

AN INTEGRATED APPROACH FOR WEF NEXUS IMPLEMENTATION UNDER WATER REUSE IN TUNISIA

UNE APPROCHE INTÉGRÉE POUR LA MISE EN ŒUVRE DU NEXUS EAU- ÉNERGIE-ALIMENTATION-ENVIRONNEMENT DANS LE CADRE DE LA RÉUTILISATION DE L'EAU EN TUNISIE

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ABSTRACT

The WEFE Nexus is designed to enhance the security of water, energy and food without disrupting ecosystems services. Despite this concept has recently gained popularity in the international community, its practical implementation remains limited. The reuse of treated wastewater (TWW) is recognized as one of the possible solutions to address water resource pressures and specific territorial issues. Therefore, it is essential to simultaneously address the various challenges that arise from the optimization of TWW use in accordance with the various mutual dependencies between WEFE sectors. Thus, multidisciplinary approaches were applied in Ouardanine region (Tunisia) to jointly identify and resolve the encountered challenges related to the WEFE nexus. Following a first step of stakeholder analysis, the Participatory System Mapping approach resulted in the creation of Causals Loops Diagrams (allowing the identification of various issues, causes, and potential impacts) and the understanding of the WEFE framework in the perimeter. Three main problems were identified in relation to the TWW use, namely the limited availability of TWW, high energy cost, and energy accessibility issues. To address these problems, a combination of interventions promoting the WEFE Nexus was proposed and co-designed by stakeholders. The innovative solution, called "Smart Reuse", which optimizes TWW use in terms of quantity and quality by using IoT. The second intervention called "Solar Pumping" involves photovoltaic panels to mitigate energy constraints. Stakeholders discussed barriers and opportunities for implementing both interventions and then proposed potential alternatives to overcome obstacles as well as the key actors to support the technology adoption on the short, medium and long term and to promote their upscaling. The proposal of a multi-stage methodological framework based on a participatory and multidisciplinary approaches, is appropriate to analyze the complex intersectoral interactions within the WEFE Nexus process, and to facilitate intervention implementation and adoption.

Keywords: Ecosystems services; Smart Reuse; Solar Pumping ; Multidisciplinary approaches; Methodological framework.

RÉSUMÉ

Le « Nexus » eau-énergie-alimentation-environnement (EEAE) vise à renforcer la sécurité de l'eau, de l'énergie et de l'alimentation sans perturber les services écosystémiques. Bien que ce concept ait récemment gagné en popularité au sein de la communauté internationale, sa mise en œuvre concrète reste limitée. La réutilisation des eaux usées traitées (EUT) est reconnue comme l'une des solutions possibles pour faire face aux pressions sur les ressources en eau et aux enjeux territoriaux spécifiques. Il est donc essentiel de relever simultanément les différents défis découlant de l'optimisation de l'utilisation des EUT, en tenant compte des diverses interdépendances entre les secteurs de l'eau, de l'énergie et de l'alimentation. Ainsi, des approches multidisciplinaires ont été mises en œuvre dans la région d'Ouardanine (Tunisie) afin d'identifier et de résoudre conjointement les défis rencontrés liés au

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nexus EEAE. À l'issue d'une première étape d'analyse des parties prenantes, l'approche de cartographie participative des systèmes a permis de créer des diagrammes de boucles causales (permettant d'identifier divers enjeux, causes et impacts potentiels) et de comprendre le cadre EEAE au sein du périmètre. Trois problèmes principaux ont été identifiés en lien avec l'utilisation des EUT (eaux usées traitées), à savoir la disponibilité limitée des EUT, le coût énergétique élevé et les problèmes d'accessibilité à l'énergie. Pour remédier à ces problèmes, une combinaison d'interventions favorisant le nexus EEAE a été proposée et conçue en collaboration avec les parties prenantes. La solution innovante, baptisée « Smart Reuse » (réutilisation intelligente), optimise l'utilisation des eaux usées en termes de quantité et de qualité grâce à l'IoT. La deuxième intervention, appelée « Solar Pumping » (Pompasolaire), fait appel à des panneaux photovoltaïques pour atténuer les contraintes énergétiques. Les parties prenantes ont discuté des obstacles et des opportunités liés à la mise en œuvre de ces deux interventions, puis ont proposé des alternatives potentielles pour surmonter les obstacles, ainsi que les acteurs clés à mobiliser pour soutenir l'adoption de ces technologies à court, moyen et long terme et pour favoriser leur développement. La proposition d'un cadre méthodologique en plusieurs étapes, fondé sur des approches participatives et multidisciplinaires, est appropriée pour analyser les interactions intersectorielles complexes au sein du processus du Nexus EEAE, et pour faciliter la mise en œuvre et l'adoption des interventions.

