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Renewable Energy for Smallholder Irrigation: A Technology Adoption Toolkit †

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Abstract: Smallholders are the backbone of livelihoods in the Global South. Yet, many remain water- and energy-insecure. For this challenge, this study presents a toolkit to stimulate the sustained adoption of renewable energy-powered water pumps for smallholder irrigation. A human-centered design method was used to co-create it. It first consisted of a prototype that was tested by experts. Their feedback was crucial to further improving the toolkit, thereby making it a more robust instrument. The design posed limitations worth considering in future research. Additionally, the spread of water pumps implies environmental and economic concerns. To enhance its benefits, the toolkit still requires thorough testing in diverse contexts.

Keywords: renewable energy; water pump; irrigation; smallholder farming; technology adoption; toolkit; co-creation

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1. Introduction

Smallholder farming is the backbone of livelihoods in the Global South. It largely sustains local economies in low- and middle-income countries. It produces roughly 80% of the food in sub-Saharan Africa and Asia, though barely accounting for 12% of the global farmland [1]. Successful smallholder farming is therefore a main pillar required for the eradication of poverty and hunger, and thus in the accomplishment of SDG 1 and SDG 2. Yet, many smallholders worldwide remain energy- and water-insecure, which is a major barrier in this endeavor [1,2].

Although conventional diesel-powered pumps are generally available in low-resource settings, their use poses economic and environmental downsides [3]. These pumps require the constant input of cost-intensive fuels, which in turn are a constant source of pollution. Renewable energy-powered pumps (RE-pumps), on the flipside, are environmentally sound, technically simpler, and more affordable alternatives. They harness clean energy (i.e., hydro, solar, wind) to drive pressurized irrigation systems, and hence, contribute to sustainably intensifying food production [4,5]. Moreover, given that RE-pumps neither depend on the availability of (inaccessible) fossil fuels, nor grid electricity, they are good candidates to support irrigated farming in rural communities.

RE-pumps are potential key technologies to leverage local-level synergies of the water–energy–food nexus. Despite the efforts to implement these technologies in smallholder settings, their uptake remains a challenge [6]. The effective adoption of RE-pumps is a complex process that depends on a number of (non-)technical factors. These pertain to the technology (e.g., cost, ease of use, trialability, complexity), the adopter (e.g., education, purchasing power, risk aversion, environmental orientation, innovation awareness), as well as the broader context (e.g., type of farm, market development, legal regulations, financial support and subsidies, institutional environment). This entangled interaction renders the decision to adopt (or not adopt) an RE-pump oftentimes to be an unclear, difficult and unstandardized process [7].

In this respect, some researchers [8–12] have focused on adoption frameworks. Others [7,13–15] have mapped the process of adoption of RE-pumps in smallholder farming. In addition, there are a (limited) number of tools [16–18] that aim to increase their adoption rates. These tools, however, do not focus on stimulating the thinking process prior to the adoption but rather create awareness and supply information to the end users. To the best of our knowledge, there are no studies on participatory tools to facilitate the decision-making of technological adoption in smallholder settings.

The objective of this paper is thus to introduce and discuss a co-designed toolkit focused on the sustained adoption of RE-pumps for smallholder farming. This toolkit provides a space for discussion between involved stakeholders (i.e., farmers, government(s), NGOs, technology manufacturers, and providers). It will help them in understanding key variables and tipping points for the applicability of RE-pumps, as well as in exploring possible business models to enable this process. To achieve that goal, first, the key adoption variables are identified from the literature. Second, a conceptual adoption framework is defined based on clusters of those variables. Third, a minimum viable product (MVP)—a first version of the toolkit consisting of a collection of tools and canvases—will be developed upon the framework. Fourth, from this first version, cyclic iterations will be carried out to arrive at a refined, co-created product.

2. Literature Review and Cases Studies

Key variables influencing the adoption of RE-pumps were identified and clustered through a literature review. Nine case studies, covering technology, socioeconomic, and business models aspects, were used for this purpose. This step was relevant to developing a sound conceptual framework for the development of the toolkit.

2.1. Cases on Technical Aspects

These aspects pertain to the biophysical characteristics of a given context, which will determine whether an RET will fulfill its expected goal. People cannot influence them or can influence them to a limited extent. These, unique to each geographic location, condition the technical performance of an RE-pump.

