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EDITED BY
Xin Qiao,
University of Nebraska System, United States

REVIEWED BY
Lucia Bortolini,
School of Agricultural Sciences and Veterinary Medicine, University of Padua, Italy
Burdette Barker,
Utah State University, United States

*CORRESPONDENCE
Sandra M. Guzmán
sandra.guzmangut@ufl.edu

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Bridging the gap between water-saving technologies and adoption in vegetable farming: insights from Florida, USA

Akshara Athelly[1], Sandra M. Guzmán[1*], Ziwen Yu[2] and Jonathan Adam Watson[2]

[1]Agricultural and Biological Engineering Department, UF/IFAS Indian River Research and Education Center, Fort Pierce, FL, United States, [2]Agricultural and Biological Engineering Department, University of Florida, Gainesville, FL, United States

Globally, agricultural water management faces significant challenges due to uneven water availability, crop diversity, and climate variability. Despite increasing access to smart irrigation technologies, adoption among vegetable farmers remains low. This study examines the willingness of Florida vegetable growers to adopt water-saving irrigation technologies, focusing on socio-economic factors, perceived barriers, and opportunities for enhanced outreach. A structured, pre-tested survey was conducted with commercial vegetable growers across Florida's major vegetable-producing regions, collecting data on irrigation practices, familiarity with technology, satisfaction, and demographic characteristics. Results showed that satisfaction with current irrigation practices and willingness to adopt new technologies were significantly influenced by farm size, education, income, and crop diversity. Farmers managing multiple crops, small-scale growers expressed a strong interest in adoption, particularly when cost-share or technical assistance programs were available. Common barriers included high initial costs, lack of technical training, and skepticism about the reliability of water-saving technologies. This study highlights the need for targeted outreach strategies that consider demographic variability, farm size, and cropping systems. Based on the results, the policy measures that simplify access to incentive information, decision-support tools, and inclusive hands-on training programs can enhance technology adoption. While focused on Florida, the findings reflect broader patterns in adoption behavior across global small- to medium-scale farming systems. These insights are valuable for policymakers, extension agents, and researchers aiming to accelerate the adoption of precision irrigation for climate-resilient agriculture.

KEYWORDS

precision irrigation, smart irrigation technologies, irrigation survey, water-saving technology, farmer perceptions, efficient irrigation management, technology adoption, socio-economic factors

1 Introduction

Global irrigation water use has more than doubled in the past fifty years, now accounting for approximately 2,800 km^3 of annual withdrawals and contributing to 34% of global agricultural production (Foley et al., 2011). In the absence of irrigation, an estimated 17% more land would be required to meet current production levels (Foley et al., 2011; Siebert and Döll, 2010). The expansion of irrigated agriculture, coupled with diminishing freshwater availability, prolonged droughts, and increasing climate variability, highlights the urgency of adopting water-saving technologies even in high-rainfall regions such as the southeastern United States (Odera et al., 2013).

Florida illustrates the complexity of this issue. Although only 2.6% of its land is irrigated, the state ranks fourth nationally in total water withdrawals, with agriculture accounting for 40% of freshwater use (USDA, 2019; Reubold, 2022). As the second-largest vegetable-producing state in the United States, Florida reported $1.39 billion in vegetable sales in 2020 (USDA National Agricultural Statistics Service, 2020). Vegetable production requires nearly twice the irrigation volume of field crops (FDACS (Florida Department of Agriculture and Consumer Services), 2023). Despite the demonstrated benefits of precision irrigation technologies, the sector continues to operate with relatively low irrigation efficiency (Van Dijl et al., 2015; Eshete et al., 2020; Zinkernagel et al., 2020), highlighting the need to understand better and address the barriers limiting technology adoption in commercial vegetable systems.

Adopting water-saving technologies in agriculture requires a multifaceted approach, one that incorporates not only technical solutions but also a nuanced understanding of farmers' perspectives and decision-making processes. Public attitudes toward environmental and agricultural issues have been shown to significantly influence policy outcomes (Melstrom and Malone, 2023), while access to information and farmer engagement are recognized as key drivers of technology adoption (Abdulai et al., 2011).

Research and extension programs have demonstrated the effectiveness of soil moisture sensors (SMS), evapotranspiration-based scheduling tools, and smart irrigation apps in improving water use efficiency and promoting adoption (Mylavarapu et al., 2009; Pronti et al., 2024; Zhuang, 2023). Educational materials and decision-support tools for SMS data interpretation and usage, evapotranspiration (ET) data, and app-based irrigation scheduling are widely available through land-grant universities and extension services (Zotarelli et al., 2010; Kisekka et al., 2010; Sharma et al., 2020; Monaghan et al., 2015; Shukla and Holt, 2014; Herrera et al., 2021; Dittmar et al., 2021). Several smart irrigation apps have been developed specifically for vegetable and tree crops, utilizing crop-specific ET parameters (Migliaccio et al., 2015; Sommer et al., 2015). Meanwhile, advanced controllers have demonstrated substantial water savings in both research and field settings (Dukes, 2012; Sheline et al., 2024). Despite these advancements and the availability of tools and training, adoption rates remain low in many regions, including Florida. This suggests that technical innovation alone is insufficient, and that greater attention must be given to the social, informational, and economic factors influencing grower decisions.