Mots-clés : Services écosystémiques ; Réutilisation intelligente; Pompasolaire; Approches multidisciplinaires; Cadre méthodologique.

INTRODUCTION

The WEFE Nexus aims to strengthen water, energy and food security, and to preserve ecosystems (UNESCO, EU and IWA, 2021). The Nexus confirms the need to consider the four sectors not as separate entities, but rather as a complex and inextricably linked whole; limiting one of these inputs would disrupt the availability of the others. Despite the WEFE Nexus concept has been the subject of theoretical studies in recent years, its practical realization remains limited. Although the implementation of this process has been the subject of several methodologies (UNESCO, EU and IWA, 2021), a holistic and multidisciplinary approach seems to be the most appropriate to successfully implement the Nexus WEFE process. The reuse of treated wastewater (TWW) is one of the possible alternatives to address water resource pressures and specific territorial challenges. This solution is strategic in agricultural irrigation, guaranteeing water and food security while protecting the ecosystem and preventing soil degradation. It represents a source that has been heavily regulated and exploited worldwide for decades. The first experiment with TWW irrigation in Tunisia dates back to 1965, but it was only in 1987 that the policy of reuse was strengthened and areas irrigated with TWW became part of the sector's regular planning. In 2023, 57.6 million m³ of TWW were reused (20%), of which 10.89 million m³ were directly reused to irrigate 2,725 hectares out of the 7,794 hectares established for irrigation with TWW (ONAS, 2023). In the Ouardanine region (Monastir Governorate), the reuse of treated wastewater began in 1997 to reduce effluents discharges into waterways and provide farmers with a reliable water resource to sustain their agricultural activities, promote ecosystem restoration, and ensure community well-being. Despite the notable success and significant progress made in water reuse, the region currently faces several challenges primarily related to resource availability and management, particularly water and energy. In this context, participatory and transdisciplinary approaches were adopted to collectively identify the main challenges related to the Water-Energy-Food-Ecosystems (WEFE) nexus encountered in the region. Indeed, the main objective of this study is to introduce the participatory approach deployed in the field to co-create, operationalize and evaluate, in a collaborative manner, relevant local interventions that address the challenges of the WEFE Nexus, while developing effective implementation strategies.

STUDY SITE

The site is located 15 km northwest of Monastir Governorate, in the Central East of Tunisia, in the treated wastewater irrigated area of Ouardanine (35° 44' 14.95"N 10° 40' 16.15"E) (Figure 1). The area exhibits a semi-arid climate with an average rainfall around 308 mm (2010-2017). In terms of water resources, the irrigated area of Ouardanine relies on the reuse of treated wastewater (TWW) is the only alternative

in this area to cope with the water shortage, preserve agricultural activity and limit environmental pollution caused by the discharge of effluents of the wastewater treatment plant (WWTP) of Ouardanine into the Geulta stream. As a result, community showed a high acceptance and buy-in of the reuse of TWW. The area started to be irrigated in 1997. Today, the total irrigated area covers 75 hectares, cultivated by approximately 46 farmers. Their main grown crops are fruit trees and geranium. Recently, irrigation water management in the study site has been disrupted following tariff policy measures (March 2021) related to energy cost recovery, leading to power cuts occurring during peak energy consumption hours. Added to this, the lack of dredging of the El Guelta stream, where effluents are discharged, which is becoming a source of nuisance for the area's ecosystem.

