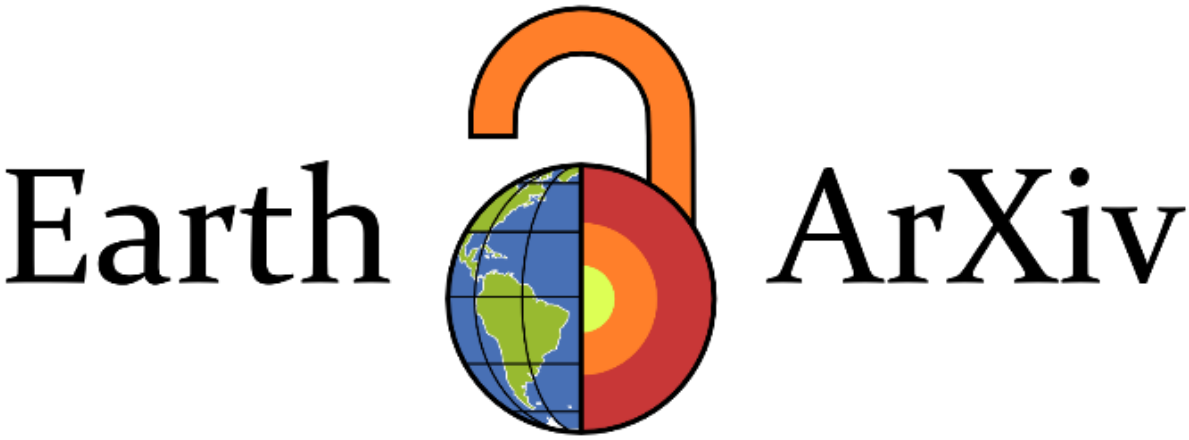

Participatory assessment of French Reed Beds (FRB) as natural based solution for rural sanitation in arid environments: insights from Ouijjane project in Morocco

Moussa Ait el kadi [a*], Lhousaine Bouchaou [a,b], Abdelwahed Chaaou [a,b], Sokaina Tadoumant [a], Chaima Aglagal [a], Soumia Gouahi [a], Abderrazak El hajri [c1], Brahim Settar [c2] and Mohammed Hssaisoune [a,b,d]

[a] Laboratory of Applied Geology and Geoenvironment, Ibn Zohr University, Agadir 80035, Morocco.
[b] International Water Research Institute (IWRI), Mohammed VI Polytechnic University (UM6P), Ben Guerir 43150, Morocco.
[c1]Migrations & Développement, 42, Bd d'Annam – Bat 4 RDC, BP 186 – 13321, Marseille Cedex 16, France.
[c2] Migrations & Développement, Imm. 30, Lotissement Assaka 3, Av. Lala Abla, 85000 Tiznit, Morocco.
[d] Faculty of Applied Sciences, Ibn Zohr University, Ait Melloul 86153, Morocco
*Corresponding author E-mail: moussa.aitelkadi@edu.uiz.ac.ma

Abstract

Rural improved sanitation remains a major challenge to achieving the UN SDG 6 goal. In this regard, this study evaluates, with local stakeholders, an operational rural sanitation project in Ouijjane commune, Morocco, using French Reed Bed (FRB) technology. Data from project documentation, as well as field interviews and focus group discussions, were used to carry out a participatory evaluation. The findings reveal, for the monitored period (2020–2021), high organic load reduction with TSS at 85%, COD between 87–90%, BOD_5 between 85–90%, and relatively high TN removal of 75%. While household interviews demonstrate a significant improvement in the sanitary situation, the focus group discussions uncover existing challenges in facility management by the local association and governance barriers. The findings also indicate the importance of post-construction follow-up and systematic evaluations in rural water projects.

Keywords: participatory assessment, rural sanitation, natural based solution, French reed bed, SDG6, rural development.

Highlights

- Participatory approach with households and local stakeholders is used to evaluate the project;
- FRB system achieved strong organic pollutant removal and demonstrate its potential in arid environments;
- Interviews confirmed significant social and environmental impact;
- Focus group discussions reveal persistent management and governance issues;
- Importance of continuous technical and management follow-up to ensure long-term sustainability of rural sanitation projects.

Introduction

Access to safe drinking water and sanitation is a fundamental human need and a key target of the United Nations' Sustainable Development Goal 6, "Water and sanitation for all" (Weststrate et al., 2019; WHO/UNICEF, 2024). Despite global efforts, 2.2 billion people still lack access to safely managed drinking water, while 3.5 billion, representing approximately 44% of the world's population, do not have access to safely managed sanitation services (WHO/UNICEF, 2024). In addition, sanitation remains a critical challenge in rural areas, where limited infrastructure, expertise, and resources hinder progress toward Sustainable Development Goal 6 (Herrera, 2019).

In developing countries, despite efforts to expand domestic water supply to rural and remote villages through various development programs, improved sanitation remains a significant challenge (World Bank, 2017; WHO, 2021). For instance, in Morocco, many households commonly discharge both greywater and blackwater into shallow pits near their homes, a practice that poses direct risks to groundwater, ecosystems, and public health. In the Anti-Atlas region, where bedrock is highly fractured and the lithology is permeable, this issue is particularly concerning. Studies have identified high concentrations of coliforms and nitrates in shallow aquifers, indicating contamination risks (Danni et al., 2019; Ait El Kadi et al., 2024). More broadly, rural sanitation in developing countries suffers from a major gap in improved services, including safe wastewater collection, treatment, disposal, and reuse. Poorly designed and inadequate sanitation systems further contribute to surface and groundwater pollution, with serious public health consequences (UNEP, 2023; Cisneros et al., 2024).

To address these challenges, Morocco has launched several rural sanitation initiatives, often with support from international donors. The National Sanitation and Wastewater Treatment Program (PNA and PNAM), led by the Ministry of Interior, aims to improve wastewater management and expand sanitation coverage in suburban and rural areas (Hdidou et al., 2021). Recently, the Moroccan government announced a major national program valued at MAD 56 billion (approximately $5.6 billion) to accelerate the deployment of wastewater treatment and sanitation infrastructure nationwide, with a particular focus on underserved rural and peri-urban areas (MWN, 2025). While previous programs aimed to improve rural sanitation coverage, only a few small rural communities benefited from collective sanitation interventions. In an effort to improve the situation, the NGO Migrations & Développement (M&D) (https://migdev.org/), in collaboration with the local community and socio-economic actors, has developed an operational pilot project to enhance sanitation in two villages located in the arid Anti-Atlas Mountains. This project introduced the French Reed Bed (FRB) technology for domestic wastewater treatment for the first time in the region. This widely adopted technology in Europe is underexplored in the African context (Hdidou et al., 2021; Gholipour et al., 2022; Werkneh, 2024).

FRBs are a type of constructed wetland used for water filtration and ecosystem regeneration. This nature-based technology offers an ecological, decentralized, and cost-effective solution for the treatment of domestic wastewater in rural areas (Molle, 2014; Masi et al., 2017; Rizzo et al., 2018). They require minimal maintenance, consume little or no energy input, and can be easily integrated into isolated rural environments (Rizzo et al., 2018). Furthermore, this technology is particularly well-suited to small communities due to its simplicity and robustness (Liénard, Boutin, and Bois, 1993; Molle, 2014). It effectively reduces organic load, nutrients, and pathogens, while also enabling the reuse of treated water for irrigation purposes (Gholipour et al., 2022).