Assessing technology adoption patterns influenced by farmer demographics enables the development of more targeted interventions, such as region-specific outreach and education programs tailored to the needs of different grower groups. Prior research on adoption of agricultural technology has consistently identified perceived risk and cost-effectiveness as key deterrents to adoption (Koundouri et al., 2006). A holistic understanding of adoption behavior must consider a range of factors, including prior knowledge, technical skills, human capital, economic constraints, and farmer attitudes toward innovation (Arabiyat et al., 2001; Coupal and Wilson, 1990; Droogers et al., 2000; Greenland et al., 2019; Koundouri et al., 2006; Santos, 1996; Whittlesey, 1985). Trust and institutional relationships between stakeholders also play a critical role. For example, Yehouenou et al. (2020) found that enrollment in best management practice (BMP) programs was closely tied to existing trust between farmers, agencies, and local authorities. He (2023) emphasized the importance of incentive payments in encouraging adoption of both nutrient and irrigation BMPs. Interestingly, Van Dijl et al. (2015) reported that greater education levels were associated with lower adoption rates of water management practices, while land ownership had no significant effect, highlighting the complex influence of socio-economic factors. Collectively, these findings suggest that demographic and contextual variables interact in shaping farmers' willingness to adopt new technologies. Understanding these dynamics in a localized context, such as Florida's vegetable sector, is essential for designing effective and inclusive programs that promote the adoption of water-saving irrigation strategies.

This study provides a novel contribution by investigating the intersection of socio-demographic characteristics and smart irrigation adoption in a highly water-dependent but understudied sector, Florida's commercial vegetable production. While prior research has focused on the technical efficiency of irrigation tools, limited attention has been given to how farmers' perceptions, satisfaction, and trust shape the adoption of technologies such as soil moisture sensors, evapotranspiration-based scheduling apps, and automated controllers. By integrating behavioral, economic, and demographic variables, this study offers a comprehensive, farmer-centered perspective on technology adoption.

To our knowledge, this is one of the first studies to specifically assess vegetable growers' willingness to adopt water-saving technologies in relation to factors such as farm characteristics and farmer demographics. The findings fill a critical gap by explaining not only whether technologies are used, but also why some farmers remain hesitant, despite having access to tools and support programs. The insights generated inform more targeted, inclusive, and effective strategies for outreach, policy design, and conservation planning. This research also serves as a benchmark for similar efforts across diverse cropping systems facing water limitations globally.

2 Materials and methods

Data collection for this study involved administering an in-person survey across Florida, USA. We conducted a pre-test with

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five local farmers to ensure the survey's reliability and validity (Abebe et al., 2020). Before the pre-test, we obtained approval from the Institutional Review Board (IRB202200392). The pre-test was conducted through face-to-face interviews, during which we paid attention to non-verbal cues to identify issues with question clarity (Churchill and Iacobucci, 2006; Miller and Salkind, 2002). We also employed cognitive interviewing to evaluate participants' understanding of the questionnaire. The objectives of the pre-test included assessing logic and flow, evaluating acceptability, question length, and adherence, assessing question quality, verifying proper introduction, and obtaining informed consent (Collins, 2003; Presser et al., 2004). Based on the pre-test results, specific adjustments were made to improve the questionnaire's clarity and relevance.

The survey instrument, developed in January 2022, was administered from August 2022 to November 2023 and included sections related to the assessment of current irrigation technologies, demographics, and socio-economic factors. The development of the survey questions was guided by a thorough literature review and consultations with experts to ensure comprehensiveness and relevance. In this study, we inquired about the respondents' familiarity and experience with various irrigation methods and technologies, including SMSs, smart irrigation apps, and controllers. Additionally, we asked questions related to factors influencing technology adoption, such as subsidies or cost-share programs, nutrient management strategies, soil sampling, and the impact of extreme weather events. Respondents were asked to indicate their level of agreement, ranging from strongly disagree to strongly agree (ratings from 1-5, respectively). To verify the validity of the responses, we repeated and duplicated questions related to the cost of technology, familiarity, and practical use of technology throughout the survey.

The in-person, 20-minute survey was conducted by interviewing vegetable farmers and farm managers who attended various commodity crop conferences. Of the 65 responses received, 63 were used in this study; two were discarded due to incompleteness. Although efforts were made to distribute the survey through farmer groups and extension networks, the most reliable information was obtained through in-person interviews at commodity events (Zhang et al., 2017). Commodity events were selected because they attracted growers who were actively engaged in production decisions and willing to participate in research discussions. While this approach may introduce selection bias toward more active or innovative growers, it ensured data quality and depth of response. Events were held in multiple production regions, including Central, South, and Northeast Florida.

Data retrieved from the responses were analyzed and grouped into four sections: a) barriers to adoption, b) factors influencing adoption, c) willingness to adopt irrigation management technologies, and d) current satisfaction with irrigation management. Table 1 summarizes all dependent and independent variables included in the analysis. Given the ordered nature of the Likert scale responses, ordinal logistic regression was applied to examine the relationship between each dependent variable (e.g., Barriers to implementing water-saving technologies, such as "I consider frequent irrigation to be critical for increasing crop yields") and all independent variables, which included demographic and farm characteristic variables. This modeling approach allows the probability of respondents selecting higher or lower levels on an ordinal outcome to be estimated as a function of multiple independent variables, assuming the relationship between each pair of outcome groups is similar (proportional odds) (Göb et al., 2007). For this study, a total of 22 models were estimated, one for each dependent variable. Prior to model estimation, we conducted descriptive analyses on each independent variable. Frequencies were calculated for categorical variables (such as gender, race, and education), and summary statistics (mean and standard deviation) were computed for continuous or ordinal predictors (such as age and gross cash income) to ensure sufficient variability and to identify categories with very low counts. The frequency distribution of each categorical variable and potential multicollinearity were evaluated before inclusion in the model. Variables or categories with very low representation (fewer than 5–10 cases) were either aggregated with similar groups or excluded to avoid unreliable inference. Although race and gender had limited representation in some categories (e.g., only 8 female respondents), these variables were included in the regression models for exploratory analysis; however, coefficients and statistical significance for these variables should be interpreted with caution, as small sample sizes in some subgroups may result in less reliable estimates. A similar process was followed for farm characteristic variables, with soil type being the only variable removed from the final model due to multicollinearity. After fitting each ordinal logistic regression model, we applied the Brant test to assess the proportional odds assumption. The Brant test indicated that this key assumption was met in all models. This methodological approach is well established for evaluating perceptions and behavioral intentions in social science and agricultural research (Feder et al., 1985; Brant, 1990; Olawuyi, 2020).

