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SAFE USE OF WASTEWATER IN AGRICULTURE

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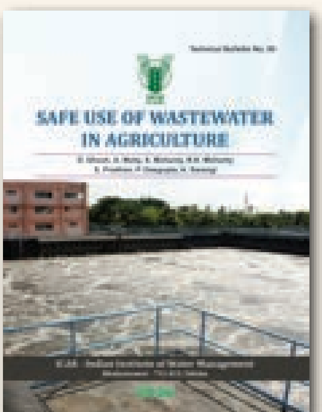

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Preface

Population growth, rapid urbanization, groundwater depletion and climate change are straining the freshwater resources for peri-urban agriculture. Wastewater has been recognised globally as an alternative source for irrigation, especially to alleviate water scarcity conditions. Wastewater, mainly categorized as municipal, agricultural and industrial wastewater, is the water generated at the end of a process or a sequence of processes or activities. Untreated wastewater from household, industry, pharmacy, and other sources carries a variety of substances such as suspended solids, sludge, heavy metals, toxic compounds, microbial populations, colour, etc., which if used to irrigate crops, can have a detrimental impact on soil, crop and human health, contaminate groundwater, and pollute the environment. Prevention measures, such as appropriate treatment technologies, soil and water quality monitoring, and careful irrigation management procedures can mitigate the risks.

Treatment of wastewater is crucial to ensure safe and long-term application. Treated wastewater ensures the reuse of water resources and acts as an organic fertilizer for soil due to the presence of macro and micronutrients. There is a growing recognition of wastewater as a potential resource especially in peri-urban areas of India. Treated wastewater holds a significant potential in the country, with a capacity to irrigate over 2.0 million hectares of agricultural land. Emphasis is on developing strategies for effective and safe reuse of wastewater in agriculture, to reduce water insecurity and environmental pollution. Necessary policies should be formulated for catering to the growing need for treated wastewater usage in the agriculture sector. Development of specific national and state-level quality standards for treated wastewater, differentiating by end-use and incorporating international guidelines to fulfill health-based targets and robust monitoring measures, is required to manage risks of contaminants in the food chain.

Adequate research is also required to develop cost-effective wastewater treatment technologies that may be implemented on a pilot scale and commercialized based on efficacy. The bulletin reviews the prospects of using wastewater from different sources in agriculture. It also documents a few research-based case studies showcasing the effects of treated and untreated wastewater on crop cultivation, human health and the environment. A number of filters have been developed by the scientists working under ICAR-Indian Institute of Water Management and the scheme of AICRP on Irrigation Water Management, to purify the detrimental components in urban wastewater and make it useful for crop production. The applicability and efficacy of these filters may be tested on a pilot scale in collaboration with government and non-governmental organizations for implementation in peri-urban agriculture.

Authors

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Wastewater Potential and Safe Use Perspective in Irrigated Agriculture

M. Das and D. Ghosh

ICAR-Indian Institute of Water Management, Bhubaneswar, Odisha

The rapid pace of human population growth has put pressure on the limited freshwater resources. As an essential ingredient of life, demands for freshwater in various sectors have been continuously rising over the last few decades. According to the report of the Food and Agriculture Organization (FAO, 2017), annual water withdrawal increased from 600 km^3/year at the beginning of twentieth century to more than 3800 km^3/year at the beginning of the twenty-first century, a nearly 6.3-fold increase (Egbuikwem et al., 2020). An Indian projection of water requirement in 2050 reflects a requirement of 1447 km^3 of fresh water, 74% of which is accounted by irrigation as assured water supply reduces yield penalty and ensures crop return under different climate change scenarios (Ministry of Statistics & Program Implementation, Govt. of India, 2016). The increased freshwater withdrawal, which is contributing to the global freshwater crisis, is also responsible for generation of large amounts of wastewater. Wastewater is the water generated at the end of a process or a sequence of processes and contains a variety of substances. For example, sewage water which is coming mainly from the domestic use, contains several inorganic and organic materials and fulfills the nutrient demand of crops to a great extent, if used for irrigation purposes. According to studies, 1.6–6.3% of the world's treated sewage is utilized to irrigate agricultural land (Ungureanu et al., 2018) and more than 10% of people worldwide consume food that has been irrigated with wastewater (Mishra et al., 2023).