The first case [19] focused on the adoption of solar irrigation technologies in the Indian province of Utter Pradesh. A survey among 1600 farmers showed adoption concerns about climate variations, water availability, and certain farm characteristics such as soil composition and the slope of the land. The second case [20] assessed the adoption of a hybrid wind–solar water pumping system in Egypt. It focused on *weather conditions* and the *climate* of the different seasons. In this case, wind and solar energy complemented each other. The third case [21] focused on food security and multiple cropping seasons in Ethiopia. Relevant variables obtained from this case were *water demand*, *growing seasons*, and *crop type*.

2.2. Cases on Socioeconomic Aspects

The adoption of RE-pumps is also related to variables that go beyond the technical sphere. Socioeconomic aspects are key to addressing the limitations and opportunities of smallholder irrigation. Here, both the institutional and broader context, as well as the individual and household levels were considered.

The fourth case [22] studied smallholders' perceptions of RE production in West Bengal, India. It concluded that farmers assess RETs based on their *holistic experiences* and *background*, reinforcing the importance of integrating the technical aspects (e.g., local climatic conditions and soil fertility), with external variables, such as *fluctuations in market prices* for agricultural inputs and outputs. Moreover, it suggested that 'early adopters' are usually higher socioeconomic actors with more access to resources (e.g., water, land, financial capital), which allows them to take the *risks* typically associated with RETs.

The fifth case [23] examined farmers' choices of water pumps in Pakistan. It found that *educated*, *younger*, and *wealthier* smallholders are more prone to adopt RE-pumps. It also indicated that *female* farmers are more likely to use RE sources. On the contrary, it identified that *lack of credit availability* prevents smallholders from adopting them.

The sixth case [14] elaborated a general review of the policy and institutional barriers to RETs adoption in Bangladesh. They considered variables such as the *lack of training programs* and *financial incentives* to encourage private sector investment, the limited *available empirical knowledge* on RETs, and lack of public awareness, among others.

These variables were organized in different clusters of resources, namely physical, human, financial, social, and natural [15,22].

2.3. Cases on Business Model Aspects

Business models and entrepreneurial processes are important as they are a blueprint for business success. These processes determine whether the adoption of a certain technology is economically feasible. By considering the financial investment and return, it can be estimated to what extent the long-term adoption will be impeded or facilitated.

The seventh case [21] assessed the demand and adoption constraints for small-scale irrigation technologies in Ethiopia. It established that variables including a *lack of access to financial advice*, the *purchase price*, or the absence of access to *financing methods* constrain or enhance the technology adoption from an economic perspective.

The eighth case [24] found that, for smallholders in Asia and sub-Saharan Africa, the adoption is oftentimes hindered by insufficient *affordability*, high *purchase prices*, and *technological illiteracy*. Furthermore, in rural areas, there is limited *access to stores* and *technological support*, which creates additional barriers to the adoption of suitable technologies.

The ninth case [13] focused on a predictive adoption framework for smallholder farming in low-income countries. It acknowledged crucial variables, among others, as *additional running costs* (e.g., fuel, replacement parts), *added labor requirements*, *information asymmetry* (such as unfamiliarity of financial benefits), and *time until break-even*.

2.4. Research Gaps

The analyzed cases show gaps such as a lack of geographic diversity and holistic consideration for adoption variables (Table 1). Most cases focused on sub-Saharan Africa or the Indian subcontinent, and a specific domain, such as certain irrigation technology. Moreover, studies tend towards linear approaches that disregard the dynamics of the adoption of RE-pumps in the real-world context. Additionally, long-term adoption is generally not observed and scholars have neglected the broader context of the environment. To avoid those pitfalls, this research has focused on developing a toolkit that holistically and dynamically considers the relevant variables related to long-term adoption.

Table 1. Cases, findings, and research gaps.