3 Results and discussion

3.1 Respondent demographics

The age distribution was relatively balanced across categories. Farmers aged 24–33, 34–43, and 54–63 each represented 19% of the respondents, while those aged 44–53 comprised 21%. Fewer participants were aged 64–73 (15%) and 74–83 (6%). This even age distribution across middle-aged groups highlights a stable generational spread within the vegetable farming sector. These values reflect broader trends in Florida agriculture but highlight the need for inclusive engagement strategies for underrepresented groups.

Educational achievements were relatively high among respondents. Forty percent held a bachelor's degree, 11% a master's degree, and 3% had education beyond a master's degree. Additionally, 16% reported having some college education, while 15% completed high school. Only a small percentage had educational levels below high school. This trend suggests a

TABLE 1 Summary of variables (grouped by category) included in the twenty-two ordinal logistic regression models.

Variable Type	Group/Category	Variable (Survey Item/Construct)	Measurement Scale
Dependent Variables	Barriers to implementing water-saving technologies	I consider frequent irrigation to be critical for increasing crop yields	5-point Likert scale (1=Strongly disagree, 5=Strongly agree)
		Technicians are the only ones who can maintain precision irrigation on a farm.	
		Extreme weather events (such as flooding or drought) have affected my crop growth and yield in the last three years.	
		Drainage is not an issue on my farm.	
		Water for irrigation is scarce on my farm.	
		Water quality for irrigation influences my crop yield	
		I know what the consumptive water use of my crop is	
	Factors associated with the adoption of water-saving technologies	Applying an adequate amount of water in the right place at the right time with precision irrigation increases crop yield	5-point Likert scale
		Investing in irrigation automation will increase profit.	
		Investing in irrigation and water quality management gives producers an economic advantage.	
		During crop establishment, it is necessary to apply frequent irrigation.	
		I only irrigate during crop establishment.	
	Willingness to adopt water-saving technologies	Willingness to implement water-saving technologies if a cost share were available	5-point Likert scale
		Willingness to implement water-saving technologies if a cost share were not available	
		Willingness to modify my irrigation scheduling method if there is scientific evidence suggesting that it can conserve water	
		Willingness to modify the irrigation scheduling method if there is scientific evidence that it can increase yield	
		I manage irrigation water to increase crop yield.	
		I manage water use to increase environmental stewardship.	
		I conduct regular soil tests for pH, nitrogen, phosphorus, and potassium.	
		I conduct regular water tests for irrigation suitability and salinity.	
	Current satisfaction with irrigation management	I am satisfied with my current irrigation scheduling practices	5-point Likert scale
		I am satisfied with my current irrigation management.	
Independent Variables	Demographic characteristics	Age	Years (age); Male/Female; Race categories; Education level
		Gender	
		Race	
		Education	
	Farm characteristics	Area (ha)	Numeric or categorical, as appropriate
		Farming experience (years)	
		Crops per year	
		Farming at the exact location (years/rental status).	
		Gross cash income.	

(Continued)

TABLE 1 Continued

Variable Type	Group/Category	Variable (Survey Item/Construct)	Measurement Scale
		Irrigation cost (%).	
		Location (region).	
		Soil type (excluded from final model).	

population with substantial formal education and a greater capacity for engaging with technical information and innovation.

Farming experience varied considerably among respondents. Approximately 37% of the farmers had between 1 and 9 years of experience, indicating a strong presence of new growers. Those with 10–19 years and 20–29 years of experience comprised 18% of the respondents. More experienced respondents with 30–39, 40–49, and 50–59 years of experience represented 10%, 8%, and 10% of the sample, respectively. These findings align with USDA National Agricultural Statistics Service (2020) data, which show that nearly one-third of Florida's farmers have less than a decade of experience.

The presence of early-career farmers, who made up 37% of our respondents, may reflect broader demographic and economic shifts, including population growth and increased interest in local food systems. Florida's population increased by 1.9% between 2021 and 2022, reaching over 22 million residents (Campbell et al., 2023; Perry et al., 2022). This growth likely contributed to an increase in participation in vegetable farming among new and urban-adjacent growers. Although race and gender data were collected, the sample was highly skewed and limited in diversity. Therefore, these variables were excluded from statistical analysis and not considered in the interpretation of results.

3.1.1 Farm size and crop diversity

Results showed that 40% of respondents operated small- to medium-sized farms (Figure 1a). This result corresponds with earlier findings from the 2007 Census of Agriculture, which reported that 87% of Florida farms are under 72 hectares (U.S. Department of Agriculture, 2007). This concentration of small- and mid-scale operations reflects the structure of Florida's diversified and labor-intensive vegetable sector.

Regarding crop diversity, most respondents (29%) cultivated two crop types, followed by 21% who grew three crops, and 15% who reported producing more than ten different crops annually (Figure 1b). The high level of crop diversification may serve as a strategy to manage agronomic and market risks and improve

