Design and Evaluation of an Automatic Scheduling-Manual Operation Tool to Bring Precision Irrigation to Resource-Constrained Farmers

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DESIGN AND EVALUATION OF AN AUTOMATIC SCHEDULING-MANUAL OPERATION TOOL TO BRING PRECISION IRRIGATION TO RESOURCE-CONSTRAINED FARMERS

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ABSTRACT

As populations increase and freshwater supplies decrease, adopting water- and energy-efficient irrigation practices is crucial, particularly in resource-constrained regions. Here, farmers are often unable to purchase the equipment used in precision irrigation, a practice that implements the automatic scheduling of irrigation events to achieve high efficiency. Currently, no irrigation methods exist that combine the automatic scheduling of irrigation events with the manual operation of valves, a common practice on low-income farms. This work introduces a de-

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sign concept for an automatic scheduling and manual operation (AS-MO) tool that addresses the efficiency needs of resource-constrained farms and integrates into current manual practices. However, it is unknown how farmers would value such a tool. Through interviews and focus groups facilitated by a series of storyboards and a physical prototype, the proposed concept was evaluated by farmers and key market stakeholders in Kenya, Jordan, and Morocco. Results showed that farmers in Kenya and Jordan in particular valued the proposed AS-MO concept because they want increased efficiency on their farms but did not want to install automatic valves for cost and complexity concerns. A possible market was also found in Morocco, but a majority of interviewed farms preferred automatic valve operation due to large farm sizes. Interviewees provided feedback on how to improve the tool's design in future iterations. If adopted at scale, this AS-MO tool could increase efficiency on farms that otherwise cannot afford current precision irrigation technology, improving sustainable agriculture worldwide.

1 INTRODUCTION

The aim of this work is to evaluate a means of bringing many of the water and energy efficiency benefits of precision irrigation to resource-constrained regions without the high equipment costs and complexity of existing methods.

The second Sustainable Development Goal (SDG 2) calls for the achievement of food security by 2030 [1]. This aim is particularly imperative in low- and middle-income regions such as East Africa (EA) and the Middle East and North Africa (MENA), where over 33% and 10% of the population, respectively, is projected to be undernourished in 2030 [2]. Numerous studies have shown that increasing access to irrigation is an effective path to achieve food security in these regions [3–5]; however, irrigation is a water- and energy-intensive process, counter to the additional aim of SDG 2 to promote sustainable agriculture. The high water use of irrigation is particularly challenging in arid and semi-arid regions like MENA and EA, respectively. Prior work has suggested that water- and energy-saving technologies could particularly benefit medium-scale farms in EA and small- to medium-scale farms in MENA, many of which have access to capital to pay for some of this technology [6]. In EA, these farms, generally sized between five and 15 acres, rely on hired manual labor to feed the growing city centers [7]. In MENA, the farm size scale is country-dependent, with the small-scale farms generally ranging from five to 25 acres and the medium-scale farms generally ranging from 50–120 acres. Both small- and medium-scale farms typically rely on hired manual labor, but medium-scale farms may also have specialized labor such as a farm manager or agronomist. The growing number of small- and medium-scale farms has the promise to increase food security in EA and MENA, but doing so sustainably remains a challenge [8, 9].

Solar-powered drip irrigation has been proposed for regions with high solar irradiance as a means to increase irrigation with minimal water and fossil fuel use [10–12]. Solar is especially applicable in rural EA where access to grid electricity can be uncommon [13]. Drip irrigation uses a network of pipes and emitters to deliver water directly to crops' roots, saving up to 50% of water compared to flood irrigation, a commonly-used method [14]. On farms with deep boreholes, this method can also be energy-efficient because less water used means less energy needed to operate a pump. In off-grid irrigation systems, the amount of energy used is critical because this value dictates the capital cost of solar panels, one of the largest system costs [6].

Further, the water- and energy-saving ability of solar-powered drip irrigation systems depends on how farmers operate the systems on a daily basis [15]. Savings can be realized when precision irrigation methods are introduced to optimally operate the system and deliver the exact amount of water needed. Many precision irrigation technologies measure farm and weather conditions, calculate ideal irrigation schedules, and use automated valves to carry out these schedules [16, 17]. Precision irrigation systems often rely on arrays of sensors, solenoid valves, and proprietary hardware and software [18–21]. These technologies increase the efficiency of irrigation systems but can cost up to tens of thousands of dollars to equip an entire farm [22].