FRB technologies present various advantages; for instance, they do not require a primary treatment system, as is the case with classical constructed wetlands. Thus, FRBs enable the simultaneous treatment of both water and sludge within a single facility. Furthermore, when the implementation site allows, as in the case of the Ouijjane project, the system operates without energy input.

Despite all the advantages of FRBs, in the semi-arid North African region, this technology remains poorly implemented and under-investigated (Gholipour et al., 2022). Moreover, post-project monitoring is a key milestone for ensuring the long-term sustainability and socio-economic impact of rural development projects. Therefore, our assessment adopts a participatory approach by integrating citizens and socio-economic actors as key stakeholders in the evaluation process, conducted five years after project implementation. In doing so, this work aims to provide an inclusive assessment to improve access to better water and sanitation services (SDG 6) in rural arid regions. Furthermore, it

identifies the advantages and barriers to the adoption of this technology in the context of North African environments.

1. **Material and methods**

1.1 **Study area**

The two reed bed stations investigated in this study are located in the villages of Assaka and Akal Melloulne, within the Ouijjane area of Tiznit Province, part of the Souss Massa region (Fig. 1). The study area is part of the western Anti-Atlas Mountains, characterized by rugged topography and an arid climate. Both villages are situated along the Oued Assaka, one of the two main tributaries of the Oued Massa. The flow of the Oued Assaka is fully regulated by the Youssef Ben Tachafine Dam, located approximately 20 kilometres downstream from the villages.

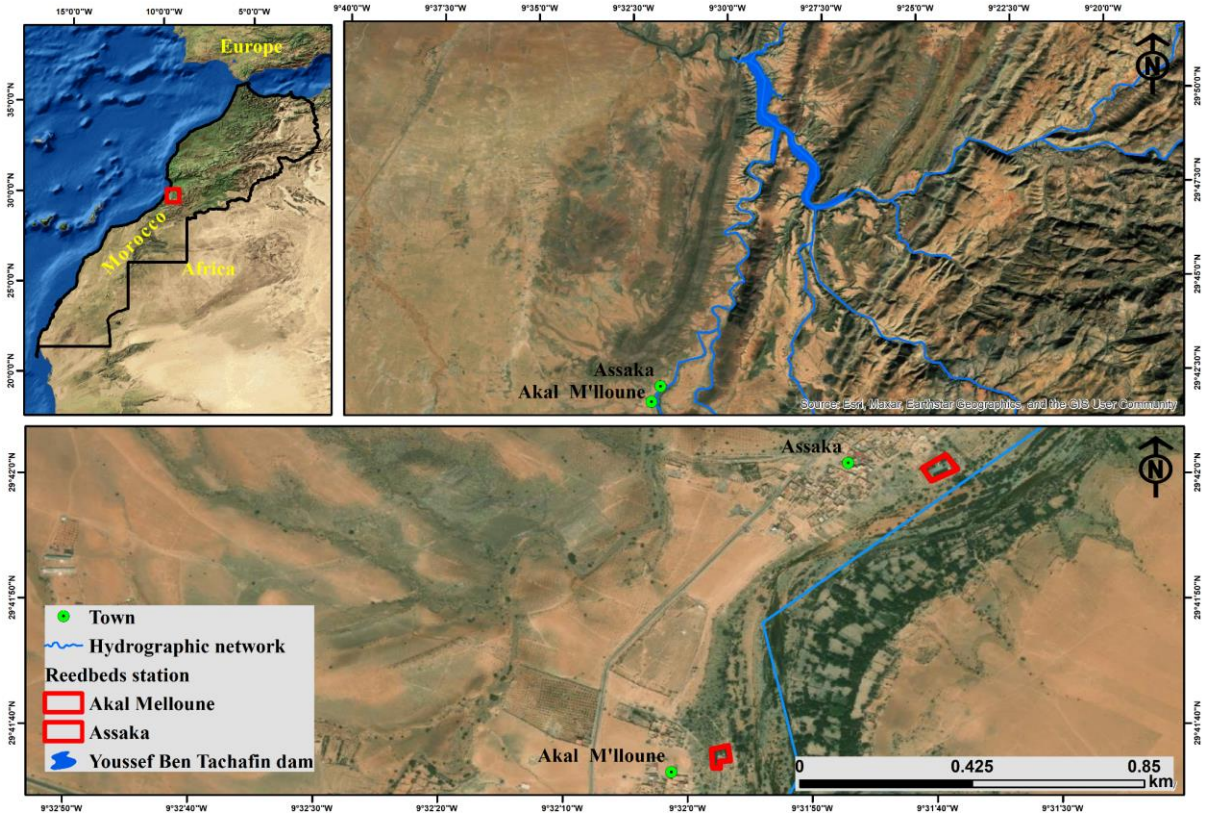

Figure 1. Geographical setting of the project

Despite the arid climate, temperatures are moderated by the combined influence of the nearby ocean and the protective barrier of the Anti-Atlas Mountains. The mean annual rainfall is about 150 mm, while the average annual temperature is 20 °C. Daily maximum temperatures can reach up to 49 °C in summer, whereas winter temperatures may drop as low as 1 °C. Relative humidity averages around 60%, and annual evaporation is estimated at 2,500 mm. Winds predominantly originate from the south or south-southeast.

Regarding domestic water and sanitation, the population is connected to the domestic water network supplied by the Youssef Ben Tachafine Dam. However, for sanitation, households use individual shallow open pits for black wastewater, while greywater is directly discharged into the village alleys. This situation threatens both public health and the Oued Assaka ecosystem. Furthermore, the discharged wastewater can easily reach the shallow aquifer and the dam reservoir downstream. This

concern was the main driver for the community and socio-economic actors, together with M&D, to develop the FRB sanitation project.

1.2 Data collection and analysis

The project was initiated in 2016 by the NGO Migrations & Développement (M&D), together with the Assaka Association, in response to the lack of improved sanitation. The technical design was carried out by an international volunteer expert (Alain Liénard) mobilized by M&D. In scientific collaboration with Ibn Zohr University, M&D provided all documentation and data for this research. The aim is to conduct a participatory assessment of the project and report the outcomes, with the goal of capitalizing on the experience and improving future projects aimed at enhancing water and sanitation both within and beyond the region. This assessment therefore integrates key project stakeholders and villagers as sources of data to evaluate the outcomes.

1.2.1 Water analyses

Due to limited funding, only six rounds of sampling were carried out at Assaka and three at the Akal Melloulne station between October 2020 and December 2021. Water samples were taken at the influent (inlet) and effluent (outlet) of the two stations to evaluate the performance of the treatment system. The analyzed parameters included temperature, pH, total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand over five days (BOD_5), and total nitrogen (TN). All samples were analyzed by a certified laboratory. Table 1 presents the parameters, analysis standards, and national limits for domestic effluents.