Use of untreated wastewater for irrigation purposes also increases the risk of contaminating crops and the soil. India generates five primary types of wastewater from i) domestic sewage, ii) commercial establishments, iii) industrial effluents, iv) municipal sewage and v) agricultural sewage. Sewage Treatment Plants (STPs) and Effluent Treatment Plants (ETPs) handle urban and industrial wastes. As per recent estimates, the installed capacity of treatment plants is 31,841 million litre per day (MLD) and actual treatment is ~27,000 MLD (Ahmad and Singhal, 2024). In Class I cities, wastewater generation increased five folds in 2009 from 1978, however the creation of sewage water treatment facilities did not increase proportionately (CPCB, 2016). According to the population count from the 2001 census, the combined sewage output of all Class I cities and Class II towns is predicted to be 29,129 MLD. In contrast, there is only 6,190 MLD of built sewage treatment capacity. The existing sewage treatment capacity and sewage production still differ by 22,939 MLD, and this difference is 78.7%. An additional 1,742.6 MLD of sewage treatment capacity is being planned or built. There is still a 21,196 MLD (72.7%) capacity shortfall in sewage treatment even if this is added to the current capacity. While about 44 billion m^3 of industrial wastewater is being generated per day (Ranade and Bhandari, 2014), of which nearly 6.2 billion litres remain untreated (The Trade Council, Embassy of Denmark, India, 2015) and gets discharged into the environment.

Among different states, Maharashtra generated the largest quantity (3.32 km^3) of sewage water (Figure 1). Union territories like Lakshadweep, Delhi and Chandigarh generate comparatively higher per-capita sewage water (178–202 l/day) than the national average (72 l/day). Region-wise, the southern region of India generates the highest quantity (7.63 km^3) of sewage water, followed by the northern region (7.33 km^3), the western region (5.2 km^3), the eastern region (3.83 km^3), the central region (1.77 km^3) and the north-eastern region (0.61 km^3) (TCI, 2015; Minhas et al., 2022).

Increasing urbanisation, industry, and lifestyle changes, together with rapid population growth, will result in higher water use and a greater amount of anthropogenic wastewater with varying compositions. Currently, 15% of India's water resources are used for domestic and industrial purposes, by 2050, this share is predicted to rise to 30%. Total yearly water requirements of the industrial sector and the urban population are projected to be around 81 and 90 km^3, respectively, by 2050 (CPCB, 2021). Wastewater generated from domestic households accounts for 50–80% of the total volume of wastewater released to the environment (Hussain et al., 2019). This has the potential to irrigate about 2.1 million ha agricultural land, contribute 4.0 million megagram (Mg) of plant nutrients, generate 2.8 million man-days of employment and reduce greenhouse gas emission by 73.7 million Mg CO_2 equivalent (Minhas et al., 2022).