Unfortunately, economic constraints in EA and MENA make it difficult for medium-scale farmers to adopt existing precision irrigation equipment. In contrast, these farms often employ local laborers to both monitor and carry out irrigation tasks using manual valves [6]. These laborers use inexpensive but time-consuming and often imprecise manual methods for determining when to irrigate, like "stick" and "ball" tests [22]. In a stick test, a laborer inserts a stick 10 cm into the soil. If it comes out with dirt attached, the soil is moist enough. In a ball test, a farmer forms a handful of dirt into a ball. If the ball crumbles when let go, the soil is too dry. The irrigation experience of hired laborers varies widely, so farms cannot rely on these binary tests to deliver the most water- and energy-efficient irrigation. Human laborers also typically rely on observations of current and past weather and crop conditions, lacking the ability to make accurate forecasts such as those used in precision irrigation. In addition, relying on past conditions alone does not account for changes in climactic conditions as global temperatures rise [23, 24]. Inaccurate forecasting of weather conditions can negatively impact the reliability of solar-powered irrigation systems on cloudy days if farms have not properly planned for future weather events.

Some existing products attempt to bridge the gap between fully automated precision irrigation and fully manual heuristic methods. However, these products are timer-based and largely fall short of delivering the efficiency and prediction benefits of precision irrigation. As two examples, the Pro-C irrigation controller (Hunter Industries, California) and the SST1200OUT irrigation timer (Rain Bird Corporation, California) are relatively low-cost products—in the $100–300 range—that control a series of solenoid valves to carry out predetermined irrigation schedules. While these products are affordable to many farms, they still rely on the farmer to determine and input the irrigation schedule. Even for the most experienced farmers, it is extremely challenging to determine an irrigation schedule that has been optimized for both water- and energy-savings. In addition, these devices cannot deliver the computationally intensive optimization benefits of conventional precision irrigation.

To identify potential opportunities to realize some of the key benefits of precision irrigation with minimal complexity and cost, Fig. 1 characterizes two of the critical actions of irrigation system control. The first looks at determining a schedule of irrigation events (e.g., scheduling), and the second at operating valves in a hydraulic network (e.g., operation). Each of these actions can be done either manually by a farmer or automatically by the system, resulting in four distinct design spaces. Fully automated precision irrigation systems are in the lower right quadrant, while fully manual methods, like stick or ball tests paired manual valves, are in the upper left. Existing irrigation timers fall into the manual scheduling and automatic operation quadrant. To the best of the authors' knowledge, no commercial technologies exist that can deliver the automatic scheduling benefits of precision irrigation to farms that primarily rely on the manual operation of valves, such as the resource-constrained farms in EA and MENA. The lower left quadrant of Fig. 1 highlights this gap in the design space.

We hypothesize that a technology in the automatic scheduling and manual operation (AS-MO) design space is well-suited for the small- to medium-scale farmers typically found in EA and MENA. Automatic scheduling that relies on low-cost sensors and cloud computing could provide farmers with irrigation schedules that have been optimized for water and energy efficiency, enabling them to access several of precision irrigation's key benefits. Further, with an AS-MO tool, these cost-constrained farms could continue to rely on manual operation, leveraging the manual labor available in these regions. This approach could minimize farmers' costs while easing adoption by simplifying the installation of new equipment.

Implementing an AS-MO irrigation control strategy has several challenges. First, a fully optimized, auto-generated schedule might change every day or even every minute as the system integrates new inputs of current weather and farm conditions. Second, the generated schedule might be highly complex. Prior work has proposed that irrigation systems strategically turn on and off different sections at different times of day to make the best use of available solar power [15]. As humans prefer easy-to-use tools, farmers might decide the frustrations of a frequently-changing schedule are not worth the efficiency benefits of precision irrigation. The perceived desire of farmers to adopt an AS-MO tool in this context is unknown but critical to its potential to create an impact in EA and MENA markets. Filling this knowledge gap requires understanding how to design an AS-MO tool that provides

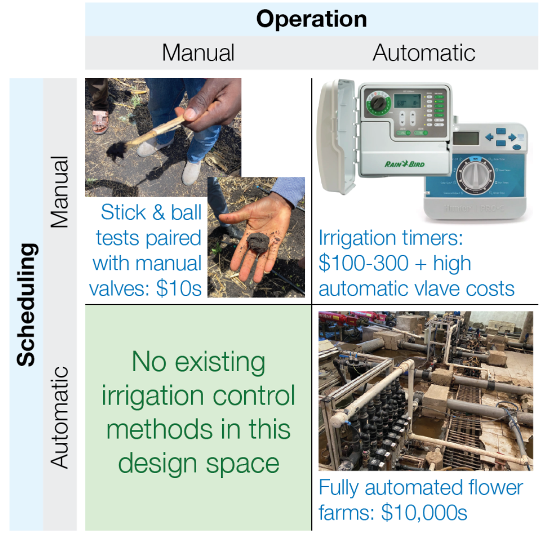

FIGURE 1: Visualization of the design space of irrigation system control methods with regard to two key elements: scheduling and operating. Existing methods typically fill three of the four design spaces. This work proposed a tool to fill the gap in the automatic scheduling and manual operation space. This work evaluates this design concept's fitness for medium-scale farmers in EA and MENA against existing solutions that use other control methods.

access to precision irrigation's efficiency benefits while aligning with the current practices of EA and MENA farms.

