Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

ISSN (O): 2320-5407
ISSN (P): 3107-4928

Article DOI:10.21474/IJAR01/23911
DOI URL: http://dx.doi.org/10.21474/IJAR01/23911

RESEARCH ARTICLE

REUSE OF TREATED WASTEWATER (TWR) FOR SUSTAINABLE AGRICULTURE IN THE SAHEL: A BIBLIOGRAPHIC SYNTHESIS

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Manuscript Info

Manuscript History
Received: 18 May 2026
Final Accepted: 20 June 2026
Published: July 2026

Abstract

In the face of an unprecedented global water crisis, exacerbated in the Sahelian zone by profound sanitation deficits, the reuse of treated wastewater (TWR) stands out as an indispensable circular-economy strategy for sustaining urban and peri-urban market gardening. This bibliographic synthesis examines TWR as an integrated value chain articulating effluent management, health safety, and agronomic sustainability. Technologically, the transition from conventional treatment to water suitable for raw horticultural irrigation requires advanced tertiary processes—membrane filtration, UV-C disinfection, or Nature-Based Solutions (NbS). These processes aim at the strict elimination of pathogens (bacteria, helminths) in compliance with WHO standards or EU Regulation 2020/741. Agronomically and economically, TWR provides a stable nutrient solution rich in nitrogen, phosphorus and potassium, enabling smallholders to reduce mineral fertiliser purchases by 40–60 % while increasing yields by 25–35 %. However, long-term viability depends on controlling critical risks: secondary soil salinisation, sodium-induced structural degradation, and bioaccumulation of toxic trace metal elements (TME) in the food chain. Finally, TWR deployment in the Sahel requires overcoming the 'disgust factor' through transparent community approaches, formalising still-incomplete national legal frameworks, and favouring decentralised management models adapted to local socioeconomic capacities.

Introduction: -

The world is confronted with an unprecedented global water crisis (ONU-INWEH, 2026), characterised by consumption progressively exceeding natural renewal capacity. Nearly three-quarters of the world population live in

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zones affected by water insecurity, a situation aggravated by the decline of more than 70 % of the main global aquifers (UN-Water, 2026). Between 2000 and 2025, annual per-capita freshwater availability fell by over 20 % globally, reaching nearly 30 % in particularly vulnerable regions such as North Africa and West Asia (FAO, 2021; 2025).

In the Sahelian region, this global vulnerability is compounded by structural sanitation deficits: the rate of safely managed sanitation remains below 25 % in urban areas and falls drastically in rural zones (WHO/UNICEF, 2024). Niger perfectly illustrates these dynamics: despite significant underground reserves and the Niger River basin, the spatio-temporal distribution of the resource is highly asymmetric, and the territory is heavily affected by climatic variability. Urban and peri-urban market gardening constitutes a vital socioeconomic pillar, supplying fresh products to urban markets and generating income for smallholders (FAO, 2023; AGRHYMET, 2025), yet it faces growing pressure for quality water.

Faced with these challenges, recourse to non-conventional water resources appears unavoidable. Treated wastewater reuse (TWR) emerges as a durable strategy allowing a reduction in pressure on conventional water resources while valorising nutrients—nitrogen (N), phosphorus (P), and potassium (K)—fully aligned with Sustainable Development Goals at the 2030 horizon (IAEA, 2025). The central scientific question addressed in this review is: How can TWR contribute to sustainable market-garden agriculture while limiting environmental and health risks?

Regulatory and Theoretical Framework:-

The WHO framework relies on risk assessment and management rather than rigid limit values. For unrestricted horticultural irrigation, WHO recommends $\leq 10^3$ E. coli /100 ml, coupled with strict helminth-egg control ($\leq$ 1 egg/litre). This 'multi-barrier' approach recognises that safety does not rest solely on the treatment plant but also on post-irrigation practices—pre-harvest intervals, vegetable washing, and peeling—providing flexibility adapted to developing-country contexts (WHO, 2006).

EU Regulation 2020/741, in force since June 2023, defines four quality classes (A–D). For Class A—raw-consumption market gardening—thresholds are stringent: E. coli $\leq$ 10 CFU/100 ml, turbidity $\leq$ 5 NTU, suspended solids $\leq$ 10 mg/L. ISO standard 16075-2:2020 integrates chemical quality criteria—electrical conductivity and sodium adsorption ratio (SAR)—to prevent salinisation of horticultural land.