Aspect	Ref.	Main Findings	Gaps
Technical	[19]	Adoption factors for solar irrigation technologies	Only considering solar-powered irrigation
	[20]	The value of a hybrid RE pumping system	Only looking at the technical variables
	[21]	Influence of RE-pumps on food security and wealth	Not purely focused on RETs

Table 1. *Cont.*

Aspect	Ref.	Main Findings	Gaps
Socioeconomic	[22]	Socioeconomic status and access to resources are key in determining the adoption rates	Focused on farmers' perceptions, ignoring the political/institutional context
	[23]	Younger, wealthier, and more educated smallholders are more likely to adopt RE-pumps	Only includes a quantitative approach to understanding adoption
	[14]	The local institutional context is crucial for ensuring the long term adoption of RET	Analyzes RET projects from a general perspective
Business model	[21]	Credit constraints are key determinants of adoption and demand for irrigation technologies	Focused on one specific region, cross-sectional, linear approach, focused on credit-constraints
	[24]	The successful adoption poses challenges related to equity, efficiency, and sustainability	Limited temporal horizon
	[13]	Costs, education, and additional requirements are relevant considerations for technology adoption	Limited temporal horizon, linear approach

3. Conceptual Framework

Based on the identified variables and clusters (Table 2), a framework that holistically combines the technical, socioeconomic, and business models aspects has been conceptualized (Figure 1). This framework was used as a compass to guide the development of the adoption toolkit.

Table 2. Clusters of key variables of RE-pump adoption.

Aspects	Clusters	Variables
Technical	Water availability	Groundwater table, aquifers, wells, surface waters, water depletion, water quality
	Climate	Weather conditions, climate change, natural disasters
	Farm characteristics	Soil type, dimensions of the farm, slope, hydraulic head, water storage
	Water demand	Irrigation schedule, crop type, irrigation type
	Durability	Robustness, quality, usability, complexity, maintenance
Socioeconomic	Physical resources	Farm size, land ownership, available infrastructure (e.g., irrigation canals, roads)
	Human resources	Skills, educational level, jobs, and sources of income
	Financial resources	Wages, services, access to loans/credit
	Social resources	Networks, gender roles, social status
	Natural resources	Access to land and water, details of agricultural system (crops, animals, inputs)
Business model	Pre-purchase	Access to physical stores/websites, advisory support, switching-costs
	Purchase	Access to finance, purchase price
	Post-purchase	Input-price, additional labor requirements
	Long-term	Time to break-even, awareness of financial benefits, cost-savings/profitability

The three-level pyramid framework shows the conditions and processes relevant to the long-term adoption of RE-pumps. The foundation (first level) consists of tangible biophysical aspects such as the climate and landscape conditions and intangible socioeconomic aspects such as wealth and education. They engage in a reciprocal interaction whereby biophysical aspects may determine socioeconomic conditions and socioeconomic development can shape the natural environment. Based on that interaction, a suitable business model (second level) must leverage the advantages and harness the limitations of the biophysical and socioeconomic aspects. A suitable business model considers factors such as access to financing methods, advisory support, or profit advantage in order to ensure that it fits the conditions of the context. The irrigation technology (third level) should be selected based on those contextual aspects, and delivered through an appropriate business model. Then the model is solid and facilitates its long-term adoption. Long-term adoption can influence the base of the pyramid by, for example, increasing wealth, providing jobs, and changing the landscape to adjust to the new agricultural infrastructure and needs. The model then requires an adjusted business model. The adoption process becomes highly dynamic. Additionally, inputs (e.g., outside knowledge, materials, machinery) are required to sustain this process. Broader factors such as global trends (e.g., food prices, trading, and consumption patterns) can influence the whole system.

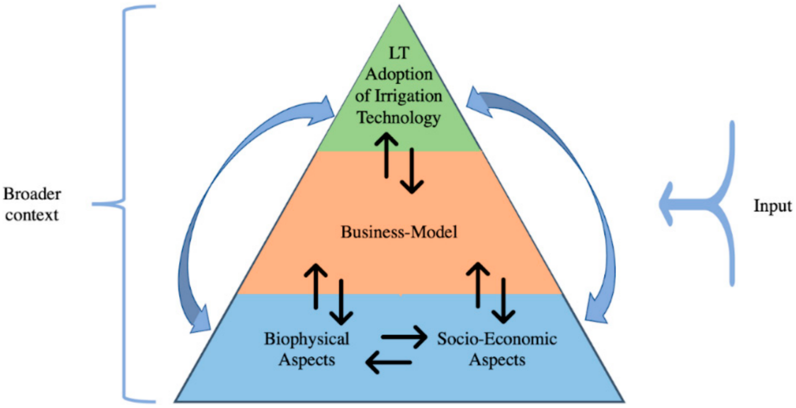

Figure 1. Proposed conceptual framework: interaction of conditions that impact the long-term adoption of irrigation technologies.