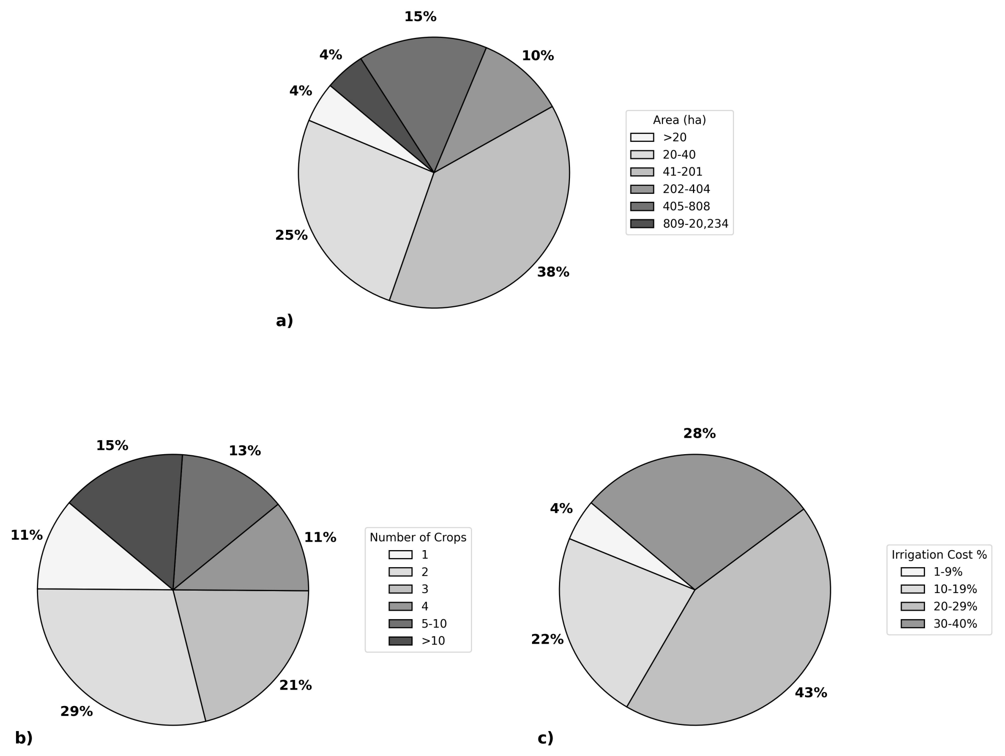

FIGURE 1
Key aspects of farm operations among respondents: **(a)** Farm area (ha), **(b)** Number of crops grown annually, and **(c)** Irrigation costs (as a percentage of total farm operating expenses).

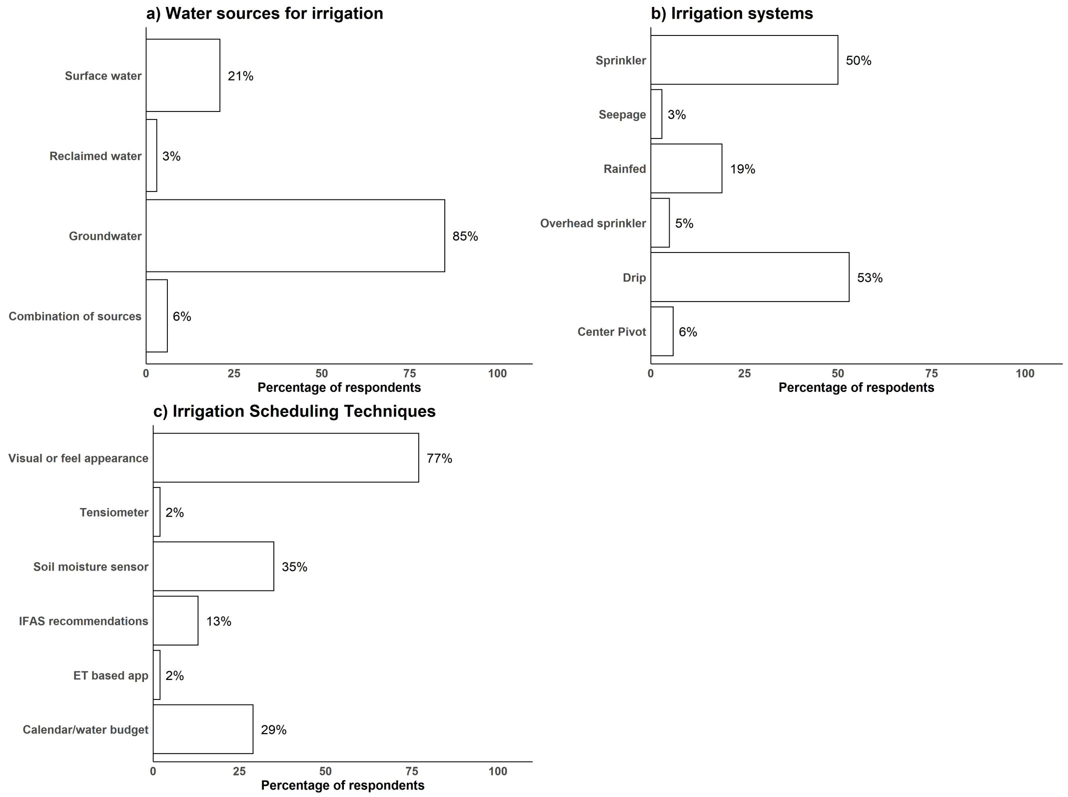

FIGURE 2
Irrigation practices preferred among survey respondents: **(a)** Water sources, **(b)** Irrigation systems, **(c)** Irrigation scheduling methods.

income sustainability. The dominant crops reported were sweet corn, cucumbers, squash, and melons. These crops together accounted for 18% of Florida's total agricultural cash receipts in 2020, contributing approximately $1.33 billion, surpassing citrus production during the same period (USDA, National Agricultural Statistics Service, 2021). These findings highlight the operational complexity of Florida vegetable farms, particularly regarding rotation planning, labor management, and water scheduling. Crop diversity and farm scale are essential for tailoring irrigation support and outreach programs.

3.1.2 Irrigation management cost

Irrigation costs were reported as a percentage of total farm operating expenses, revealing a significant financial burden for many growers (Figure 1c). The most common cost range was 20–29%, reported by 43.6% of respondents. An additional 28.7% of respondents indicated irrigation expenses accounted for 30–40% of their total costs, while 22.8% reported a lower range of 10–19%. These results suggest that irrigation represents a substantial input cost, particularly for smaller or newer farms. 37% of the respondents with less than nine years of farming experience were more likely to report greater irrigation costs, potentially reflecting the upfront investments required for new system installation and management. Respondents were asked to estimate the percentage of annual production costs associated with irrigation management, which may have included water usage, fuel or electricity for pumping, labor, maintenance, and in some cases, amortized capital costs for equipment. While we did not disaggregate these categories in the survey, this comprehensive interpretation aligns with common farm budgeting practices in Florida's vegetable sector. These findings are crucial for designing incentive programs that offset the initial costs associated with adopting water-saving technologies.