At continental level, the African Union through AMCOW promotes the African Water Management Strategy (2016–2025), encouraging harmonisation of microbiological criteria on the WHO multi-barrier model. ECOWAS (2021) insists on integrated water resource management (IWRM) and the valorisation of urban effluents for peri-urban agriculture. Niger's legal arsenal—Water Code (Ordinance No. 2010-09) and PAGIRE 2017–2030—explicitly identifies TWR as a strategic option for market gardening, though the absence of implementing decrees on microbiological standards obliges the country to rely on WHO guidelines for its pilot irrigation projects (Ministry of Hydraulics, 2024).

Evolution of Treatment Technologies:-

Transitioning from conventional to market-gardening-grade water requires a major technological step. Conventional wastewater treatment plants (activated sludge—secondary treatment) protect the natural environment but do not guarantee the sanitary safety required for crops consumed raw. EU Class A compliance mandates systematic tertiary treatment or a polishing step (EU, 2020).

Among advanced technologies, membrane filtration—ultrafiltration (UF) and membrane bioreactors (MBR)—provides an absolute physical barrier against pathogens, producing water of constant microbiological quality independent of inlet load variations (Zitouni et al., 2024). However, high energy demands and membrane fouling costs limit adoption to high-value economic zones. UV-C disinfection, well documented for its efficacy, generates no toxic by-products, unlike chlorination, thereby preserving sensitive horticultural plant physiology (Ghernaout&Elboughdiri, 2025). An emerging trend (2020–2026) favours Nature-Based Solutions (NbS)—vegetated discharge zones and tertiary lagooning—which, while less high-throughput, provide complementary polishing and foster local biodiversity. Under Sahelian conditions, NbScapitalise on strong solar irradiation as a natural UV disinfection resource, with simple local maintenance. Their primary limitation is high evaporation loss.

Table 1. Comparative analysis of treatment technologies and Sahel adaptability.

Technology	Investment & Operation Cost	Treatment Efficacy	Sahel Adaptation
Membrane Filtration (UF/MBR)	High – energy, membrane replacement, technical expertise	Excellent – absolute barrier against viruses, bacteria, parasites	Low–moderate: sand fouling risk; unstable power grid; rare local expertise
UV-C Disinfection	Moderate–high – power consumption, lamp replacement	Very good on bacteria/viruses if upstream turbidity is very low	Moderate: requires rigorous upstream treatment; sensitive to power cuts without solar backup
Nature-Based Solutions (NbS/Lagooning)	Low – reduced infrastructure, simple maintenance, no chemical inputs	Moderate–good – depends on retention time and climate	Excellent: capitalises on Sahelian solar radiation for natural disinfection; simple local upkeep

Economic and Agronomic Impacts:-

TWR provides a stable nutrient-rich irrigation solution that restructures operational costs for horticultural farms, primarily through input savings. Based on FAO (2021) regional syntheses, reductions in mineral fertiliser purchases (40–60 % overall) lower the cost of production per growing cycle by 30–45 %, thereby increasing financial viability. Displacement of deep pumping also reduces energy costs by 20–30 % compared with conventional boreholes subject to continuous water-table drawdown (pS-Eau, 2022).

Agronomically, continuous TWR irrigation yields 25–35 % higher outputs for market-garden crops (onion, tomato, cabbage) owing to immediate bioavailability of ammoniacal nitrogen and dissolved organic matter, and 20–30 % biomass gains for cereal and fodder crops. The constant flow of treatment stations decouples production from rainfall variability, securing up to three cropping rotations per year and guaranteeing uninterrupted supply of fresh produce to urban markets. At the macroscale, TWR substitutes potable water extracted from slowly renewing aquifers, directly preserving strategic freshwater reserves (pS-Eau, 2022). Regular organic inputs improve sandy soil porosity and water-retention capacity, creating a local barrier against desertification (Abdou *et al*., 2026).

Environmental Impacts: A Fragile Balance:-

While TWR offers undeniable water-resource benefits, three major threats to soil health must be managed rigorously. Trace metal element (TME) accumulation: prolonged irrigation with even partially treated wastewater leads to the progressive accumulation of cadmium, lead, and chromium in the topsoil. Unlike organic compounds, heavy metals are not biodegradable and accumulate irreversibly in surface horizons (Eurofins Biomnis, 2025). They are subsequently absorbed by crop roots, posing direct plant-phytotoxicity risks and human health hazards through food-chain bioaccumulation (CIHEAM, 2024).