4. Methodology

A human-centered design method, consisting of four stages, was used to develop the toolkit (Figure 2). First, based on the classification of relevant adoption variables, a minimum viable product (a version of a product with just enough features to be usable by early customers who can then provide feedback for future product development) (MVP) was designed [25]. Second, an internal iteration to test the MVP was conducted through role-play sessions [26]. Third, an external iteration of the MVP was carried out with stakeholders involved in the topic [27]. Fourth, the toolkit will be deployed in actual on-field cases with smallholders. This last step, which fell out of the temporal scope of the present paper, will provide further insights for the refinement of the toolkit and the later data collection and improvement.

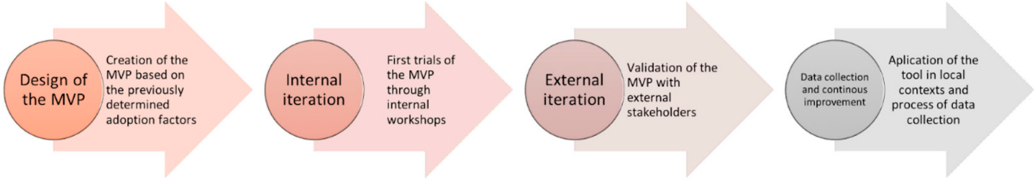

Figure 2. Steps towards the development of the toolkit.

The design method sought to facilitate the co-creation process, by bringing different actors together from the early stages, thereby aiming for a more holistic toolkit.

4.1. Design of the MVP

The MVP consisted of a number of canvases, which were articulated around the key adoption variables and clusters previously identified. These canvases were an early prototype of the envisioned tools, subjected to quick design and trial [25]. As this procedure was partly based on assumptions, the MVP was subsequently tested and improved in controlled environments.

4.2. Internal Iteration

To validate the MVP, a first web-based iteration was conducted through role-playing sessions. This technique is useful to test ideas in complex dynamic systems such as the adoption of RETs. It rapidly generates new insights and shows the limitations of the proposed designs.

To our goal, independent experts in the fields of irrigation, innovation, energy, and water management were purposively approached. Different roles of decision-makers involved in the adoption of RE-pumps were assigned to these participants. They were instructed to test the ease of use and completeness of the MVP and to highlight as many unaccounted/inconsistent elements as possible. Their feedback was collected through a semi-structured questionnaire. It included a number of open questions that captured the viewpoint of the participant. It also considered multiple-choice questions about the quality of the role-play. The feedback was analyzed and used to refine the MVP.

4.3. External Iteration

Purposely selected stakeholders were presented with an improved version of the toolkit. These actors were actually involved in the implementation of RE-pumps for smallholder farming. Similar to the internal iteration, they were asked to test the ease of use and completeness of the toolkit. Their feedback was collected through semi-structured questionnaires. Through this step, the toolkit was further refined considering the changing preferences, emerging technologies, and varying ranges of stakeholders.

4.4. Deployment and Continuous Improvement

In a final step, yet to be conducted due to the limited scope of the present research, the toolkit will be used in smallholder communities. This step will collect data from the end users to further improve the toolkit.

5. Results

5.1. Design of the MVP

The MVP consisted of three sub-canvases, one main canvas, and a business model booklet. The three sub-canvases sequentially covered socioeconomic, technical, and business model aspects. These ensured the interaction of the identified clusters of key variables. The first one aimed to determine the socioeconomic profile of the participant. The second one sought to pinpoint whether a certain RE-pump is suitable in the given context. The third one, based on the first two, mapped the financial and market conditions.

The main canvas was split into two sections. The first section translated and summarized the contents of the sub-canvases by means of visual scoring systems. It highlights key points of the participant's current situation. The second section engages in a reflection process on what is required to effectively adopt the desired RE-pump, thereby facilitating later decisions. Lastly, the booklet presented different business models that might help bridge the gaps that the user identified and reflected upon in the concluding section. Its goal is to educate and inspire participants on different delivery options available/desirable in the given context. The Supplementary Material of the toolkit can be found in [28].

5.2. Internal Iteration

Four experts tested the MVP and provided their feedback. It focused on the understandability, usefulness, and missing parts of the different canvases. The feedback revealed two main needs: overall clarification in terminology and questioning, and the simplification of any forms of calculations of technical and financial aspects. The second need in particular may involve high susceptibility to errors, thus reducing the confidence of the participant in filling it correctly. Because of this, it was decided to greatly simplify any calculation or to eventually leave it out completely.