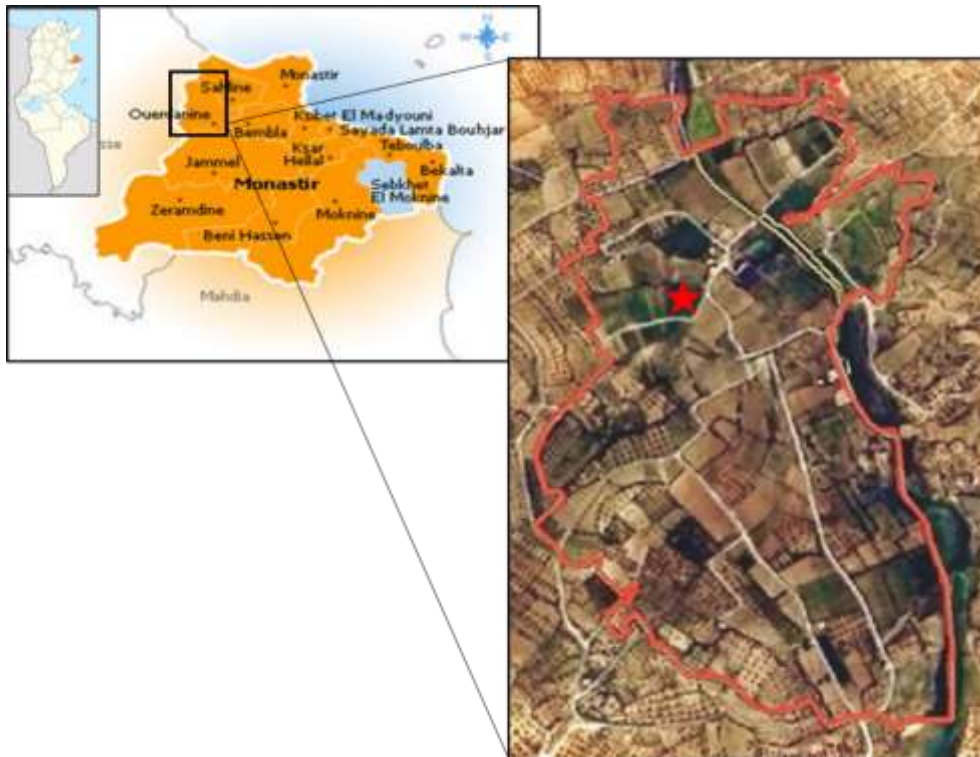


Figure 1. Location of the TWW irrigated area of Ouardanine, Tunisia.

METHODOLOGY

The methodology deployed during this work is based on a participatory approach aimed at strengthening the engagement of stakeholders in decision-making and co-creation of solutions. It was carried out in several stages, ranging from stakeholder analysis to the application of various multidisciplinary approaches during a series of workshops (Figure 2). The Participatory System Dynamics Modeling (PSDM) will be used as a platform to articulate knowledge and perceptions regarding WEFE management. It is based on the realization of a series of participatory workshops.

The aim of the first workshop was to assess the status quo of the WEFE nexus and underlying problems. Stakeholders discussed and identified jointly WEFE issues in the site by developing a first version of causal loop diagram (CLD) and then underline its main interlinkages and feedback structures (causes and impacts). The 2nd Workshop aimed to validate the final CLD which allowed stakeholders to propose and co-create possible solutions and interventions by identifying key leverages points (barriers and opportunities) in the study zone. In the 3rd Workshop preliminary results were presented and stakeholders were able to explore principal implementation pathways and upscaling strategies of the solution in a transdisciplinary manner and the key actors which are needed to be engaged.

The objective of the final workshop was to present the results of the interventions regarding the implementation of the WEFE Nexus framework in the context of TWW reuse in Ouerdanine perimeter. It also aimed to lead discussions around the stakeholders, policies and society at the service of innovations for the reuse of TWW in agriculture and possible opportunity for the marketing of the innovative intervention

