Conclusion

Influenced by economic profitability and environmental adaptability, many farmers are transitioning from cereal and horticultural crops towards olive tree cultivation. Groundwater has emerged as the predominant irrigation source, but farmers now face sustainability challenges associated with water depletion and salinity. Our results show that 83 % of farmers expressed concerns about declining groundwater levels, while 40 % reported salinity as a major challenge. Only 52 % of farmers indicated a willingness to cooperate on groundwater management, highlighting barriers to collective action. Additionally, landowners showed higher adoption rates of drip irrigation compared to tenants, reflecting tenure-related disparities. Our findings show that land tenure type shapes farmers' perceived control and groundwater management decisions, with ownership engendering a more sustainable long-term mindset compared to tenancy. Farmers' attitudes and PBC strongly influence their intention to use groundwater and adopt drip irrigation. Notably, intention significantly predicts adoption behaviour. Influencing intention by addressing attitudes and PBC can promote more sustainable irrigation behaviours.

The methodological approaches used in this study, while innovative, have certain limitations. The reliance on structured interviews and inductive coding, while effective for capturing in-depth qualitative data, may introduce potential biases due to the single-researcher coding process and the inherent subjectivity of qualitative methods. Additionally, the use of the TPB and SEM, though well-suited for examining relationships between behavioural drivers, may oversimplify complex socio-environmental factors and feedback dynamics. Future studies could address these limitations by incorporating complementary modelling approaches, such as Agent-Based Models, to better capture the emergent and interactive aspects of farmer decision-making. Furthermore, the geographic focus on the Al Haouz Basin may limit the generalisability of the findings to other arid and semi-arid regions, as behavioural drivers may vary under different socio-economic and environmental conditions. Expanding the scope to include diverse regions and evaluating policy interventions across contexts would enhance the applicability of these insights to broader agricultural water management challenges. Overall, our research emphasizes the need for integrated solutions that consider technological innovations along with social, economic, and policy interventions. Sustainable agricultural and water management in arid regions necessitates strategies that balance productivity, profitability, and environmental resilience while empowering local communities. Further research can build upon these findings to support equitable and sustainable resource use.

CRediT authorship contribution statement

Toby W. Waine: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Funding acquisition, Conceptualization. **Joanna Zawadzka:** Software, Formal analysis. **Alice E. Milne:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Ron Corstanje:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **EL FARTASSI Imane:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Helen Metcalfe:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rafiq El Alami:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Alhousseine Diarra:** Writing – original draft, Software, Investigation, Formal analysis. **Vasthi Alonso-Chavez:** Writing – original draft, Validation, Investigation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Latent variables and observed statements for drip irrigation adoption

Latent variables	Observed statements
Behaviour	I am planning to adopt drip irrigation
Intention	I am willing to apply for a drip irrigation subsidy
	I am willing to dig a well
Social norms	I am aware that the government is promoting the adoption of drip irrigation
	My neighbours are satisfied with drip irrigation
Attitude	I am satisfied with drip irrigation efficiency
	I am satisfied with groundwater salinity
	I am satisfied with the groundwater supply
PBC	My type of tenure facilitates the adoption of drip irrigation
	My farm size facilitates the adoption of drip irrigation

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2025.109789.

Data availability

Data will be made available on request.

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