5.3. External Iteration

Ten external experts were contacted to conduct these tests. They were selected to cover a diverse range of RE-pumps manufacturers, distributors, NGOs, and academics. Just three of them provided feedback. As for the internal iteration, they were asked for the understandability, usefulness, and missing parts of the toolkit. Their feedback focused on keeping the tool simple in terms of calculations and length. The main canvas was deemed as particularly unclear. They suggested the addition of more images to increase clarity. As missing points, they identified gender-related factors and the portability of different pumping systems.

5.4. Deployment and Continuous Improvement

As pointed out above, the deployment of the iterated toolkit is out of the scope of the present work. As such, it remains pending to engage in a process of continuous improvement. Nonetheless, the expected result from this last stage is to co-produce, alongside actual smallholders and related actors, a refined toolkit resulting from a participatory process of knowledge sharing. Moreover, the regular use of this holistic toolkit may facilitate the field data collection that ensures its continuous improvement.

6. Discussion and Conclusions

Key adoption variables and their interactions reflect the complexity of RE-pump adoption in smallholder settings. This aligns well with studies highlighting smallholder agricultural innovation as a complex process [12,13]. This multifaceted process requires a comprehensive look at the technology itself, local socioeconomic processes, and their connections with local and national contexts. As a response, the designed toolkit aimed to holistically integrate those relevant adoption variables. For this purpose, the human-centered design approach allowed for the translation of the clusters into an MVP that was piloted later [27]. Through two iterative cycles of testing and feedback, it was possible to engage experts in the co-creation of the toolkit. These actors keenly spotted pitfalls and lack of clarity within the canvases, in consonance with [27]. More importantly, their pooled knowledge enabled the shared improvement of the toolkit, which thereby may capture more accurately the real-world dynamics of RE-pump adoption. At the same time, those iterations showed the toolkit's capacity to be flexibly adapted to different requirements.

The toolkit provides ground to surpass the limitations of traditional top-down, linear, and short-term approaches to technological adoption [12]. It offers a space for stakeholders to identify, reflect, discuss, and negotiate crucial enablers and barriers in the uptake of RE-pumps. On this basis, the toolkit also has the potential to delineate possible roadmaps for the whole adoption process, from the introduction of the RE-pump to its sustained adoption. The application of the toolkit, however, should not be limited to the purchase or use of a water pump with virtually no emissions. It must rather be understood as a means of bridging gaps between smallholder farming and sustainable agricultural mechanization and production. In the long run, this synergy can create a larger positive impact on food security, economic development, responsible production, and overall sustainable development of societies in the Global South.

The design of the toolkit also posed a number of limitations worth considering. Web-based piloting was a useful way to overcome fieldwork limitations related to the ongoing COVID-19 crisis [29]. However, it also prevented the gathering of on-the-ground data from actual smallholders. These actors would have exposed the toolkit to perspectives that the current research has likely overlooked, despite the efforts of the research team. Follow-up proposals for field piloting are therefore crucial to ensure its further improvement. Another limitation is that the testing consisted of merely two iterations and seven experts. More actors, fulfilling diverse roles, must thus be incorporated to ensure more robust completeness of the tool.

The application of the toolkit, and its potential contribution to increasing adoption rates of RE-pumps in smallholder farming, also has implications and possible downsides. The uncontrolled spread of seemingly 'pump-for-free' technologies may pose a risk of aquifer over-abstraction [30]. Excessive reliance on groundwater sources is likely to exacerbate climate change impacts and diminish the resilience of local populations [31]. Depending on the type of water source and pumping intake, it may also become a severe threat to aquatic life and ecosystems [32]. Less evidently, sudden (massive) introduction of off-the-grid technologies may create disturbances and/or shocks in local energy markets, which may affect the most impoverished households [30]. These implications, albeit beyond the scope of the present work, are certainly worth considering for future research and relevant agricultural policymaking.

In conclusion, the presented toolkit still has a long way ahead. It requires thorough testing with a larger diversity of actors and contexts. Additionally, and given the dynamics of technology adoption, the toolkit must not become a finished package at any given point, but rather a product that needs to be dynamically adjusted over time and across latitudes. In this sense, this has been a first attempt to set the thick lines of a holistic, participatory discussion on the adoption of RE-pumps for smallholder irrigation. Future iterations will offer grounds to keep adjusting it to more specific needs and situations.

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