To evaluate the potential viability of an AS-MO tool in the EA and MENA marketplace and to better understand how farmers might value and interact with such a tool in practice, this paper addresses the following research aims:

1. Characterize an AS-MO tool architecture that effectively transmits key benefits of precision irrigation while integrating into the current practices and capabilities of target farms, informed by prior market analysis and recent innovations.
2. Substantiate the value of an AS-MO tool among potential users in EA and MENA markets and assess their desire to adopt a tool with this architecture, relying on storyboard-based interviews and focus groups.
3. Assess target farmers' satisfaction with a proposed user interface for an AS-MO tool and identify avenues for improvement, based on interactions with a medium-fidelity prototype of the tool within interviews and focus groups.

2 THE PROPOSED AS-MO TOOL

To introduce automatic scheduling and manual operation on EA and MENA farms, a tool was sought that (1) requires a low infrastructure investment and (2) does not require complex maintenance. To facilitate automatic scheduling, multiple precision irrigation algorithms, including the ones mentioned in Section 1, were evaluated for their fitness against these user needs. A scheduling theory being developed by the Global Engineering and Research (GEAR) Lab was chosen.

The left-hand side of Fig. 2 shows how an AS-MO tool implementing this theory could meet the needs of EA and MENA farmers. This theory leverages cloud computing to build an optimal irrigation schedule and characterize soil moisture without the use of soil moisture sensors, which are expensive and complex to calibrate. It does this using soil water balance calculations and several inputs from the farm [14, 25]. Farm inputs include readings from several simple weather sensors, solar panel power readings, and user inputs regarding system component specifications and agronomy details, such as solar array capacity, pump operating points, irrigation block areas, crop types, and soil texture. By relying on cloud computing and machine learning, this theory enables cost-constrained farmers to gain access to the forecasting benefits of precision irrigation. Doing so with few inexpensive sensors meets farmers' need for minimal infrastructure and maintenance.

Further, the GEAR Lab theory strategically coordinates irrigation events throughout the farm (top left of Fig. 2), which increases system reliability on cloudy days and reduces the capital cost of solar-powered systems. By predicting and then matching the pumping energy needed to meet crop water demand (light blue boxes in the power-time plot) with the forecasted available power (dark blue line), the tool can efficiently schedule irrigation events. For example, the tool might schedule one, two, or three blocks to be open during periods of forecasted low, medium, and high solar irradiance, respectively. Generating schedules in this way has the potential to reduce power system costs by up to 30% for medium-scale Kenyan farms [6, 22].

Scheduling algorithms, including the GEAR Lab theory, often rely on frequently-updated irrigation events to most efficiently meet irrigation demands. In an AS-MO tool, these schedules must be communicated to farmers in a way that is easy to follow. To accomplish this, the proposed tool was designed to send messages to farmers' cell phones, products which are increasingly more common in low-resource countries [26]. Researchers have shown that Short Message Service (SMS) reminders can improve health outcomes in Kenya. These frequent, timely reminders have improved immunization timeliness and adherence to antiretroviral treatment [27, 28]. This work hypothesizes that the idea of frequent notifications can effectively address the challenge of implementing complex irrigation schedules on resource-constrained farms.

The tool sends notifications with schedule information to farmers throughout the day (right-hand side of Fig. 2). At the beginning of each day, the tool determines an irrigation schedule and presents it to the farmer. The farmer has the option to accept or slightly modify this preliminary schedule. Once the accepted schedule begins, the tool sends additional messages to the farmer's phone, reminding them to manually open or close valves according to the schedule (lower right of Fig. 2). The farmer would then manually open or close valves as directed and then confirms the action was complete.

At the end of an irrigation event, the farmer has the option to add 10 additional minutes of irrigation time if they notice insufficient water delivery. In a preliminary evaluation of this AS-MO concept conducted in October 2021, the ability for farmers to slightly adjust the irrigation schedule during the day was found to be important [22]. This time-adding feature was integrated into the design concept to meet this user need. The order and duration of irrigation events were still automatically scheduled and communicated to farmers to enable manual valve operation. These interactions are repeated throughout the day, according to the predetermined irrigation schedule.