3.1.3 Water sources for irrigation

Most farmers (85%) reported using groundwater as their primary source for irrigation, while 21% used surface water and 6% relied on a combination of sources (Figure 2a). Only 3% reported using reclaimed water. These patterns align with broader irrigation trends across Florida and the southeastern U.S., where groundwater is often preferred due to its year-round availability and reliability (Marella, 2020; Qin et al., 2024). In coastal regions, surface water use is more common due to lower groundwater quality, while mixed-source strategies are typically employed during drought periods (Aumen, 1995; Daroub et al., 2009). These findings emphasize the importance of water quality monitoring and source diversification, especially for farms in hydrologically vulnerable areas.

3.1.4 Irrigation systems and irrigation methods

Among respondents, drip irrigation emerged as the most common method, used by 53% of growers, followed closely by sprinkler systems at 50% (Figure 2b). Many farms used multiple systems, reflecting Florida's diverse cropping systems and field conditions. Additional methods included rainfed systems (19%), center pivot (6%), overhead sprinklers (5%), and seepage irrigation (3%). The widespread use of drip irrigation reflects increasing awareness of water conservation benefits among growers. However, seepage irrigation, a form of subirrigation, is widely used in Florida's vegetable production systems. It involves managing shallow ditches and canals to raise the water table, allowing water to seep upward into the root zone through capillary action (Smajstrla and Haman, 1998). Its persistent usage underscores the need for targeted outreach in regions with high transition barriers (Rogers et al., 2018; Zotarelli et al., 2019).

In terms of irrigation scheduling, 77% of respondents reported relying on visual and feel assessments of soil conditions (Figure 2c), while 35% used SMS. Calendar-based methods were employed by 29%, and only 2% reported using ET-based mobile apps or tensiometers. Despite their proven benefits, the limited adoption of app-based tools may be attributed to trust issues, difficulty interpreting data, or lack of familiarity with digital interfaces (Sharma et al., 2022; Migliaccio et al., 2015). These results indicate a gap between availability and application of data-driven tools, suggesting that user-friendly designs, trust-building, and extension support are essential to advancing adoption (Taghvaeian et al., 2020).

3.2 Barriers to the adoption of smart irrigation technologies

The statement "I consider frequent irrigation is critical for increasing crop yields" received a high mean score of 4.5 (SD = 0.9), indicating a strong consensus among respondents regarding the importance of frequent irrigation (Table 2). The statement "Technicians are the only ones that can maintain precision irrigation on a farm" had a mean score of 2.7 (SD = 1.7), reflecting moderate agreement and suggesting a degree of uncertainty or reliance on technical expertise among farmers. This perception was significantly associated with farm location ($p < 0.05$), indicating the need for site-specific irrigation management recommendations considering local soil and environmental conditions and water availability. The prior familiarity of respondents with variable-rate irrigation and other precision irrigation technologies in North Florida could have influenced the responses obtained. Deh-Haghi et al. (2020) noted that a lack of knowledge and technical expertise regarding the operation and maintenance of water-saving technologies significantly impacts the adoption and continued use of these technologies. The complexities associated with technologies and the fear of unknown potential risks, such as those affecting soil health, influence technology adoption.

Respondents strongly agreed with the statement, "Extreme weather events such as flooding or drought have affected my crop growth and yield in the last three years" (mean = 4.2, SD = 1.5). 73% of the respondents "strongly agree" that extreme weather events have impacted their crops in the past three years. This agreement is an expected response, given the increasing frequency of extreme events across the state over the past five years (Ferrarezi et al., 2020). The flood damage in South Florida during Hurricane Irma was estimated to have resulted in $180 million in losses across vegetable production fields and $760 million in losses across fruit production fields (Mayo, 2017).

Farmers showed neutrality towards the statement "Drainage is not an issue on my farm" (mean = 3.1, SD = 1.7). However, the significant association between farm location ($p < 0.05$) indicates differences in drainage challenges across regions. In contrast, the statement "Water for irrigation is scarce on my farm" received a lower mean score of 2.5 (SD = 1.8), with significance across farming years, gross cash income, and irrigation costs ($p < 0.01$), indicating the financial and practical constraints associated with water scarcity. There is a correlation between those who report spending the highest percentage of their budget on irrigation and a greater perception of facing water scarcity issues. Respondents from North Florida experience greater water scarcity issues (mean = 3.8, "agree") compared to those from Central (mean = 2.7, "disagree") and South Florida (mean = 1.6, "strongly disagree"), which is also related to the state's hydrologic conditions.

The statement "Water quality for irrigation influences my crop yield" (mean = 4.3, SD = 1.4) was significantly correlated with farm area (ha) ($p < 0.01$), gross cash income ($p < 0.01$), irrigation cost ($p < 0.05$), and farm location ($p < 0.05$). Water quality concerns were more pronounced among smaller farms and those with lower incomes, possibly due to their reliance on groundwater and issues such as saltwater intrusion (Bayabil et al., 2021). The statement "I know what the consumptive water use of my crop is" (mean = 3.1, SD = 1.5), showing no significant associations, indicates a potential gap in crop-specific water use, highlighting an area for extension services to address.