Parameter	Analysis standard	National limit (mg/l)
TSS	NF EN 872	150
COD	ISO 151705	250
BOD5	NF EN 1899-2	120
TN	NM ISO 5663-2001	N/A

Table 1. Measured parameters and national limit for wastewater disposal

1.2.1 Focus group

A focus group is a qualitative method used to gather in-depth insights from project stakeholders through guided group discussions. It helps explore shared experiences, perceptions, and power dynamics among actors. This method fosters stakeholder engagement and aligns with participatory research approaches (Alasuutari, Brannen, and Bickman, 2008). In our case, key project stakeholders were invited one week before the meeting. The focus group gathering was organized in Tiznit, the provincial center, which is convenient for all participants. Table 2 below illustrates the stakeholders engaged in the project and their principal duties.

Stakeholder	Role and duties in the project
Migrations & Développement (M&D) NGO	Identification of the potential, technical

	expertise, funding (International funding 79%), project management and leadership.
Association Assaka	First initiative and investigation with M&D, mobilisation of villagers, land acquisition for treatment and financial contribution (5%). Post-construction management.
Conseil provincial Tiznit	Financial contribution (13%), facilitation of administrative procedures.
Commune Ouijjane	Financial contribution (3%), coordination with stakeholders.

Table 2. Ouijjane project stakeholders

Figure 2. Focus group session with project stakeholders

The focus group session lasts for 40 minutes with three open questions:

- According to you, what is your assessment of the project from technical and management perspectives?
- What are potential current or future threats to the project?
- Do you think that scientific expertise is useful in rural development projects? According to your experience, how would this expertise be implemented in water and sanitation projects?

The focus group sessions were audio-recorded and subsequently transcribed in Arabic. The Arabic transcripts were then translated into English for analysis. To process and analyse the textual data, thematic analysis was used to identify patterns, key themes, and stakeholder perceptions. Particular attention was given to participants' views on, and willingness to collaborate with, scientists in the monitoring and evaluation of rural water and sanitation projects.

1.2.2 Interviews

A semi-structured questionnaire is used to assess the profiles of household inhabitants and their perception of the project and impact as well as their participation in rural development initiatives and scientific monitoring.

This questionnaire is composed of four sections: (1) socio-demographic; (2) Water and sanitation services; (3); Rural development initiatives (4) scientific expertise. (See supplementary material).

A total of (n=36) interviews with village households, including women (n= 15) and men (n=20). The local language (*Tachlhit*) is used by the research team to facilitate communication. Furthermore, women are interviewed by female researchers to align with local cultural values and encourage women to freely express their opinion.

1.3 Overview of the Ouijjane project

The sanitation system implemented in both villages follows three main steps. First, wastewater is collected through a separate gravity-based network that only gathers domestic wastewater. Rainwater, including runoff from roofs and drainage, is valorized through underground cisterns locally called *Tanoudfi*. This practice is widely adopted by Occidental Anti-Atlas communities. Thus, the wastewater collection system is strictly separative.

At the entrance of the FRB station, wastewater undergoes a simple screening process to remove large debris that could clog the system, followed by sand removal through sedimentation. The settled solids are manually cleaned due to the low flow velocity. Wastewater is then directed in batches using a self-priming siphon to vertical filters. This batch feeding allows for better oxygenation and distribution of the raw water across the filter bed.

The main treatment stage consists of three vertical flow filters that operate alternately. Each filter is fed for three days and then rests for six days. These filters purify the water through aerobic biological processes as the wastewater percolates through layers of fine to coarse gravel (Molle, 2014). Finally, in the third step, treated water is collected in a reuse tank and used for irrigating trees (carob, olive, and argan).

These stages are illustrated in Figure 2, while Table 3 presents key technical design characteristics of the two treatment facilities based on M&D contract specifications.

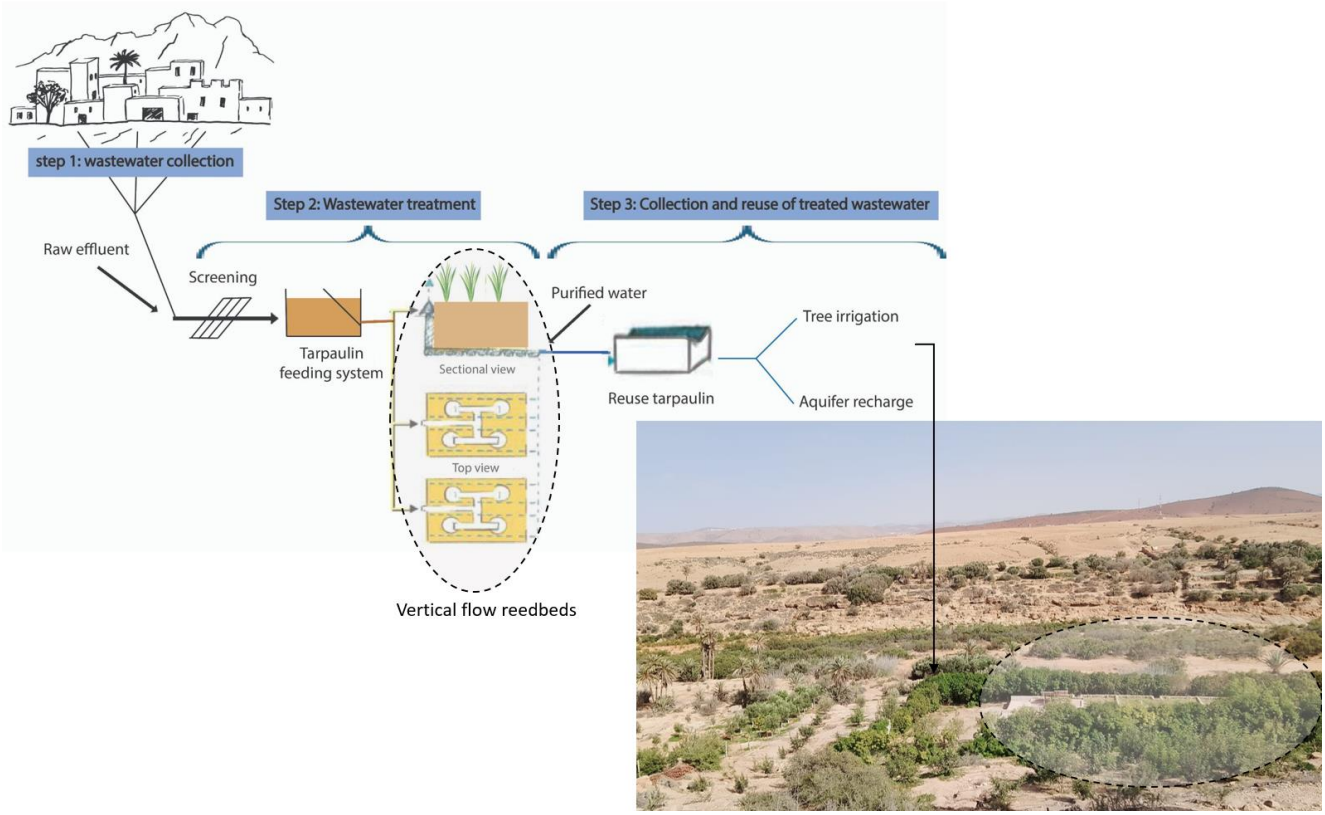

Figure 3. Simplified design of FRB sanitation system adopted in two villages (Photo: Assaka station).