3 DESIGN OF AN INTERACTION PROTOTYPE

A physical prototype of the AS-MO tool that simulated a farmer's daily interaction with it was designed. Prototypes are known to increase the quality of feedback given by interview participants because they allow a potential user to imagine interacting with the proposed device [29,30]. This mechanism was used to evaluate how farmers and stakeholders respond to the basic elements of an AS-MO tool. The prototype itself consisted of three components: a mobile phone, a control box, and a weather station (Fig. 3).

The phone was equipped with Telegram, a common messaging app (Telegram FZ-LLC, 2023). Telegram users can have conversations with bots that deliver pre-programmed messages, and these bots can ask users short answer questions that determine the messaging path the bot takes next. For this study, a Telegram bot was created to walk participants through the following set of simulated AS-MO tool interactions:

- Provide farmers with a sample daily irrigation schedule, simulating the first message a farmer would receive each morning;
- Ask farmers if they approved of that day's irrigation schedule;
- Send a message prompting the farmer to manually open or close a valve when an irrigation event started or ended, respectively;
- Give farmers the ability to add an additional 10 minutes of irrigation time when an irrigation block is scheduled to end, and then update the schedule based on this choice; and
- Give farmers the ability to skip a block before irrigation starts, and then update the schedule based on this choice.

These interactions aimed to allow the research team to elicit feedback on these core design decisions.

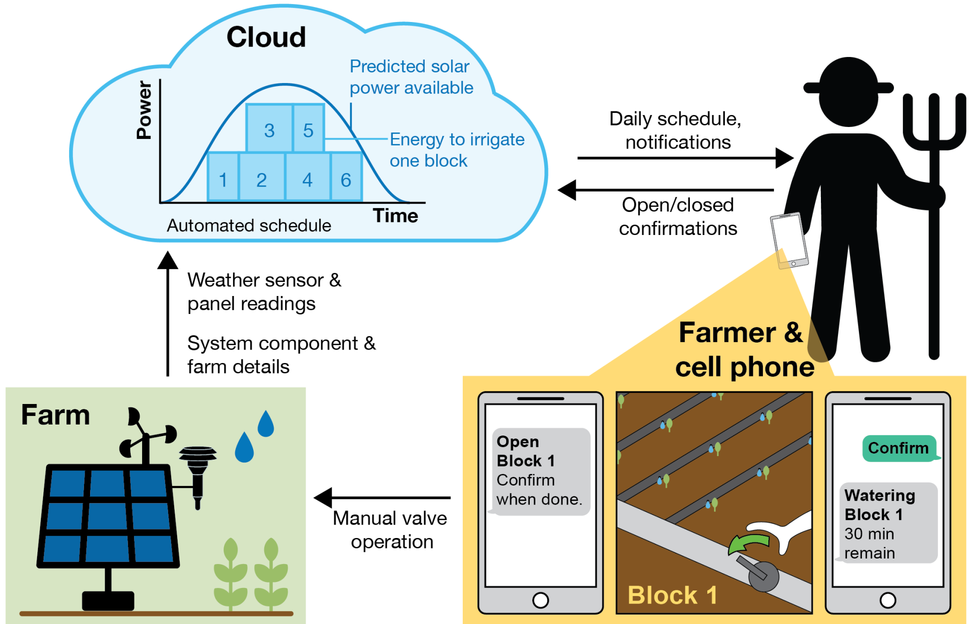

FIGURE 2: A depiction of the proposed AS-MO tool and the system on which it relies. Details about the farm and irrigation system are fed into a cloud-based algorithm that automatically generates an efficient irrigation schedule. This schedule is then communicated to a farmer's phone via notifications that are sent at the beginning of the day and at the start and end of each irrigation event. These messages direct a farmer to carry out the generated schedule by manually operating valves. When farmers confirm that actions have been completed, it informs the algorithm how closely the schedule was followed so it can adjust the next day's schedule accordingly.

The prototype control box consisted of an e-Ink screen mounted on a black box of a similar size anticipated for the controller (approximately 230x150x70 mm). Inside the box was a battery and a Raspberry Pi that carried out the Telegram bot's script. The box did not have any physical modes of interaction (e.g., buttons or dials), but it was designed to:

- Display the open/closed status of irrigation blocks based on confirmations a participant made in Telegram;
- Display a countdown telling the user when the next irrigation event was scheduled to occur; and
- Demonstrate to participants the anticipated size of a permanently-mounted control box.