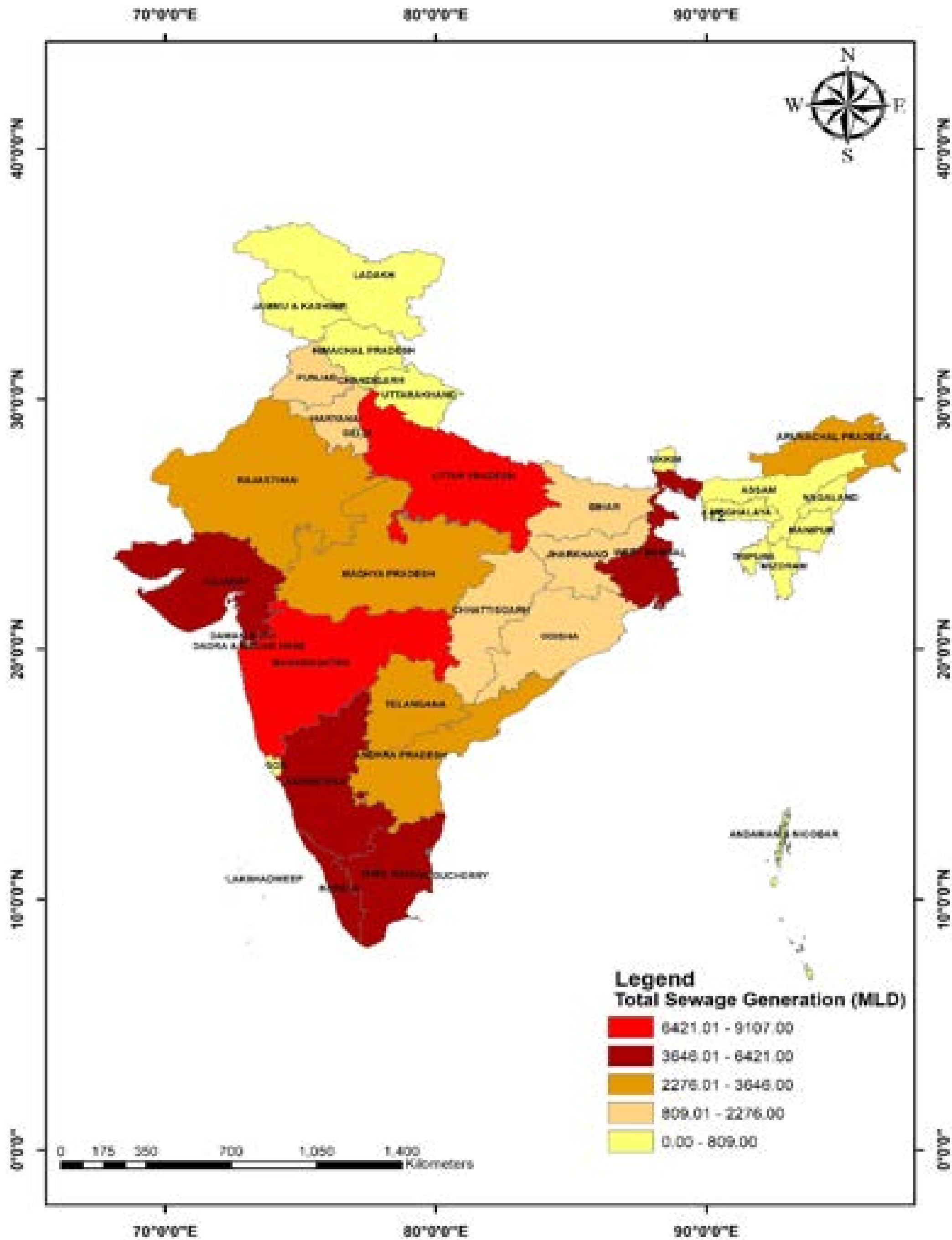

Figure 1. State-wise sewage generation in India

Being an unconventional water source, wastewater offers enormous potential to narrow down the demand – supply gap towards a water-secure future (Jones et al., 2021). Wastewater is increasingly recognized as a reliable and cost-effective water source, particularly for agricultural applications; however, wastewater remains an "untapped" and "undervalued" resource (WWAP, 2017), especially in India. Wastewater treatment aims to improve the quality of "used" water sources to reduce contaminant levels below sectoral quality thresholds for reuse or to minimize the environmental impacts of wastewater return flows. However, much of the wastewater currently reused is inadequately treated or even untreated due to multiple issues.

Agriculture is the focused sector of wastewater reuse because of its wider adaptability and acceptability to receive variety of substances. But many times, the reuse fails to achieve the desired extent despite the considerable content of nutrients and biological substances in the wastewater. Nevertheless, wastewater irrigation is a taboo, as untreated wastewater is widespread in the environment and growers are not sure about the safety of the produce. However, use of wastewater as irrigation is a mere reality. Issues related to its use need to be addressed while looking into the expansion of wastewater irrigated agriculture.

Issues in Wastewater Irrigation

Wastewater varies in nature and its constituents. Domestic sewage water is apparently good, as it seems to supply organic matter and plant nutrients. However, mixing it with municipal sewage alters its composition by introducing undesirable compounds or elements. Wastewater from industries starkly varies from one industry to another, depending on the type of industry and the nature of raw materials used. Due to such a wide diversity, guidelines issued for wastewater use are a serious challenge for scientists and researchers. Moreover, information on the impact of prolonged use of wastewater on crops, soil properties and groundwater at shallow depths is piecemeal and inadequate to formulate the standards of its appropriate use in irrigation.