Specification	Unit	Assaka	Akal Melloulne
Horizon project population	inhabitant	624	320
Design ratio	m^2/PE	0.6	0.6
Total surface	m^2	396.75	270.75
Surface of each of 3 filter	m^2	132.25	90.25
Automatic siphon dimension	m	3.25 x 2.18 x 1.45	2.5 x 1.8 x 1.45
Filter media layers (from the top)			
⌀ 3-8 mm	cm	60	60
⌀ 10-20 mm	cm	30	30
Type of plants	*Phragmites australis*		
Material of construction	Excavated in the soil, soil embankments, and armed concrete for the basins.		

Table 3. FRB key technical design characteristics (source: M&D specification contract)

2 Results

2.1 Treatment performance

2.1.1 Akal Melloulne station

Fig.4 present three analysis taken before and after treatment in different seasons (March, October and December) of 2021. These analyses include key wastewater quality parameters frequently used to evaluate the organic loads in water; Chemical Oxygen Demand (COD), Biochemical Oxygen Demand over five days (BOD_5) in addition to Total Suspended Solids (TSS), and Total Nitrogen (TN).

The results show a reduction in concentration levels after treatment. The TSS concentrations decreased from 120 mg/L to values well below discharge national thresholds of 150mg/L. For this parameter, we observe that it is under national limit even before the treatment. For COD, values declined from above 1,200 mg/L to levels below 150 mg/L and align with the national limit of 250mg/L. Regarding BOD_5, it was reduced from over 800 mg/L to less than 100 mg/L, and also align with national limit of 120mg/L. For TN, results showed a notable to moderate to relatively high reduction from approximately 150 mg/L to below 40 mg/L. These temporal patterns are supported by the calculated removal efficiencies presented in Fig.5, which show removal rates of 90% for both COD and BOD_5, 85.42% for TSS, and 75.67% for TN.

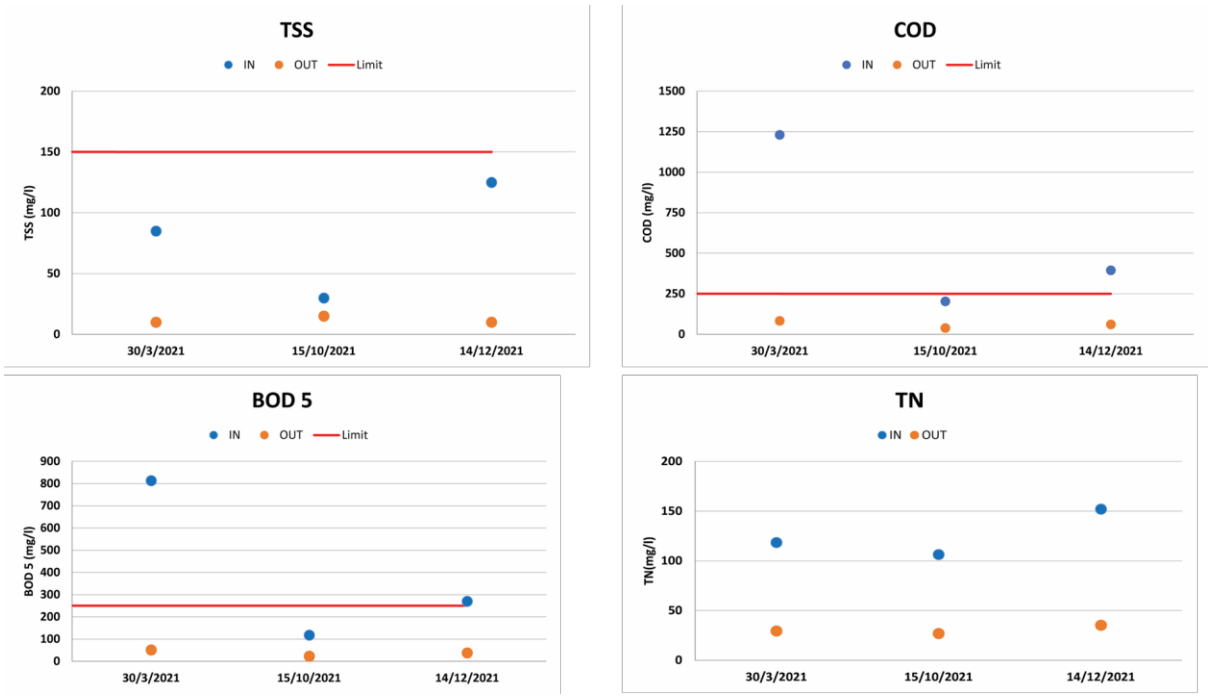

Figure 4. Temporal variation of TSS, COD, BOD_5, and TN at the inlet (IN) and outlet (OUT) of the Akal Melloulne station.

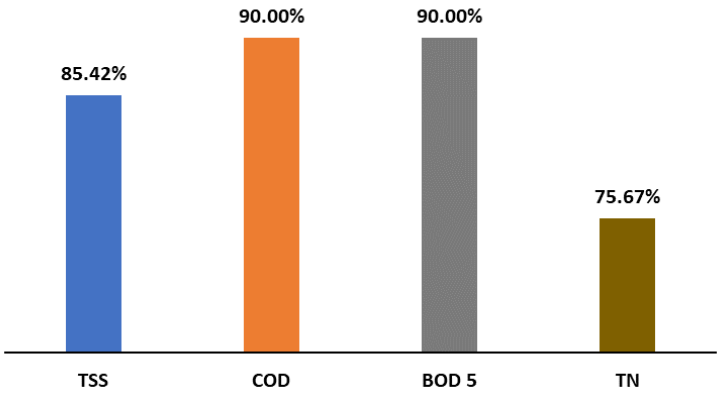

Figure 5. Removal efficiency of BOD_5, COD, TSS, and TN at the Akal Melloulne station.

2.1.2 Assaka station

Fig.6 present six analyses taken before and after treatment in different seasons covering a period between October 2020 and December 2021. These analyses include key wastewater quality parameters frequently used to evaluate the organic loads in water; Chemical Oxygen Demand (COD), Biochemical Oxygen Demand over five days (BOD_5) in addition to Total Suspended Solids (TSS), and Total Nitrogen (TN).

The results show a reduction in concentration levels after treatment. The TSS concentrations decreased from 70 mg/L to values well under 35 which is far below discharge national thresholds of 150mg/L. For this parameter, we observe the same pattern as in Akal Melloulne station: the TSS values are under national limit even before the treatment. For COD, values declined from 966 mg/L to levels below 120 mg/L and align with the national limit of 250mg/L. Regarding BOD_5, it was reduced from 480 mg/L as a maximum for the monitored period in (in October 2020) to less than 61 mg/L, and also align with national limit of 120mg/L. For TN, results showed a notable to moderate to relatively high reduction from 221 mg/L to below 68 mg/L. Therefore, for the observed period, removal efficiencies on average were 67.85% for TSS, 87.30% for COD, 85.50% for BOD_5 and 77.63% for TN (Fig.7). These values show high efficiency in the removal of organic pollutants, particularly COD and BOD_5, with good performance in the removal of suspended solids and total nitrogen.