The prototype weather station included the number and type of weather sensors that would be required to generate an optimized irrigation schedule, including wind speed, wind direction, ambient light, solar irradiance, precipitation, temperature, and humidity. This allowed the research team to elicit feedback on the weather information that participants found most valuable.

4 PROTOTYPE-BASED INTERVIEW METHODS

The physical prototype was designed to help participants describe what would be most valuable and most frustrating about using the AS-MO tool. To reach these aims, interviews and focus groups were conducted with potential users and market stakeholders in Kenya, Jordan, and Morocco, an approach inspired by Lean Startup methodologies [31].

During interviews and focus groups, participants were first introduced to the tool design concept with a set of storyboards using a protocol designed for a preliminary study to evaluate the concept [22]. After the storyboard introduction, participants were given the physical prototype designed to help them answer questions relating to the value and daily use of the proposed tool. Specifically, (1) What is the most useful information they think the tool could provide? (2) How do farmers think they would or would not use the tool daily? and (3) What drawbacks do they think they would encounter when using the tool? Specific interview questions targeted these broader research questions, but the semi-structured nature of the interviews and focus groups meant that not all participants were asked the same specific questions.

During the study, it was made clear to participants that interacting with the prototype alone would not open or close valves, as the valves would not be automatic. Rather, the user would manually perform these actions in the field and then use Telegram on the phone to confirm once complete.

As the prototype was intended to assess user interactions rather than the efficacy of the automatic schedule determination, a mock irrigation schedule was presented to the user. The dura-

FIGURE 3: The three components of the physical prototype used to facilitate interviews and focus groups. The phone (A) was equipped with a Telegram bot that stepped farmers through a key set of interactions with the tool. The control box (B) displayed the status of these interactions and directed farmers to interact on the phone. The low-cost weather station (C) showed farmers what data the tool might collect: wind speed, wind direction, ambient light, solar irradiance, precipitation, temperature, and humidity.

tions of irrigation events were also shortened for the study, and participants were made aware of these adjustments.

In total, 22 prototype-based interviews and focus groups with farmers were conducted (seven in Kenya, five in Morocco, and 10 in Jordan), involving a total of 40 farmers (13 farmers in Kenya, 11 in Morocco, and 16 in Jordan). These farmers were associated with 22 farms, ranging from 3–10 acres in Kenya, 5–120 acres in Morocco, and 4–120 acres in Jordan. These farm size ranges in all three countries were representative of the ranges in each country for which solar-powered drip irrigation would be most feasible [6]. Eight Kenyan farmers had previously participated in the preliminary set of interviews and focus groups, so they were already familiar with the design concept [22]. Unfortunately, due to travel complications, three interviews in Morocco were conducted without the physical prototype. These protocols involved only the storyboards.

The prototyped-based interviews were also conducted with 30 stakeholders (five in Kenya, five in Jordan, and 20 in Morocco) who were broadly familiar with the EA irrigation market were also recruited for interviews. Stakeholders included irrigation engineers, managers of irrigation equipment distributors, borehole drillers, agronomists, and government officials. These stakeholders represented professional viewpoints of different sectors of the irrigation and agriculture markets. They have collectively helped thousands of farmers improve their farms, so they could provide perspectives on a large population of farmers in ways that individual farmers could not. Interviews with stakeholders followed a similar protocol as interviews with farmers and sought to assess the tool's potential as a viable product in EA and MENA markets. All interviews and focus groups took place in March 2022, and all protocols were approved by the Massachusetts Institute of Technology Institutional Review Board (protocol E-4098).

5 RESULTS

5.1 Substantiation of the tool's value

In 23 out of 36 interviews (nine in Kenya, seven in Morocco, and seven in Jordan), farmers asserted that the AS-MO tool would likely be adopted by farmers in the target user group, a result consistent with prior work [22].

The most valuable benefits of the tool according to participants were alleviating water scarcity concerns and preventing over-irrigation. Farmers and stakeholders alike noted that climate change has altered seasonal rains such that they are no longer predictable. Farmers can no longer reliably anticipate water availability based on historical trends. Participants claimed that an automatic scheduling tool could aid them as they plan irrigation events.

Farmers in particular also noted that the tool could save them effort, money, and time. In contrast, three stakeholders and two farmers were concerned that using the tool could potentially increase the amount of time that a laborer was needed on the farm. This discrepancy suggests the need to explore whether the tool saves or increases labor and time when used over long periods.

5.2 Farmer scheduling and operation preferences

Figure 4 summarizes the scheduling and operation preferences noted from the 36 farmer and stakeholder interviews and focus groups. Operation preferences are broken down by country.