3.3 Factors that influence the adoption of smart irrigation technologies

Respondents strongly agreed that precision irrigation contributes to increased crop yield (mean = 4.6, SD = 0.9) (Table 3). This perception was significantly associated with farm area (ha) ($p < 0.001$) and gross cash income ($p < 0.05$), with small-scale farmers perceiving greater benefits. Communication and educational strategies targeting these groups should emphasize the environmental and productivity advantages of precision and smart irrigation technologies. Smaller-scale farmers were more likely to view precision irrigation as a tool for enhancing yield than their larger counterparts. Similarly, respondents earning between $150,000 and $350,000 annually were more supportive of precision irrigation than those earning below $150,000. This trend may reflect the greater relative cost burden of precision systems for small and new farms (Salazar and Rand, 2016). A related study, conducted by Yehouenou et al. (2020), found that 65% of farmers cited installation costs as a barrier to adoption, with 25% reporting

TABLE 2 Demographic factors associated with barriers to implementing smart irrigation technologies.

Variable	Mean	SD	Area (ha)	Farming experience	Crops per year	Same location farming	Gross cash income	Irrigation cost %	Farm Location	Education	Age
I consider frequent irrigation to be critical for increasing crop yields	4.5	0.9	NS	NS	NS	NS	NS	NS	NS	NS	NS
Technicians are the only ones who can maintain precision irrigation on a farm	2.7	1.7	NS	NS	NS	NS	NS	NS	*	NS	NS
Extreme weather events, such as flooding or drought, have affected my crop growth and yield in the last three years	4.2	1.5	NS	NS	NS	NS	NS	NS	NS	NS	NS
Drainage is not an issue on my farm	3.1	1.7	NS	NS	NS	NS	NS	NS	*	NS	NS
Water for irrigation is scarce on my farm	2.5	1.7	NS	NS	NS	*	*	***	*	NS	NS
Water quality for irrigation influences my crop yield	4.3	1.4	**	NS	NS	NS	**	*	*	NS	NS
I know what the consumptive water use of my crop is	3.1	1.5	NS	NS	NS	NS	NS	NS	NS	NS	NS

*Refers to p value < 0.05, **p value < 0.01, ***p value < 0.001. NS, statistically not significant.
SD is the standard deviation. Mean values are in relation to the following scale: 1, Strongly Disagree; 2, Disagree; 3, Neither Agree nor Disagree; 4, Agree; 5, Strongly Agree; 6, Not Applicable.

that they could not afford the installation. Increasing small farmer participation in state-level subsidy and incentive programs could help close this gap (Deh-Haghi et al., 2020). However, practical solutions must also address the unique technical and managerial challenges faced by low-income and small-scale farms (Robotham and McArthur, 2001; Cantor and Strochlic, 2009; Goodwin and Gouldthorpe, 2013).

The belief that irrigation automation increases profitability (mean = 4.3, SD = 1.1) was significantly associated with the number of crops grown annually ($p < 0.01$). Respondents recognized economic benefits from automation, particularly growers and those managing diverse cropping systems. Similarly, investment in irrigation and water quality management was perceived as advantageous (mean = 4.4, SD = 1.2), with significant associations found for crop diversity ($p < 0.01$). Farmers cultivating 5–10 or more than 10 crops annually showed greater interest in irrigation automation than those growing only one or two crops.

The importance of frequent irrigation during crop establishment also received high agreement (mean = 4.7, SD = 0.9), with significant associations with the age of the farmer ($p < 0.05$). This pattern may reflect greater environmental awareness and openness to innovation among younger farmers (Baumgart-Getz et al., 2012). In contrast, views on limiting irrigation to crop establishment were more variable (mean = 3.8, SD = 1.7), and no significant associations were observed between these views and demographic or operational variables. This indicates diverse on-farm practices and perceptions regarding irrigation timing, highlighting the need for further research and tailored extension support to guide optimal strategies across different farm types.

3.4 Respondent's willingness to adopt water-saving irrigation technologies

Respondents expressed a strong willingness to adopt water-saving technologies if financial assistance, such as cost-share programs, were available (mean = 4.4, SD = 1.3), with significant associations observed between this willingness and farm area (ha) and the number of crops grown annually ($p < 0.05$) (Table 4). In contrast, willingness dropped without cost-share support (mean = 3.4, SD = 1.7), underscoring the importance of financial incentives in facilitating technology adoption. Farmers operating smaller farms (<20 ha) expressed lower interest in modifying their current irrigation scheduling practices (mean = 3.8, indicating neutral to moderate agreement) compared to those managing mid-sized (202–404 ha, mean = 4.2) and large farms (405–808 ha, mean = 4.8), who reported strong agreement. These findings align with Enyew (2024), who found that economic factors play a central role in shaping farmers' willingness to invest in irrigation improvements. Larger farms are often more cost-efficient per unit area and have better access to subsidies (Buttel et al., 1985; Fuglie, 1999). Moreover, 90% of large farms in the United States are family-operated and typically have a longer history of program participation (MacDonald and Hoppe, 2017), which may facilitate greater BMP adoption.

Time and labor constraints remain a significant challenge for smaller operations. According to Robotham and McArthur (2001); Schofer (2000), and Goodwin and Gouldthorpe (2013), many small farmers lack the time and personnel needed to pursue education and manage day-to-day operations simultaneously. Our findings support these conclusions, emphasizing the need for targeted outreach, including time-flexible support resources and application guidance for small-scale farmers.

TABLE 3 Demographic factors associated with the respondents' adoption of water-saving technologies.