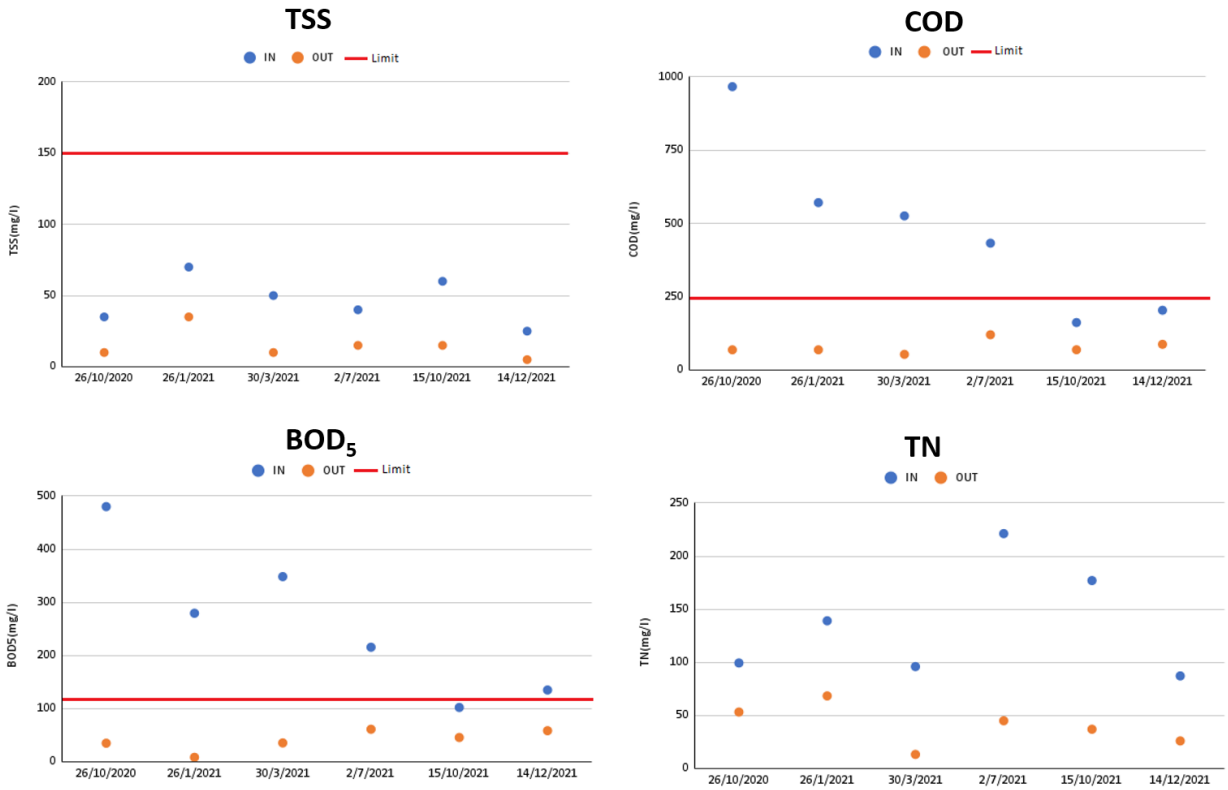

Figure 6. Temporal variation of TSS, COD, BOD_5, and TN at the inlet (IN) and outlet (OUT) of the Assaka station.

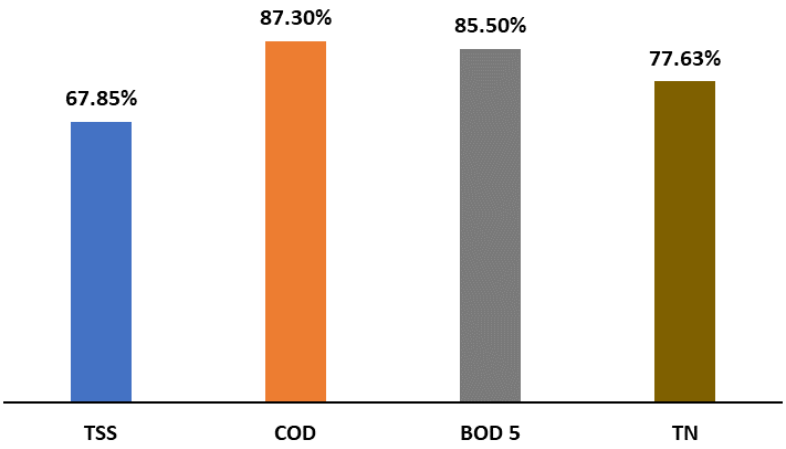

Figure 7. Removal efficiency of BOD_5, COD, TSS, and TN at the Assaka station.

2.2 Focus group and interviews

2.2.1 Focus group

Our analysis of the focus group data reveals three principal themes: (1) technical execution of the project; (2) mismanagement and governance issues; and (3) advancing researcher–local actor collaboration.

At the technical level, the implementation of the project was generally well received by participants, despite some unforeseen issues such as challenges in laying out the network or acquiring the land

for the treatment plant. The president of the Assaka Association noted: “Despite technical issues, our collaboration with M&D and local authorities facilitated administrative procedures, while the competence of the supervising engineer and the construction company allowed adjustments to the initial plans to fit the new configuration.”.

Regarding management, once construction was completed, competition emerged between social groups in the two villages. This ultimately resulted in the Akal Melloulne station being managed by an association from the village that had not been involved in the project's planning or execution. According to the M&D representative: “Since they changed the agent, we have reported several cases of mismanagement. The agent does not respect the 3/6-day feeding and resting schedule for each filter. We interacted and explained how this simple operation works, but I feel there is some negligence.”

All stakeholders emphasized the crucial importance of the financial contribution of the local community to various rural development projects, including sanitation and domestic water. The representative of the provincial council argued: “In these projects, the 5% contribution of the targeted community is recommended by international donors. As they say, ‘Everything you do for me, without me, is against me.”. Initially, a contribution of 5 MAD ($0.50) per month was proposed by the Assaka Association, but people complained and eventually refused to pay. Later in the discussion, the president of the Assaka Association and the representative of the Ouijjane commune revealed that false promises made to the community by some political candidates were at the core of the opposition to paying the contribution. The president of the Assaka Association also reported that an annual small grant of 5,000 MAD ($500) from the commune had previously been provided to support management, but this funding is no longer granted by the new executive board of the Ouijjane commune.

For the reuse effort, at the beginning, the association planned to develop a plant nursery, but the lack of vision and, especially, an adequate business model led to the decline of this plan. As reported by the president of Assaka association:

> “There was an initiative at the beginning to valorize the treated water by creating a plant nursery. The association volunteers started the reuse project and planted the reeds to be used in the Akal Melloulne and Ameln stations (villages at 90 km). Later on, the volunteering movement lost enthusiasm as we couldn’t find a strategy to make the reuse activity profitable, at least to provide a decent wage for young workers.”

Participants emphasized the importance of scientific expertise in rural development projects. However, some misunderstandings may arise between researchers and local actors, as expressed by one of the participants:

> “No one can deny the importance of scientific research. But I think that researchers focus on their problems, which are sometimes not exactly the community’s. We have heard several times about the integration of the university into its socio-economic context, but in reality, there are many divergences between what the community needs and what research

delivers. Also, local people need some level of simplification to understand scientific research and its tangible impact."