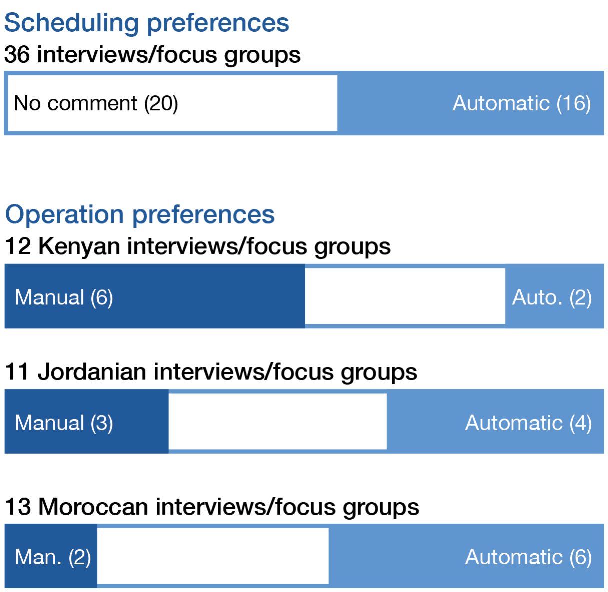

FIGURE 4: A summary of both farmer and stakeholder preferences for scheduling and operation. Automatic scheduling was preferred over manual scheduling by all participants who had a preference. Preference for manual operation over automatic operation differed by country. Not all participants mentioned a preference, so they are visualized by the white space.

In 13 of 22 interviews, farmers noted that they particularly appreciated the automatic scheduling aspect of the AS-MO tool. This result suggests that this is an important feature for Jordanian and Moroccan farmers in addition to Kenyan farmers. Farmers noted that an automatically-determined schedule specific to their farm and weather conditions could improve their yields.

There was disagreement among farmers on their preference for manual versus automatic operation of valves. In 12 interviews (two in Kenya, four in Jordan, and six in Morocco), farmer or stakeholder participants preferred automatic valve operation, while in 11 interviews (six in Kenya, three in Jordan, and two in Morocco), manual valve operation was preferred. The preference for automatic operation was particularly driven by MENA participants who operated or served on larger farms. On larger farms, participants claimed that automatic operation was worth the investment because laborers would otherwise need to walk long distances to manually operate valves, wasting time and potentially increasing labor costs. Several of the larger farms had already installed automated solenoid valves and asked if the tool could be adapted to operate those valves.

Kenyan farmers in particular favored manual valve operation over automatic operation, with only two of seven Kenyan farmers claiming a preference for automatic valves. Here, manual valves were heavily preferred over solenoid valves due to their low cost. Study participants also noted that the reliability and familiarity with manual valves in the region could benefit Kenyan farmers more than solenoid valves. Several participants in Jordan also had a preference for manual valves, suggesting that an AS-MO tool could have promise in these markets.

In all three countries, the majority of farmers liked the ability to add more time or change the schedule slightly, suggesting that they value retaining some degree of manual control.

Participants in all three countries commented on the importance of demonstrating the tool to farmers before they would be likely to adopt the technology, a result consistent with literature about farmers in Tanzania, South Africa, and Morocco [32–34]. Nine farmers claimed they would need to closely monitor the tool on their own farm for a period of time before trusting that the automatic schedule determination was sufficient. This result stresses the importance of demonstrating the tool before farmers can realize its full benefits.

5.3 Features to consider adding to the AS-MO tool

Study participants suggested several features that they would like to see in future iterations of the AS-MO tool design. Both farmers and stakeholders expressed a preference for using a custom app to communicate with the AS-MO tool as opposed to using a messaging app like Telegram. Participants claimed that a custom app would provide more functionality, citing several key benefits.

First, participants noted that inputting the farm details needed for the automatic scheduling aspects of the tool could be easier with a custom app. Farmers and agronomists agreed that they would accept the need to update farm details when they change crops as long as it was easy. Several farmers reported changing their crop selections every few weeks, while others remained more consistent. Participants noted that the process of entering and updating farm details could be cumbersome if not designed well. A custom app would allow for the greatest flexibility when inputting these key details.

Second, a custom app would allow different users to visualize their farm data in different ways, reflecting differences in the types of information that various stakeholders reported finding the most valuable. Farm managers and farm employees reported that detailed data on crop irrigation needs and weather forecasts would be most valuable. Conversely, farm owners reported that they would be less concerned with their farm's daily operational status and more concerned with the overall status. Distributors noted that they could use system operating data to monitor the equipment that they had sold that might still be under warranty. These results demonstrate that a variety of interfaces highlighting different information might be needed to account for the diversity of user roles, which a custom app could provide.