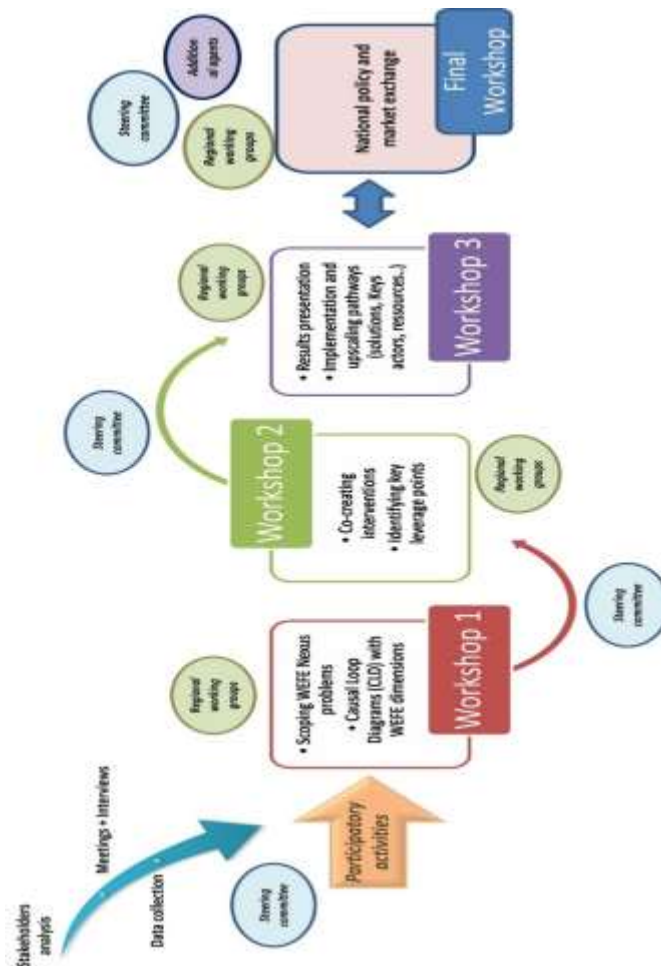


Figure 2. Participatory process deployed at the level of the Ouerdanine perimeter, Tunisia

RESULTS

Stakeholder's analysis

The stakeholders who can affect or are affected by the implementation of the WEFE nexus framework have been identified, and to strengthen their engagement, local, regional, and national actors will be organized into three groups that will together form a Communities of Practices: (1) a **Steering Committee (SC)** comprising twelve representatives from key local, regional, and national stakeholders of the WEFE Nexus sectors involved in the reclaimed reuse sector. Its missions are to monitor and discuss activities progress and to make decisions jointly through meetings. It is also involved in the trainings on the methods and tools used in the study and can participate in the animation and facilitation, especially during the workshops and field visits. (2) a **Regional Working Group (RWG)**, bringing together more than fifty participants from the first workshop, representatives from various WEFE Nexus sectors. The RWG and other local and regional stakeholders took part in the participatory workshops to

discuss issues and co-create adequate interventions. (3) **The community of practice** will be composed of the SC, the RWG members and stakeholders that were not involved in the workshops and they will be targeted through general communication and outreach activities: website, videos, social media, etc.

Identification of WEFE Nexus issues

The first workshop was based on a Participatory System Mapping approach leading to creation of Causals Loops Diagrams (CLDs) and the identification of various challenges encountered in the study area, their causes and potential consequences, and so the comprehension of the WEFE framework in the perimeter. In total, three CLDs were created (Figure 3) through which three problems were identified in relation to the use of TWW in the study site and taking into account the interconnections that exist between the four dimensions of the WEFE nexus:

(1) The Energy availability: Power outages during peak hours (11 am to 4 pm) are the main causes, disrupted by tariff measures related to energy cost recovery. Added to this, the lack of alternative energy sources for water pumping and the limited capacity of infrastructure, leading to low availability of treated wastewater for irrigating crops during the hot season, which negatively impacts yields and can lead to a drop in farmers' income.

(2) The Energy cost: Because of the Lack of renewable energy, the limited capacity of the power line push back and the necessity to cover the energy cost depending on the pumped TWW volume and so to irrigated parcel size. As a result, the pumping of wastewater is often interrupted to reduce the energy bill covered by the farmers' association (GDA), despite the high demand for water. This situation can lead to an unbalanced distribution of water among farmers and thus affect the availability of water for irrigation and negatively influence the yield of agricultural production.

(3) The limited availability of the treated wastewater (TWW): Due to power cut for water pumping, the Lack of storage and the poor maintenance of the infrastructure in addition to Energy price, the amount of TWW is reduced and interrupted. According to farmers, the irrigated area receives only 30 to 50% of its water needs due to limited infrastructure, equipment and poor water management, especially during periods of high-water demand. Furthermore, the deterioration in the quality of TWW could lead to the interruption of water distribution due to the discharge of industrial effluents into the sanitation network, supported by poor enforcement of regulations.

The final Causal Loop Diagram (Figure 3.B) resulting from the combination of the 3 preliminary CLDs (Figure 3.A), created by the stakeholders, emphasizes the same WEFE-related issues.