The participants stressed the need to monitor the quality of wastewater discharges at the treatment plants in order to better control their impact on the ecosystem and develop viable reuse strategies. In this regard, the agreement between M&D and Ibn Zohr University was welcomed, along with suggestions to improve monitoring frequency, particularly through the establishment of a multi-stakeholder partnership including village associations and the Ouijjane commune. A follow-up meeting is proposed with a technical and financial proposal for the convention.

2.2.2 Interviews

The socio-economic profile of residents in the surveyed communities (Fig. 7) reveals an aging demographic, with 36.1% of respondents aged over 60. Most villagers (86.1%) are permanent residents, while a minority consists of seasonal migrants who typically return during summer holidays and religious celebrations. Livelihoods are predominantly based on agriculture and livestock farming (42%), reflecting a strong dependence on primary sector activities.

According to the interviews, the permanent population of the villages is dominated by women and elderly men. While women expressed their willingness to participate in Income Generating Activities (IGA), they also reported the failure of some initiatives due to mismanagement or unclear vision. A portion of the elderly men are retirees from France, as first- or second-generation members of the Moroccan diaspora. This group expressed their attachment to the village, and some have started small agri-livestock initiatives.

All interviewees agreed on the issue of water scarcity since the blockage of the Oued Assaka channel (locally called Targua) upstream. In this regard, we observed several dried-out trees (almond, carob, olive, and argan) and small uncultivated plots along the Oued Assaka. This channel used to be managed jointly by several villages and is now blocked upstream. Since this research focuses on the sanitation project, we decided to explore the channel issue in a separate investigation.

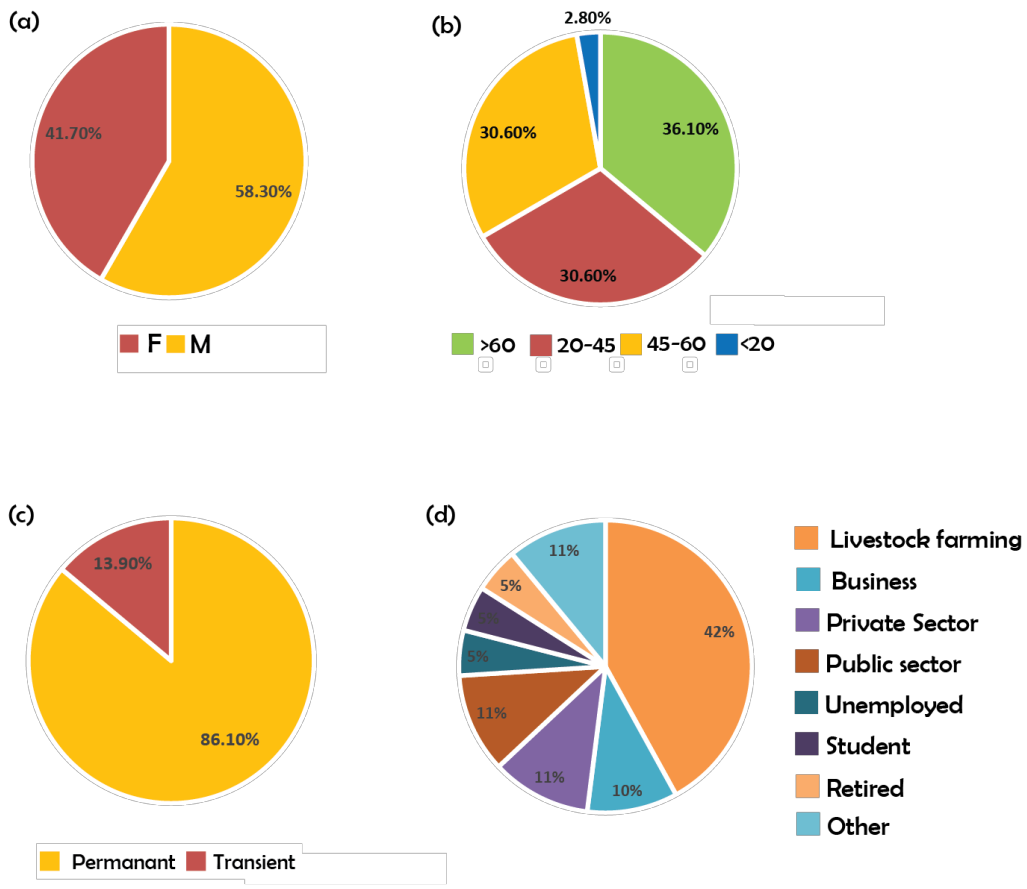

Figure 8. Socio-demographic characteristics of interviewees: (a) gender distribution; (b) age group distribution; (c) residential status and (d) source of income.

Access to basic infrastructure is notably high, with 97.22% of households connected to the drinking water network and 94.29% to the sanitation system. These results confirm the statements made by project stakeholders during the focus group session. Nonetheless, challenges such as low water pressure and low flow were reported by some interviewees. Only 26.5% of residents reported being members of cooperatives, associations, or other income-generating activities. In addition, about 88% of interviewees expressed their willingness to participate in community-based initiatives, and many indicated a strong willingness to collaborate with researchers in research-action projects.

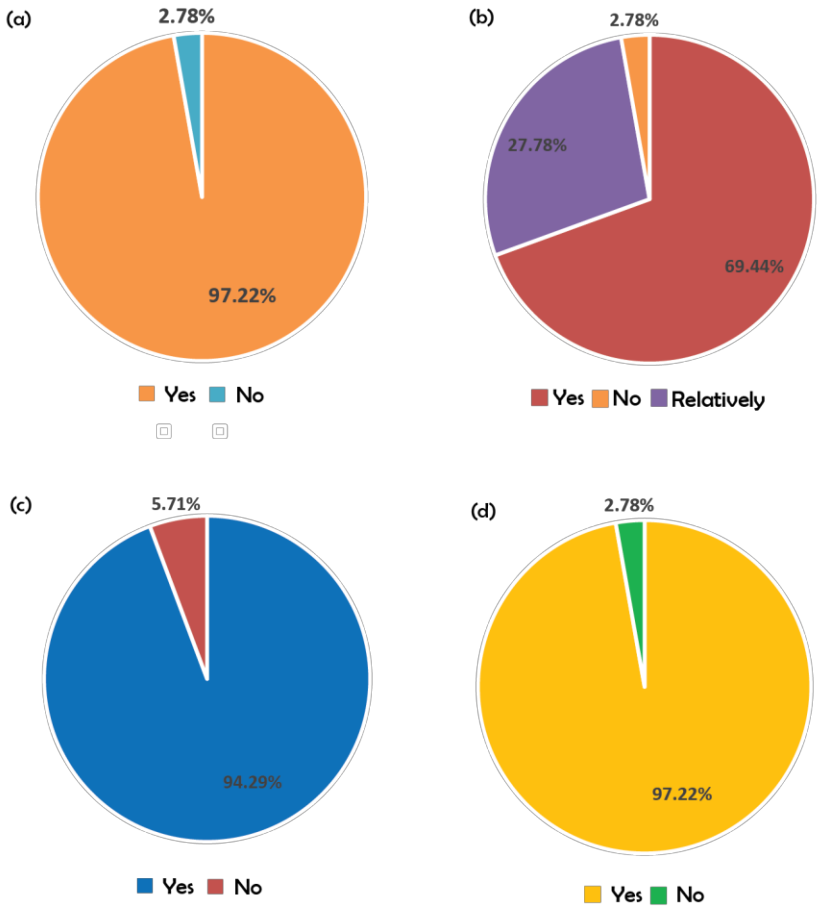

Figure 9. Water and sanitation service coverage and user satisfaction interviewees: (a) connection to the drinking water network; (b) satisfaction with the drinking water service; (c) connection to the sanitation network; and (d) satisfaction with the sanitation service.