Finally, several participants were concerned that a messaging-based interaction could be difficult for illiterate laborers to use. An app would allow for the use of more symbols, or even voiced instructions, making the tool more accessible.

In addition to a custom app, another key feature was mentioned by study participants as being potentially useful. While most farmers preferred for the main interaction to be through their phones, 11 participants suggested that farmers should have the ability to interact with the control box without a phone. Numerous reasons were cited as to why a phone might not be available. For example, the phone could be broken, the battery could be dead, someone else could be using the phone, or the cellular service could be poor. Seven participants in Jordan and Morocco claimed that a well-designed app would be sufficient and that they would not need any interaction with the control box. However, these participants had larger farms with potentially more access to capital and did not report having the phone and service problems reported more frequently on smaller farms. These results suggest that critical interactions with the AS-MO tool should be integrated into a control box design so that farmers who need it have consistent access.

6 DISCUSSION

This work demonstrated that the proposed AS-MO tool has the potential to bring the efficiency benefits of precision irrigation to medium-scale farms in Kenya and small- and medium-scale farms in Jordan and Morocco. It could do this by bridging the gap between existing, expensive precision irrigation technologies and affordable, easy-to-adopt irrigation methods.

Data from the study validated the assumptions made in Section 1 about the potential benefits of an AS-MO irrigation control method over the other methods in Fig. 1. First, compared to both manual scheduling methods (top half of Fig. 1), an AS-MO tool was hypothesized to address problems that are hard for humans to solve alone, such as creating efficient, reliable irrigation schedules. Discussions with farmers confirmed that doing so was difficult, time-consuming, and sometimes not possible without the use of sensors and calculations. The increase in efficiency and reliability provided by automatic scheduling was found valuable by most farmers, confirming initial hypotheses.

Second, compared to automatic control and automatic operation (bottom right of Fig. 1), AS-MO was predicted to deliver value to farmers for its familiarity and affordability. Some farmers preferred manual valves over automatic ones because they were concerned about the reliability of solenoid valves, a technology with which they had little familiarity. Several farmers also valued the ability to continue visually inspecting each block after each irrigation event. Farmers' preferences to continue certain practices that are currently a part of many farms' operations suggest equipment familiarity is a priority. Farmers, particularly farm owners, also expressed interest in the AS-MO tool because it was lower cost than a fully-automated system, suggesting that the tool's affordability is also a priority for the targeted farms.

Results from Kenya, Jordan, and Morocco are anticipated to be applicable to the larger regions of EA and MENA, respectively, so differences in farmer preferences between the three countries could also predict differences in the two regions. One key difference between the regions was that it appeared that several interviewed Jordanian and Moroccan farmers were more familiar with current precision irrigation techniques than farmers in Kenya were. They were more excited about a fully automated system because they knew and trusted automated valves. On the other hand, Kenyan farmers and stakeholders more frequently expressed skepticism about automated valves, claiming they might break frequently.

A second difference between the regions was that there were mixed preferences for manual valve operation over automatic in Jordan and Morocco compared to a strong preference for manual operation in Kenya. While these results showed a slight preference for full automation in the Jordanian and Moroccan markets, it does not necessarily mean that an AS-MO tool could not provide value in the MENA region. Wider ranges of farm sizes were interviewed in Jordan and Morocco than in Kenya, and the larger farms were particularly interested in automatic valves. These large farms appeared to have more access to capital than the other studied farms, suggesting that the AS-MO tool concept might not be applicable to farms that fit this profile. However, there was strong interest in manual valves among the smaller farms in Jordan and Morocco which appeared to have less access to capital, suggesting there is likely a MENA market sector that is interested in an AS-MO tool in the way the Kenyan farmers were. Future exploration of the EA and MENA markets could confirm if the differences seen in Kenya, Jordan, and Morocco reflect the differences between EA and MENA as whole regions.

The proposed AS-MO tool could potentially be a good segue product for farmers who are transitioning from fully manual to fully automated. Several study participants pointed out that it would be beneficial for the tool to be adapted to include automatic valve operation, especially on larger or wealthier farms. This result suggests the participants saw the potential for the AS-MO tool to be "upgraded" from a semi-manual/semi-automatic tool to a fully automatic tool according to users' needs. There are likely cases where a farm first sees a need to address the challenge of automating irrigation schedules, so they adopt the AS-MO tool. Once that farm grows to the point where manual valve operation also becomes challenging, the farm could install solenoid valves and a new control box to operate them. At this point, the farm could continue using the same automatic scheduling methods as the AS-MO tool used, so the irrigation schedules are familiar and trusted. In the app, the farmer could input that the farm is now fully automated, and the tool could control the solenoid valves rather than sending instructions to laborers' cell phones. If this tool could ease the transition from fully manual to fully automatic, it could help farmers adopt further benefits of conventional precision irrigation, like automatic operation.