Variable	Mean	SD	Area (ha)	Farming experience	Crops per year	Farming at the same location	Gross cash income	Irrigation cost %	Farm Location	Education	Age
Applying an adequate amount of water in the right place at the right time with precision irrigation increases crop yield	4.6	0.9	***	NS	NS	NS	*	NS	NS	NS	NS
Investing in irrigation automation will increase profit	4.3	1.1	NS	NS	**	NS	NS	NS	NS	NS	NS
Investing in irrigation and water quality management gives producers an economic advantage	4.4	1.2	NS	NS	**	NS	NS	NS	NS	NS	NS
During crop establishment, it is necessary to apply frequent irrigation	4.6	0.9	NS	NS	NS	NS	NS	NS	NS	NS	*
I only irrigate during crop establishment	3.8	1.7	NS	NS	NS	NS	NS	NS	NS	NS	NS

*Refers to p value < 0.05, **p value < 0.01, ***p < 0.001, - p value < 0.001. NS, statistically not significant.
SD is the standard deviation. Mean values are in relation to the following scale: 1, Strongly Disagree; 2, Disagree; 3, Neither Agree nor Disagree; 4, Agree; 5, Strongly Agree; 6, Not Applicable.

Willingness to modify irrigation scheduling based on scientific evidence showing water conservation benefits received strong agreement (mean = 4.3, SD = 1.3). This willingness was even greater when scientific evidence suggested a potential increase in yield (mean = 4.7, SD = 0.8), with a significant association found between crop diversity and this willingness ($p < 0.05$). These results highlight the value of field demonstrations and on-farm trials, demonstrating both productivity and resource-use benefits of scheduling tools across diverse cropping systems (Barrett et al., 2021).

The statement "I manage irrigation water to increase crop yield" received the highest agreement overall (mean = 4.8, SD = 0.5), with significant relationships to farm location ($p < 0.05$). Growers managing row crops and using sprinkler systems tended to focus more on yield outcomes, while vegetable growers using drip or seepage systems placed greater emphasis on managing drainage and hydrological conditions. These findings align with earlier research highlighting the connection between environmental awareness and cleaner production practices (Ortiz et al., 2023). As Choe and Schuett (2020) emphasize, effective environmental change depends on deeper engagement across stakeholder groups.

Similarly, the statement "I manage water use to increase environmental stewardship" received a high level of agreement (mean = 4.1, SD = 1.4), though it showed no statistically significant associations with demographic variables. This suggests a shared awareness of environmental responsibility, regardless of background. Targeted communication about how specific irrigation methods, such as drip and seepage, affect local water systems could enhance stewardship engagement in regions like South Florida, where water table dynamics and rainfall events are key concerns.

For example, programs such as Florida's Mobile Irrigation Labs (FDACS (Florida Department of Agriculture and Consumer Services, 2017) offer tailored assistance with on-farm water quantity and quality management. Expanding these programs in vegetable production regions, particularly seepage irrigation, may enhance technology adoption by addressing technical and trust-based barriers (Gazula et al., 2007). Moreover, pilot studies and hands-on training in water-nutrient management can offer direct experience and reinforce farmer confidence (Qi et al., 2024). Routine soil testing for pH, nitrogen, phosphorus, and potassium was moderately agreed upon (mean = 3.7, SD = 1.8), while routine water testing for irrigation suitability and salinity received lower agreement (mean = 3.1, SD = 1.9). These findings suggest potential areas for extension interventions to enhance water management awareness and promote more frequent monitoring of both soil and water quality.

3.5 Respondent's satisfaction with their current irrigation practices

Overall satisfaction with current irrigation scheduling practices was moderate, with a mean score of 3.8 (SD = 1.5). Satisfaction levels showed significant associations with respondents' education and age ($p < 0.01$), as well as with farm area (ha) and farming experience ($p < 0.05$) (Table 5). Farmers who had completed only grades 9–11 reported the highest satisfaction levels, while those with a master's degree or greater reported lower satisfaction levels. These results suggest that more highly educated farmers may be more critical of their current practices or more aware of potential areas for improvement. As such, providing these farmers with advanced training and evidence of improved outcomes could help encourage adoption of newer scheduling tools.

Farmers operating on smaller farms (<20 ha) also reported lower satisfaction with their current irrigation scheduling (mean = 3.1), compared to those managing larger farms (>20 ha), who reported mean satisfaction levels above 4.0. This discrepancy highlights the need to tailor extension programs for small

TABLE 4 Demographic factors associated with respondents' willingness to adopt water-saving technologies.

Variable	Mean	SD	Area (ha)	Farming experience	Crops per year	Same location farming	Gross cash income	Irrigation cost %	Farm Location	Education	Age
Willingness to implement water-saving technologies if a cost share were available	4.4	1.3	*	NS	*	NS	NS	NS	NS	NS	NS
Willingness to implement water-saving technologies if a cost share were not available	3.4	1.7	NS	NS	NS	NS	NS	NS	NS	NS	NS
Willingness to modify my irrigation scheduling method if there is scientific evidence suggesting that it can conserve water	4.3	1.3	NS	NS	NS	NS	NS	NS	NS	NS	NS
Willingness to modify the irrigation scheduling method if there is scientific evidence that it can increase yield	4.7	0.8	NS	NS	*	NS	NS	NS	NS	NS	NS
I manage irrigation water to increase crop yield	4.8	0.5	NS	NS	NS	NS	NS	NS	*	NS	NS
I manage water use to increase environmental stewardship	4.1	1.4	NS	NS	NS	NS	NS	NS	NS	NS	NS
I conduct regular soil tests for pH, nitrogen, phosphorus, and potassium	3.7	1.8	NS	NS	NS	NS	NS	NS	NS	NS	NS
I conduct regular water tests for irrigation suitability, salinity, etc.	3.1	1.9	NS	NS	NS	NS	NS	NS	NS	NS	NS

*Refers to p value < 0.05. NS, statistically not significant.
SD is the standard deviation. Mean values are in relation to the following scale: 1, Strongly Disagree; 2, Disagree; 3, Neither Agree nor Disagree; 4, Agree; 5, Strongly Agree; 6, Not Applicable.

farmers, particularly by addressing common barriers such as lack of time, labor, or access to technical assistance (Gaul et al., 2009). Flexible delivery models, such as online learning modules or on-farm demonstrations, may help alleviate these constraints.