When asked about priorities and messages to researchers and rural development stakeholders, interviewees emphasized several crucial needs. The search for solutions to water scarcity was the most frequently reported concern, particularly to support subsistence agriculture and livestock. Many highlighted the importance of viable and profitable income-generating activities, alongside training in their management and basic literacy programs. The need for regular monitoring of water quality, covering aquifers, household supplies, and treated wastewater, was also stressed. Inadequate solid waste management remains a concern for villagers, as does the call to improve the overall quality of household water.

3 Discussion

3.1 Reed beds performance and potential reuse in arid environments

Overall, for the monitored period, the findings suggest that the single-stage FRB system is effective in removing biodegradable organic matter at both the Assaka and Akal Melloulne stations. These early monitoring results reveal high treatment efficiency, particularly for key indicators of organic pollution such as Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD_5), and Total Suspended Solids (TSS), with removal rates exceeding 90%, 85%, and 90%, respectively. Total Nitrogen (TN) removal was more moderate, averaging around 75%. Notably, the Akal Melloulne station slightly outperformed Assaka, particularly in reducing suspended solids, suggesting that localized factors such

as flow variability or vegetation density may influence performance, highlighting the need for regular monitoring and adequate maintenance.

These findings align with results from similar constructed wetland systems in Mediterranean regions, where warm climates and extended photoperiods support effective biological treatment processes. In southern France, for example, Molle et al. (2005) documented organic matter removal efficiencies above 85% using horizontal subsurface flow wetlands. Comparable performances have been reported in other Mediterranean contexts, where reductions in TSS, COD, and BOD_5 often exceed 80% (Rizzo et al., 2018; Bouchama, 2022). However, nitrogen removal remains a common challenge in Mediterranean systems, often constrained by limited denitrification under warm, oxygen-poor conditions a pattern mirrored in the Ouijjane systems.

The broader significance of these results extends to North African countries facing increasing water scarcity, rural sanitation gaps, and energy constraints. These countries share similar agro-climatic conditions and rural development challenges. The Ouijjane FRB project operates energy-free and aligns closely with the Water-Energy-Food-Ecosystem (WEFE) nexus by offering synergistic benefits across all four sectors (Kataki et al., 2021; Gholipour et al., 2022). By treating wastewater without external energy inputs, the project reduces pressure on the energy system while enabling water reuse for irrigation of key crops (e.g., argan and carob) that serve local communities as both food and income sources (Barkaoui et al., 2022).

In the occidental Anti-Atlas, communities largely depend on family farming and small semi-intensive livestock as primary sources of income (see Fig. 7). In this context, the reuse of treated wastewater emerges as a valuable opportunity to enhance agricultural productivity and climate resilience. In the village of Assaka, the local association initiated a pilot project to reuse treated effluent for irrigating drought-resilient tree species such as carob, olive, and argan. An earlier effort to establish a plant nursery in the same area was discontinued due to limited economic feasibility and insufficient training and technical support. These experiences highlight the critical importance of post-project follow-up, long-term capacity building, and robust assessment of the socio-economic viability of rural development interventions (World Bank, 1988; Nickel et al., 2018).

At the national level, the absence of a specific regulatory framework for wastewater reuse in agriculture remains a major barrier to scaling up such initiatives. The lack of standardized guidelines on water quality thresholds, permissible uses, and risk mitigation limits the integration of treated effluent into farming systems despite some pilot experiences (Hdidou et al., 2021). Moreover, effective reuse requires routine monitoring, particularly of nutrient loads, salinity levels, and pathogenic risks, to safeguard both crops and public health (Malki et al., 2017; Hdidou et al., 2021; Mansir et al., 2024).

3.2 Social and environmental impact

According to the assessment conducted by Migrations & Development (M&D) prior to implementation, the introduction of domestic water supply in 2014 led to a significant increase in water consumption and, consequently, in wastewater generation. At that time, villagers reported that blackwater was disposed of in shallow pits, while greywater was often discharged directly into village alleys. This practice resulted in serious sanitary and environmental issues, including the proliferation

of mosquitoes in stagnant wastewater, unpleasant odors, and heightened risks of waterborne diseases (M&D, 2020).

Five years after project implementation, our field investigation reveals a marked improvement in local sanitation conditions. Both community members and institutional stakeholders expressed strong satisfaction with the outcomes (Fig. 8). Residents reported a safer and cleaner living environment, with a notable decline in public health concerns previously linked to unmanaged wastewater. The establishment of a sanitation network significantly reduced the physical and financial burden of manually emptying filled pits previously used for individual wastewater discharge. This shift also alleviated environmental degradation in public spaces. Importantly, women who previously carried heavy laundry near distant wells highlighted the convenience and dignity gained from improved in-house sanitation infrastructure.

Regarding environmental impact, in the arid context of the Anti-Atlas, FRB sanitation systems provide multiple environmental benefits. They reduce the direct discharge of untreated wastewater into fragile ecosystems, thereby protecting soils and watercourses from contamination. The reuse of treated effluent supports the irrigation of drought-resistant trees, enhancing vegetation cover and combating desertification. These systems also promote groundwater recharge through slow percolation. Previous reuse pilot experiences in the region have shown promising results with valuable crops such as olive (Mansir et al., 2024).

Fig. 9 summarizes the spatial arrangement of operational decentralized reed bed stations at Akal Melloulne and Assaka, located along the Assaka Wadi. Treated wastewater from the stations presents potential for reuse in irrigating agroforestry smallholdings with endemic species, particularly drought-resistant species such as olive, carob, and argan, thereby contributing to local agroecological resilience. Percolation from these reuse zones supports gradual aquifer recharge, offering a nature-

based contribution to groundwater. The photos (a and b) illustrate the transformation of degraded spaces into productive, green landscapes around two stations.