Technical Aspects of Wastewater Reuse

Agricultural land use is one of the determining factors for deciding water quality for irrigation (Allan and Flecker, 1993), as it induces change in organic inputs, modifies temperature and chemical quality of applied water. For example, Na and Ca significantly inhibited Zn, Pb and Cd sorption in the acidic pH range (Lim et al., 2002). Soil wetness guides wastewater application, especially in poorly drained soils (Carlile, 1980), because a higher soil moisture content reduces the chance of converting ammonium to nitrate ions in N-enriched wastewater. Considering this, a comprehensive investigation was carried out by Das and Kumar (2009) with the effluents of twenty different industries. The effluents were characterized by twenty-four attributes and disclosed the effluents' potential for use. Comparing these with corresponding irrigation water quality standards, the probability of reusing effluent was interpreted in the first approach. On the basis of relevant properties of major soil types, predominant in a particular region, soil-based usability of effluent was worked out in the second approach. Emphasizing the limitation of groundwater development where it exceeded 50% exploitation level, the land–form and major soil type were identified, and then by applying a soil-based approach for using effluent, the area-specific usability of it was projected in the third approach. Besides, different effluent quality indicators were established by applying multivariate statistics to monitor periodic quality of wastewater during irrigation (Das, 2009).

Assessment of effluent in the above-mentioned ways builds up reliability of its reuse and consequently diminishes the chances of degrading soil and water resources (Das, 2010). Following these approaches, wastewaters coming out from different agro-industries were used for irrigation (Das et al., 2008, 2009a, 2009b).

Technological Approaches for Wastewater Use

Wastewater varies widely in quality and also undergoes changes after application in the soil. Soil plays a pivotal role in moderating the quality of water used for irrigation. Thus, considering water composition, soil type, irrigation methods and nature of growing crops, comprehensive guidelines are rarely available to guide the safe use of wastewater in agriculture. In the absence of such guidelines, periodic assessment of soil properties and crop quality is crucial for promoting the safe use of wastewater in irrigation.

Despite freshwater scarcity, a vast quantity of wastewater remains untapped owing to unclear perceptions about the water and its consequences on the environment. Enforcement of Environmental Protection Agency (EPA) norms and their regulation process are not transparent, so people's fear of damage to the productivity of cultivated land from the reuse of industrial wastewater is somewhat genuine to a certain extent. Nevertheless, with the increasing crisis of freshwater availability, use of this water in agriculture is imminent.

Astute management practices could ameliorate the risk and promote safe use in this sector. By using location-specific soil characteristics, physical landforms and comparing wastewater compositions with standard irrigation water quality criteria, different approaches have been developed to assess the potential of wastewater and work out the feasibility of its use in crop production. These approaches are simple, environment-friendly and help to promote appropriate use of wastewater without impairment of environmental quality. As environmental safety and food security are the major concerns in the use of wastewater, these approaches need to be screened through the perceptions and expertise of multicultural respondents, including water quality experts, water management planners/researchers, farm water users and social workers. In the process, the approaches get modified, made known and publicized, which could promote wastewater reuse more effectively in agricultural perspectives. The Activated Sludge Process, Upflow Anaerobic Sludge Blanket, Sequencing Batch