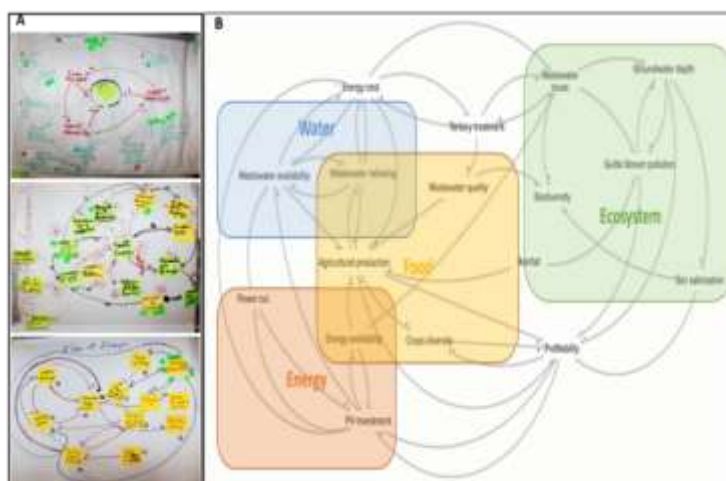


Figure 3. A) Preliminary Causals Loops Diagrams and B) Final Causal Loop Diagram including the main WEFE Nexus related problems in the TWW irrigated area of Ouardanine (Tunisia)

Co-created Interventions

Following the identification of three key problems, mainly related to water and energy components, the collaborative approach during the second workshop attempted to co-create interventions to resolve these problems. Accordingly, two solutions have been identified:

(1) The “**Smart Reuse**” is an innovation aiming to rationalize and optimize the irrigation water by improving TWW and nutrient management in quantity and quality, by using IoT-based tools: **A smart weather station**, for a real-time monitoring of weather parameters, a **set of smart low-cost soil moisture sensors** to improve irrigation scheduling and a **Smart water quality sensors** for the real-time monitoring of the physicochemical parameters of TWW (pH, EC, COD/BOD/TOC,N,K, etc..). The sensors will be connected to the **nutrient-balance tool “Richwater”** developed jointly by BIOAZUL and Smart Logger to be tested under the Tunisian context to better manage nutrients in TWW and reduce the use of fertilizers.

(2) The “**solar pumping**” intervention, which involves photovoltaic-powered water pumping during the peak hours’ demand. This solution recently endorsed by the regional authorities.

Leverage points and key actors

Barriers and corrective measures that have been identified by all local stakeholders for implementing interventions in the study site, can be summarized as follows: For (1) **Economic factors and technology funding**, stakeholders emphasized the lack of funds and investment incentives as well as the high cost of instruments as main obstacles facing the implementation and adoption of the interventions. As main solutions, they proposed the creation of specific bank financing and grants for the purchase of smart technology solutions, or the distribution of financial aid sources according to the type of beneficiaries. For (2) **Resources management-related to technology Implementation**, the main barriers identified are related to the current situation of availability (lack) and management of TWW. And to address these problems it was suggested to use all accessible TWW and increase the water tariff to cover the cost of energy and network maintenance. Another solution is to diversify irrigated crops to reduce the discharge of TWW, while supporting the need to modernize and expand infrastructure and more specifically the irrigation network to make the maximum amount of water available for irrigation.

For (3) Community Engagement Measures, The main problem cited is the lack of communication. To this end, the proposed solutions aim to facilitate the exchange of information and knowledge among local stakeholders through awareness-raising and outreach activities such as organizing information days, field visits, practical training, meetings, and workshops, which contribute to the dissemination of results and provide practical recommendations to farmers. And For (4) **Institutional and regulatory measures**, the main barriers identified were the lack of incentives and subsidies for investment as well as the current water management situation. To face these problems, proposed solutions were focused on the establishment of good governance through the establishment of a new regulatory framework accompanied by an evaluation of water and energy resource management indicators and strengthened administrative and financial control of the GDA, as well as the possibility of recruiting permanent technical staff to guarantee reliable and transparent services.

In addition, stakeholders also identified the actors likely to pave the way for change in Ouardanine and for the adoption and promoting the upscaling of interventions on the short, mid and long terms. Indeed, the majority of identified stakeholders was designated as having a strong interest and influences to support the adoption of innovation. These key actors come from different local, regional and national scales, whether from the public or private sector and covering all components of the WEFE Nexus, and farmers’ unions at different levels.

The participation of the private sector, whether as consultants or as startups, was encouraged, as well as the agency for promoting investment in the agricultural sector, and some banks to support farmers and innovative technologies through mentoring programs and special financing.