Secondary salinisation: treated wastewater often contains elevated concentrations of dissolved salts (chlorides, sulphates). Where evapotranspiration exceeds water input—as is typical in the Sahel—these salts crystallise in the root zone, increasing osmotic pressure and impairing plant water uptake (FAO, 2025). This phenomenon currently affects over 10 % of cultivated surfaces worldwide and can reduce yields by up to 25 % (Veille CEP, 2025).
Sodium-induced structural degradation (sodisation): accumulation of sodium ions (Na^+) provokes dispersion of clay particles, rupturing soil aggregates (Encyclopédie de l'environnement, 2024). The resulting pore clogging drastically reduces air and water permeability, causing compaction, asphyxiation of microorganisms, and increased runoff and erosion risk (AFES, 2023). Additionally, the introduction of residual antibiotics and personal-care products exerts selective toxic pressure on soil microfauna, reducing decomposition capacity (CNRS, 2025), while TME accumulation in microfauna tissues disrupts higher trophic chains and soil ecosystem health (IRD, 2024).

Social and Health Impacts:-

Agricultural workers represent the most directly exposed group: cutaneous contact and inhalation of aerosols charged with pathogenic bacteria (Salmonella, E. coli) or enteric viruses increase the incidence of diarrhoeal and respiratory diseases; helminth eggs are particularly resistant to conventional treatment processes (WHO, 2025). For consumers, the main risk lies in consuming raw vegetables irrigated with contaminated water—pathogens can

adhere to plant surfaces or internalise in tissues, rendering domestic washing insufficient (EFSA, 2025). The 'One Health' approach, interconnecting human, animal, and ecological health, is now central to managing these risks.
Acceptability constitutes the most complex barrier to TWR generalisation. The 'disgust factor' (yuck factor)—a visceral aversion related to the water's origin—remains prominent. Studies in Tunisia and Morocco (2020–2025) show that acceptability is high for urban uses (golf courses, green spaces) but falls sharply for market-garden crops consumed raw (Ameskur et al., 2023). In the Sahel, particularly in peri-urban Niamey, farmers express strong reluctance to handle water explicitly labelled as 'treated wastewater', preferring river or well water despite its biological degradation (Abdoulaye & Issa, 2024). Lack of technical literacy amplifies distrust of state infrastructure.
Israel's model—recycling nearly 90 % of wastewater for agriculture, with extremely high public acceptance—demonstrates that massive investment in advanced (tertiary/quaternary) treatment eliminates the root cause of negative risk perception by offering technically flawless, standardised, economically advantageous water (Zaier et al., 2024). The key lever is transparency and participatory demonstration: pilot farms that show tangible economic benefits transform perceptions from 'waste' to 'valorisable resource' (IAV Hassan II, 2025).

Table 2. Synthesis of main pathogens and exposure routes.

Pathogen	Associated Disease	Main Transmission Route
Escherichia coli / Salmonella	Diarrhoea, severe gastroenteritis	Consumption of poorly washed raw vegetables; direct contact
Hepatitis A virus / Norovirus	Acute viral hepatitis, epidemic gastroenteritis	Ingestion of contaminated water or soiled food
Helminths (intestinal worms)	Intestinal parasitoses, anaemia	Direct contact with soil or water; handling without PPE
Multidrug-resistant bacteria (MDR)	Complex community infections	Transfer via food chain to human microbiome

Research Gaps and Structural Challenges:-
Despite advances projected to 2026, several significant research gaps persist, particularly for the Sahel context. Globally: (1) the 'cocktail effect' of pharmaceutical residue mixtures and emerging contaminants in soils remains poorly characterised (CNRS, 2025; Académie des Sciences, 2024); (2) mechanisms of antimicrobial resistance gene transfer from irrigation water to endophytic bacteria and thence to the human microbiome are incompletely elucidated (The Lancet Microbe, 2024); (3) nanoplastics (< 1 µm) represent a quasi-unexplored frontier with potential for root absorption and bioaccumulation in edible plant parts (EFSA, 2025).