Interestingly, farmers with 50–59 years of experience expressed the least satisfaction with their scheduling practices (mean = 2.6), compared to those with fewer than 49 years of experience (mean = 3.3+). This generational divide may reflect the deep knowledge and expectations of highly experienced farmers and a stronger awareness of how water management affects long-term productivity. On the other hand, younger farmers may be more critical of inefficiencies due to their openness to data-driven tools and concern for environmental sustainability (Bajaj et al., 2023).

This study offers new insights into the adoption of smart irrigation technologies by examining how demographic and operational differences shape Florida vegetable growers' willingness, satisfaction, and perceived barriers. Unlike previous studies focusing primarily on technical or economic feasibility, our results highlight that farmer experience, area, and crop diversity also profoundly influence adoption decisions. For instance, we found that small-scale farmers were more likely to see yield benefits from precision irrigation. These findings underscore the need to tailor communication and education programs to specific grower groups, especially when promoting conservation tools (Van Dijl et al., 2015; Yehouenou et al., 2020; Deh-Haghi et al., 2020).

Regional and contextual factors also played a key role. Farmers in North Florida reported greater concern about water scarcity and irrigation costs, while those in South Florida were more focused on drainage and managing excess water, which reflects the diverse hydrologic conditions across the state (Aumen, 1995; Daroub et al.,

TABLE 5 Demographic factors associated with respondents' current satisfaction with their irrigation management.

Variable	Mean	SD	Area (ha)	Farming experience	Crops per year	Same location farming	Gross cash income	Irrigation cost %	Farm Location	Education	Age
I am satisfied with my current irrigation scheduling practices	3.8	1.5	*	*	NS	NS	NS	NS	NS	**	**
I am satisfied with my current irrigation management	3.8	1.5	NS	NS	NS	NS	*	NS	NS	*	NS

*p value < 0.05, **p value < 0.01. NS, statistically not significant. SD is the standard deviation. Scale: 1, Strongly Disagree; 2, Disagree; 3, Neither Agree nor Disagree; 4, Agree; 5, Strongly Agree; 6, Not Applicable.

2009; Ferrarezi et al., 2020). Despite most respondents agreeing that extreme weather has affected their yield in recent years, only 2% reported using ET-based apps, and fewer than 40% used soil moisture sensors. This gap between the availability of technology and its on-farm use highlights ongoing challenges related to trust, complexity, and data interpretation (Migliaccio et al., 2015; Sharma et al., 2022).

Our results suggest that open-access tools alone are not enough. Adoption improves when these tools are supported by in-person guidance, simplified interfaces, and peer-to-peer demonstrations (Goodwin and Gouldthorpe, 2013; Taghvaeian et al., 2020). We found that small-scale and new farmers, in particular, face challenges in accessing cost-share programs and attending training, a finding that was echoed in previous studies (Robotham and McArthur, 2001; Gaul et al., 2009). Extension personnel remain key, especially when they provide tailored support directly at the farm and connect farmers with university-led resources, such as Florida Automated Weather Network (FAWN) and "My Florida Farm Weather" (Lusher et al., 2008; Migliaccio et al., 2015).

To help address these gaps, our study highlights the value of online, farmer-friendly educational materials, such as videos, fact sheets, and simplified tools (Abioye et al., 2020; García et al., 2020; Salm et al., 2018; Fabregas et al., 2022). Additionally, creating centralized platforms with clear cost-share application steps and promoting mentorship between experienced and new farmers could further improve uptake. Overall, this research highlights how demographics, trust, and on-the-ground realities must be part of the conversation when building policies and programs aimed at expanding smart irrigation adoption.

4 Conclusion

Water-saving technologies offer promising solutions for optimizing irrigation scheduling, enabling farmers to make more informed decisions about both the timing and volume of water applied to crops. This study highlights several critical insights into the factors shaping vegetable farmers' willingness to adopt such technologies in Florida. In particular, the findings emphasize the importance of targeted adoption strategies that cater to the distinct needs of small-scale, new, and demographically diverse farmers.

Our results emphasize that the adoption of precision and smart irrigation tools is not just a technical challenge but a social and educational one. These gaps have been shown to necessitate holistic educational frameworks that are culturally and contextually relevant and supported by well-designed incentive and cost-sharing programs, particularly for small and resource-limited farms. Trained county extension personnel will continue to play a central role in bridging the gap between innovation and implementation by providing tailored, in-field support and facilitating access to digital tools.

Our findings also reveal geographic patterns in adoption priorities: farmers in North Florida, who grow row crops with center pivot systems, were more interested in yield-improvement demonstrations, while vegetable growers in Central and South Florida, who use drip or seepage systems, emphasized water quality and environmental concerns. Additionally, multi-crop farmers were more willing to adopt water-saving technologies even without financial incentives, suggesting that broader crop management complexity may encourage innovation.

To improve adoption outcomes, future programs should prioritize research and outreach focused on variable-rate application, irrigation timing, and delivery system improvements, particularly for vegetable growers using drip, micro-sprinkler, and seepage irrigation systems. These efforts should be led by technical experts working alongside growers to co-develop solutions. Ultimately, future research should evaluate the effectiveness of current extension programs and investigate how relationships with universities, agencies, and industry impact the broader adoption of smart irrigation practices.

Data availability statement

The datasets presented in this article are not readily available because Survey is subject to IRB rules. Requests to access the datasets should be directed to Sandra M. Guzman, sandra.guzmangut@ufl.edu.

Ethics statement

The studies involving humans were approved by Institutional Review Board University of Florida IRB#: IRB202200392. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

AA: Investigation, Writing – original draft, Conceptualization, Methodology, Formal Analysis, Validation. SG: Investigation, Funding acquisition, Writing – review & editing, Validation, Conceptualization, Resources, Project administration, Supervision, Formal Analysis. ZY: Funding acquisition, Writing – review & editing, Project administration, Supervision. JW: Writing – review & editing, Formal Analysis, Supervision, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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