DISCUSSION

Causal loop diagram (CLD) scoop for WEFE Nexus Implementation

Causal loop diagrams (CLDs) are a method for providing a visual and cartographic representation of the relationships between system elements and their interactions, leading to an understanding of what motivates the system's behavioral problems and its dynamics (Adam, 2014). Their use dates back at least to the 1970s (Barbrook-Johnson and Penn, 2022) and is based on three fundamental elements: boxes, connections, and feedback loops. Several relevant potential applications can be linked to the use of CLDs, beyond mapping the main structural factors of a behavior or problem (Sterman, 2000), but also informing the design of an intervention or policy, or developing a theory of change to guide its evaluation (McGill et al., 2021). They can also be used as direct inputs or complements to other research work and tools (Pruyt, 2017; Jamal et al., 2020).

Another distinctive feature of CLDs, is their ability to assess complex systems that require addressing multiple problems and themes simultaneously. This is the case with the WEFE Nexus approach, which, despite its potential, faces several obstacles hindering its practical implementation and its holistic approach to the mutual interdependencies between its various sectors: water, energy, food, and ecosystems. In this context, the CLD method appears to be the preferred solution for addressing the interactions that exist between different multidisciplinary systems, while emphasizing synergies and trade-offs between sectors. Indeed, multiple studies have recently demonstrated that spatial data models (SDMs) and in particular CLDs have significant potential in WEFE Nexus studies (Giordano et al. 2025, Bahri, 2020; Zhang et al., 2021) and to promote the stakeholder's engagement in modeling activities. Thus, this study presents an opportunity to WEFE Nexus implementation by applying a participatory model based on the use of CLDs combined with several multidisciplinary sources and tools, and the active participation of stakeholders who had the privilege of constructing their CLDs based on their respective experiences. The distinctive feature of this work is that the various possible interactions that exist between the different sectors of the WEFE nexus were treated separately, initially, to offer the actors the opportunity to showcase their know-how and points of view, to promote discussion and communication and to ensure that their perspectives and knowledge were reflected in the system representation. Ultimately, three CLDs were initially proposed, leading to a general CLD resulting from the merging of the first three and which considered all interactions, synergies, and trade-offs.

Participatory approach for the benefit of WEFE Nexus

Participation is a shared perception and a factor of accountability leading to joint decision-making. It begins with consultation, goes through negotiation to lead to decision-making and action (AMSED 2009). This approach attempts to establish a legitimate representation of all stakeholders by trying to aggregate information and make it available and to balance the power relations and decision-making power between all participants (De Vente et al., 2016). However, the proper functioning of this approach faces multiple challenges. The most relevant challenge is the pre-existing conflicts between populations and development agents and decision-makers, due to their divergent views on problems and solutions. This is why the composition of the groups involved in participatory processes and their associated preferences strongly influence the quality of the results (Newig and Fritsch (2009) and this is why various studies propose the prior identification of stakeholders as an essential condition for achieving the desired objectives (Reed et al. 2009, Stanghellini 2010).

Despite the complexity of combining the treatment of several fundamental factors at the same time and the risks of falling into undetermined conflicts between different water-energy-food-ecosystems sectors of the WEFE Nexus, the participatory approach within this study and with its different tools and multiple multidisciplinary approaches made it possible to identify a very significant commitment of stakeholders, promoting freedom of expression and exchange between actors to find the right compromises. Based on the case study, the most determining factors for the success of the implementation of the WEFE Nexus framework, was first a good organization of the participatory process, whether through the choice of studying multidisciplinary techniques deployed throughout the process and the good chronology in the application of these tools, second a and good communication between the different actors and third

a concordance between the objectives and results of the processes and the policies and the implementation of the solutions.

CONCLUSION

The participatory approach integrated to a multidisciplinary methods proved to be effective in strengthening stakeholders' engagement, structuring the WEFE Nexus framework, and facilitating intervention adoption. Taking into account technical and socio-economic constraints, these efforts contribute to a more integrated and sustainable resource management strategy for water reuse. The main results showed that the key obstacles identified by the stakeholders include the limited availability of TWW, high energy cost, and energy accessibility issues. A combination of interventions promoting the WEFE Nexus was proposed as the "Smart Reuse" (the project intervention) and the "solar pumping" (alternative solution). These interventions would improve the efficiency and sustainability of wastewater reuse in agriculture, thus meeting current challenges and future needs. Also, stakeholders identified well-structured levers for action, integrating systems modeling with economic and social sciences to improve the effectiveness of stakeholder participation and bridge the gap between the theory and practice of the WEFE Nexus framework, thus marking the transition to effective Nexus governance. While current results remain encouraging, the full potential of the methodology has yet to be explored in terms of direct policy outcomes and scaling up implementation.

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