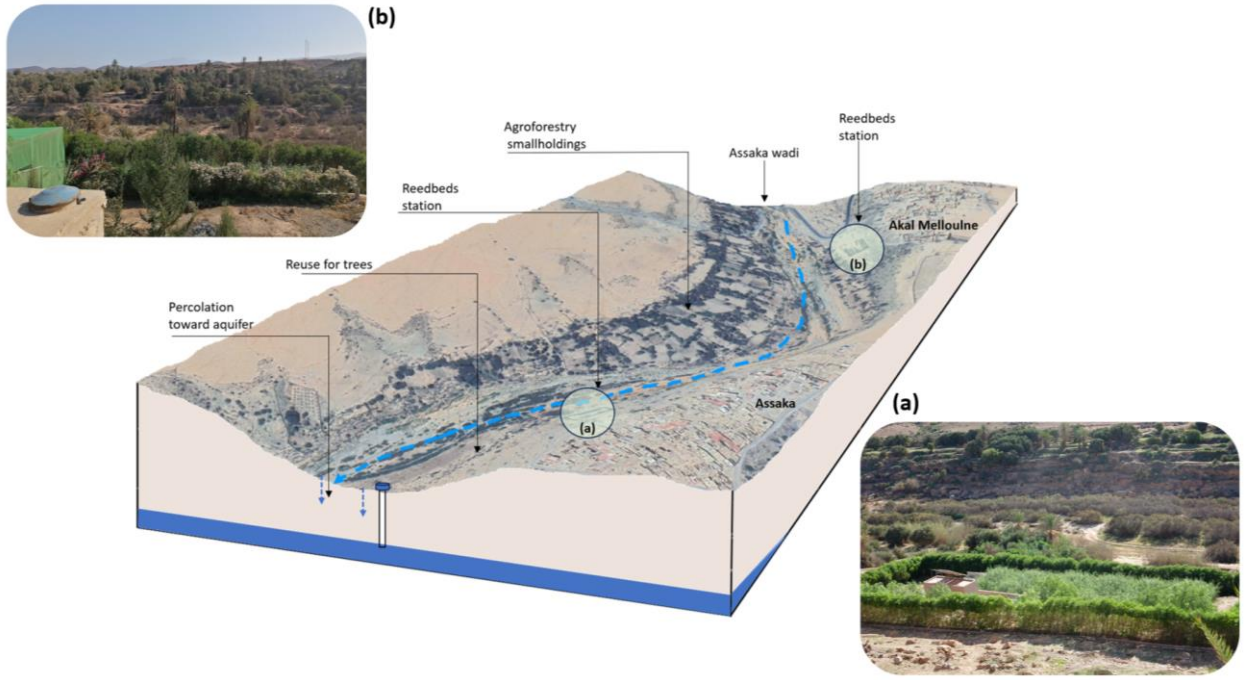

Figure 10. Conceptual model of Ouijjane project and its socio-environmental services

3.3 Governance challenges

Although M&D conducted practical training sessions for the Assaka association on the management of treatment plants, field observations reveal some mismanagement practices. For instance, the association does not use a reporting manual to document routine checks, number of feedings and maintenance operations, as recommended by the guide produced by M&D and translated into Arabic to facilitate monitoring. At Akal Melloulne, findings reveal rising social competition between the two villages, primarily driven by political interests to gain leadership positions in provincial and communal councils. These tensions threaten the sustainability of the treatment plant. Although the Akal Melloulne association designated an agent to oversee the facilities, this individual did not receive practical training for daily monitoring and maintenance operations. Furthermore, the lack of funding undermines the durability of both facilities. The Assaka association reported that they previously received a small annual grant of USD 500 from the commune for facility management; however, following a change in commune leadership in 2021, this grant was no longer provided due to change in the commune leadership. Such funding is therefore highly vulnerable to political tensions and broader water resource governance crises (Bergh and Phil, 2009; Khadra and Sagardoy, 2019).

Under Moroccan regulation, multiple actors intervene in the domestic water and sanitation sector. These include the Hydraulic Basin Agency as basin water coordinator; provincial and regional authorities (Ministry of Interior), which finance large programs such as PAGER, INDH, and PNAM; Regional Multi-Service Societies, recently created as competent actors in water distribution and sanitation; ONEE-Eau, a public enterprise managing domestic water production; and local communes, responsible for water and sanitation within their territories. Due to the limited capacity of rural

communes to manage domestic water and sanitation projects, concessions are often granted to local associations created specifically for this purpose. In this regard, the CESE (Conseil Économique, Social et Environnemental: https://www.cese.ma/) recognizes that "the multiplicity of stakeholders has become a constraint to effective water governance at the national, regional, and local levels" (CESE, 2014, p. 35). Institutional fragmentation is widely reported as a barrier to effective governance in both national and global contexts (Bergh and Phil, 2009; Kim, Keane, and Bernard, 2015; Lukat et al., 2023). At the local level, the main challenges facing associations responsible for managing rural domestic water and sanitation services include deficiencies in technical and managerial skills, as well as limited funding. Field experience also reveals that political interference significantly affects project outcomes. For example, some locally elected elites use these associations as platforms for political gain. By securing positions within the executive bureau, they often prioritize supporters, allowing them to access water services without payment for extended periods. This results in financial deficits and an inability to manage facilities or carry out required maintenance. Such free-riding pattern has undermined the sustainability of several rural water projects, despite significant state investments through programs such as PAGER and INDH. Previous studies have highlighted how the lack of enforcement in local water projects contributes to free-riding and poor cost recovery (Whittington et al., 2009; Komakech and Van Der Zaag, 2013).

Despite increasing national commitments to rural sanitation, significant governance and capacity gaps continue to limit the long-term impact of public investments. Under Morocco's ongoing program (PNAM: Plan National d'Assainissement Mutualisé), the state continues to subsidize rural sanitation projects by up to 70%, with a ceiling of 7 million MAD (approximately USD 771,000) per project. While these subsidies reflect a strong policy commitment to improving sanitation access in under-served areas, the sustainability of many implemented projects remains in question. A major constraint lies in the underestimation of non-technical dimensions of sanitation delivery. Although a substantial portion of PNAM funds is allocated to engineering studies and infrastructure contracts, relatively little attention is given to capacity building and community-level monitoring. In practice, the absence of locally embedded technical expertise and weak managerial structures often results in inadequate operation and maintenance of systems, particularly in small or dispersed rural areas. Moreover, the top-down nature of project planning, heavily focused on infrastructure delivery, excludes participatory governance, which is essential for community ownership and accountability (Tribbe et al., 2021). Without building technical and managerial capacity in local communes and user associations, the likelihood of system failures, poor performance, and reduced public trust increases (Chumbula and Massawe, 2018). Sustainable rural sanitation, as part of SDG 6, therefore requires a more balanced approach, where construction investments are matched by efforts to strengthen daily management, effective governance, and community engagement.

Conclusion

The Ouijjane FRB project demonstrates the technical viability and socio-environmental relevance of reed bed sanitation in rural arid environments. High removal efficiencies of organic pollutants indicate the potential of low-cost, energy-free nature-based solutions (NbS) to address sanitation gaps in water-scarce areas of the Anti-Atlas and other similar dry environments. Importantly, these outcomes resonate with Mediterranean and North African contexts, where climate conditions and rural livelihoods share comparable constraints and opportunities.

Beyond treatment performance, the reuse of treated effluent for irrigating drought-resilient agroforestry species (e.g., argan and carob) highlights the contribution of FRBs to local food production and ecosystem restoration. The project outcomes align with the Water-Energy-Food-Ecosystem (WEFE) nexus paradigm and support progress toward SDG 6 (Clean Water and Sanitation) and SDG 15 (Life on Land).

Despite this potential, the sustainability of rural sanitation projects cannot rely on infrastructure alone. The findings reveal that the project continues to face enduring governance challenges, including institutional fragmentation, the absence of regulatory frameworks for agricultural reuse, and limited post-project support. Furthermore, local political tensions remain a threat to the long-term durability of such investments.

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