For the Sahel specifically: (i) kinetics of salt and TME accumulation under extreme evapotranspiration rates, which lack temperate-zone leaching, need multi-decade predictive models (FAO, 2025); (ii) impacts of continuous moisture and organic loading on endemic soil microfauna adapted to seasonal dormancy cycles remain unknown; (iii) airborne contamination by helminth eggs transported in Harmattan dust from irrigated soils constitutes a major underinvestigated public health risk (Institut Pasteur de Dakar, 2025).

Structural constraints compound these scientific gaps: a critical shortage of reference laboratories capable of quantifying micropolluants in capital cities; insufficient high-resolution hydrogeological data on shallow aquifer dynamics; and weak institutional capacity—outdated legislation, insufficient trained inspectors, and consequent unchecked informal irrigation practices (WASCAL, 2024; ECOWAS, 2025).

Integrated Management Models Adapted to Developing Countries:-
For developing countries, and particularly arid zones such as the Sahel, management models replicated from Northern countries often fail due to cost and technical complexity. The viable alternative combines three complementary pillars. Decentralised management with Nature-Based Solutions: small treatment units at neighbourhood or village scale reduce pumping costs, enable direct peri-urban market-garden reuse, and are manageable by local communities without dependence on a failing national infrastructure. Lagooning and planted-reed filters require minimal energy and skilled maintenance (World Bank, 2025).

Multi-barrier field management: rather than targeting pure water at the plant outlet—often unattainable—the model integrates field-level practices: selection of low-risk crops (fruit trees over leafy vegetables), pre-harvest irrigation cutoffs to allow natural UV inactivation of pathogens, and drip-irrigation to prevent contact with foliage. Sahelian solar irradiation is a free, abundant disinfection resource (WHO Africa, 2024). Participatory governance and Waste-to-Value economics: Water User Associations (WUAs) participate in decision-making and quality monitoring. Cost recovery relies not solely on tariffs but on valorisation of by-products—sale of treated sludge as organic compost and biogas production. This 'Waste-to-Value' model transforms the treatment station into a profitable economic unit capable of financing its own maintenance (FAO, 2025; UN Water, 2026). Public–private partnerships (micro-BOT contracts) can supply the technical expertise that public agencies lack, provided social tariffing protects vulnerable smallholder access (African Union, 2025).

Strategic Alignment with Sustainable Development Goals:-

Table 3. TWR contribution to the 2030 Agenda.

SDG	Key Target	TWR Contribution in Market Gardening
SDG 2 – Zero Hunger	Ensure food security, improve nutrition and promote sustainable agriculture	Guarantees regular horticultural yields year-round, including dry season; increases local supply of micronutrient-rich fresh produce
SDG 6 – Clean Water & Sanitation	Substantially increase recycling and safe reuse of water globally by 2030 (Target 6.3)	Reduces pressure on aquifers and surface freshwater; valorises the water cycle through controlled treatment techniques
SDG 13 – Climate Action	Strengthen resilience and adaptive capacity to climate hazards	Provides a water resource decoupled from rainfall variability; enables proactive agrosystem adaptation to climate disruption

Conclusion and Policy Recommendations:-

The viability of treated wastewater reuse at the 2030–2050 horizon rests on a complex balance between economic imperatives, environmental challenges, and social imperatives. Systemic benefits—aquifer recharge, drastic reduction of watercourse pollution—offer a major lever for climate resilience. However, TME accumulation, soil salinisation, and the still poorly understood impacts of pharmaceutical residues on microfauna demand rigorous scientific monitoring, particularly in fragile zones such as the Sahel.

Protection of public health and overcoming the 'disgust factor' require placing the human dimension at the centre of projects. Ultimately, the success of this strategy depends on decentralised management models guaranteeing equitable water access for smallholders, thereby securing local food sovereignty. This ambition calls for multi-actor governance—decision-makers, scientists, and citizens—collaborating to transform wastewater into a driver of social justice and environmental sustainability.

Three political orientations are essential: (1) update regulatory frameworks by substituting Western standards with adaptive quality criteria based on the WHO successive-barriers approach; (2) establish fiscal incentives and targeted subsidies for smallholders adopting drip-irrigation systems; (3) institutionalise local consultation platforms including WUAs to co-build social tariff structures and guarantee equitable access.

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