This work demonstrates the successful use of a methodology in which the research team identified opportunities to automate complex tasks while designing ways for users to complete these tasks in simpler, manual ways. The goal of this approach was to gain some benefits of automation while also realizing other benefits of manual work in order to lower overall product costs. Interviewees suggested this semi-automatic/semi-manual product architecture could be valuable if applied to fertigation, suggesting that this approach could have implications past the specific example of irrigation in the MENA and EA markets. Additional opportunities could include home gardening or landscaping. To apply a semi-automatic/semi-manual architecture to a new area, it is helpful for researchers and designers to break down a problem into the necessary actions (e.g., scheduling and operation, in this case). They can then understand which actions are simpler to perform manually and which would be more difficult. For the difficult actions only, researchers and designers would then identify ways in which technology could improve those actions. New technology may need to be invented to communicate complex operations to users who are carrying out manual actions. This strategy of pairing automated actions with manual actions could open new areas for innovation while serving users' needs best.

Several limitations existed in this study. The small number of farmer interviews does not necessarily give a generalized opinion of all potential users in EA and MENA. To attempt to mitigate this limitation, lead users, early adopters, and market stakeholders were recruited for the study. However, because these participants were more familiar with advanced technology, they might have a higher preference for automation than the general population would. This may have led to more disinterest in the AS-MO tool than is potentially accurate in a group of target users.

A second limitation is that users did not interact with a fully-functioning prototype for an extended period of time. The prototype performed basic interactions, not in-frequent or edge-case interactions like inputting details of a farm or managing a failure in the system. The prototype also did not calculate an irrigation schedule specific to a farm but instead used a preprogrammed schedule. Had farmers seen a higher fidelity prototype, they might have had a stronger critique of the automatic scheduling aspect of the tool, especially if it calculated a schedule drastically different than they expect.

7 CONCLUSIONS AND FUTURE WORK

The objective of this work was to evaluate a potential means of bringing the water and energy efficiency benefits of precision irrigation to resource-constrained regions like EA and MENA. To do this, a design concept for an AS-MO tool that could communicate complex but efficient irrigation events to farmers was characterized. To evaluate this concept a set of storyboards and a physical prototype of the tool were used in Kenya, Jordan, and Morocco to facilitate further interviews and focus groups with farmers and stakeholders.

The results demonstrated that the proposed AS-MO tool has the potential to enable target farmers to realize the energy- and water-saving benefits of precision irrigation. The majority of all interviewed farmers were interested in the automatic scheduling aspect of the AS-MO tool. They recognized how implementing water- and energy-efficient schedules could save them time, effort, and money on their farms. Kenyan farmers and small-scale farmers in Jordan and Morocco also liked the manual valve operation that an AS-MO tool affords. They felt more confident in adopting low-cost, familiar hardware like manual valves over solenoid valves.

Interviews with farmers and stakeholders also provided insights on how farmers might best interact with the AS-MO tool. Results suggested that a smartphone app should be designed in order to enable key user interactions with the tool. Results showed that it was valuable to give farmers the flexibility to change the predetermined schedule, even slightly. Farmers liked the ability to add time to each irrigation event in case they thought the tool delivered an insufficient amount. They also liked they could shorten, pause, or cancel an event if needed. An app-based interaction should include different data visualizations for various user profiles, such as managers, owners, and laborers. Further, a limited set of critical interactions should be made possible on the permanently-mounted control box for when phones are unavailable. A screen that shows the status and several buttons or a dial could meet this user need.

Stakeholders and farm owners in a position to buy such a tool suggested the tool has the potential to become a viable commercial product in the studied countries. Several stakeholders claimed it could benefit the growing number of solar-powered drip irrigation users.

To bring the AS-MO tool design concept to fruition, further research is needed to learn how farmers interact with a functioning AS-MO tool for an extended period of time. This study only addressed the core functions of the proposed AS-MO tool. Other functions need to be prototyped and tested. It is also necessary to study the interactions farmers have with the AS-MO tool over the course of a season to understand how to improve it for future users. This tool must be demonstrated under these conditions to gain further user feedback. The study also assumed that the perspectives of Kenyan farmers and Jordanian and Moroccan farmers would represent the perspectives of EA and MENA farmers, respectively. Future work should expand regional coverage to confirm or deny this assumption. With these next steps, future development on an AS-MO tool could help bring water-and energy-efficient irrigation to resource-constrained regions like EA and MENA.

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