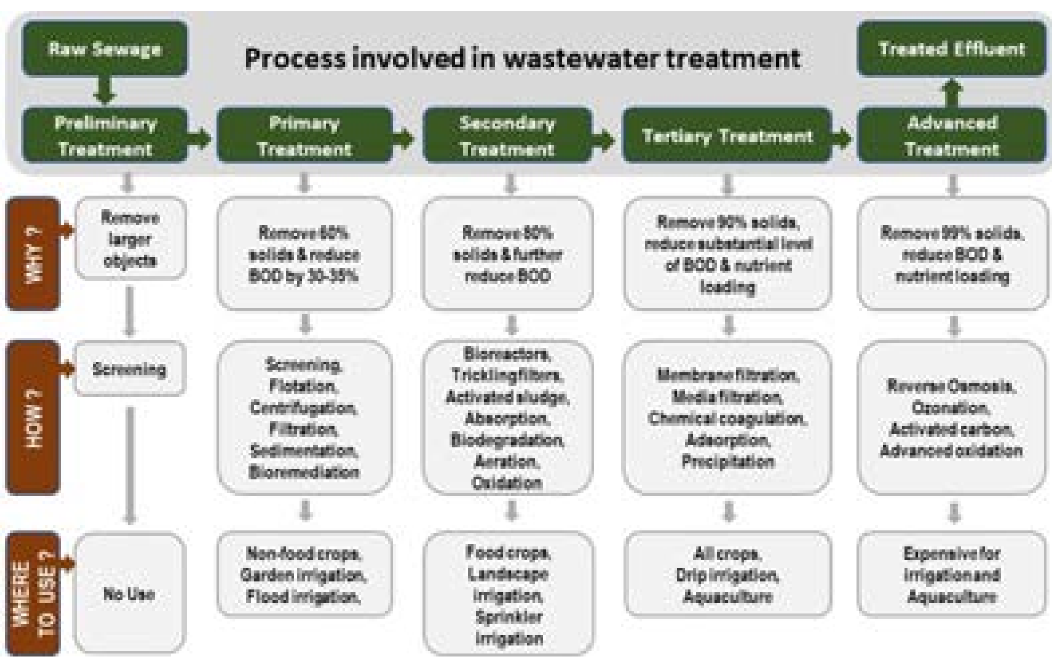

Figure 2. Process involved in wastewater treatment and its reuse potential

(Source: modified and conceptualized from WHO and UN-HABITAT, 2018; Singh, 2021, Minhas et al., 2022)

Reactors, and Membrane Bioreactors are the four types of wastewater treatment methods available. The processes involved in wastewater treatment and its reuse potential are illustrated in Figure 2. Based upon the approaches, different field and laboratory studies were formulated and carried out in different soils.

Experiences of Agro-based Industrial Wastewater Use in Crop Production

Use of agro-based paper factory wastewater

Effluent of agro-based paper mill is generally rich in organic matter and contains different amounts of suspended solids, alkali and alkaline earth metals, chloride and sulfate ions (Yong et al., 1992). Depending on the nature of inputs and pulping technology practices, the amount of a particular constituent or a group of constituents varies.

Experiments were conducted with the Emami Paper Mill effluent, a newsprint manufacturing unit in Balasore, Odisha, producing 4,500–5,000 m^3 of effluent per day and discharging it into the nearby water stream. *In vitro* use of this effluent reduced the germination rate in maize (cv. DHM 103) but improved the vigour index. The *in situ* experiment with maize in a Ca-deficient (4.02 mg/kg), low-P (1.38 mg/kg), sandy loam non-saline soil (*Aeric Haplaquepts*) with effluent irrigation (through different treatments) subsequently revealed that leaf area index and plant height at knee-height stage were increased by 32 to 33% and 4 to 28%, but the impact on cob length/girth/weight was not much evident. Grain yield was also improved by 3 to 6%, while other yield-attributing characters *viz.*, grains/cob and grain weight/cob weight ratio, were enhanced by 19 to 29% and 1.2 to 11%, respectively, owing to irrigation with paper mill effluent over 'normal practice' as the control.

At knee-height stage, N concentration was reduced to the tune of 1.23 to 2.04 times in the first year, while P, K and Ca concentrations increased by 1.10 to 1.47, 1.02 to 1.09 and 1.93 to 3.07 times, respectively, under effluent irrigation over freshwater. Similarly, Ca concentration also increased (1.6 to 3.81 times), followed by N (1.21 to 1.32 times) and P (1.08 to 1.11 times) in the second year, without manifesting any consistent trend with effluent concentration in general. Nutrient concentration, however, got augmented over freshwater irrigation in the order of Mg > K ≈ P > Ca > N (Figure 3).

Soil fertility also improved to the tune of 1.18–1.34 folds with an increase in organic carbon. There was 1.22, 1.21, 1.09 and 1.8 times increase in humus carbon, available P, K and N content, respectively with effluent irrigation. Exchangeable Ca and Mg contents also increased by 1.03 to 1.04 and 1.3 to 1.74 times over freshwater irrigation (Figure 4). However, no carry-over effect of effluent irrigation was noticed in the succeeding year of study. Thus, the effluent of Emami Paper Mill was found useful in increasing crop (maize) yield, nutrient uptake and improving soil fertility, and could be used for irrigation in acidic non-saline soil during freshwater crisis.

Use of agro-based distillery wastewater

Treated spent-wash, especially from cane sugar molasses distillery, is an enriched source of various plant nutrients. It could alleviate soil constraints and improve the environment to the level suitable for plant growth if properly managed under a specific situation. Irrigation with highly saline, organic matter-enriched neutral agro-based treated distillery wastewater @ 50/50 or 70/30 dilutions with freshwater proved suitable for growing groundnut (after 15 to 20 days of sowing) and alternate application of wastewater with freshwater for sugarcane. This reduced 50% water use

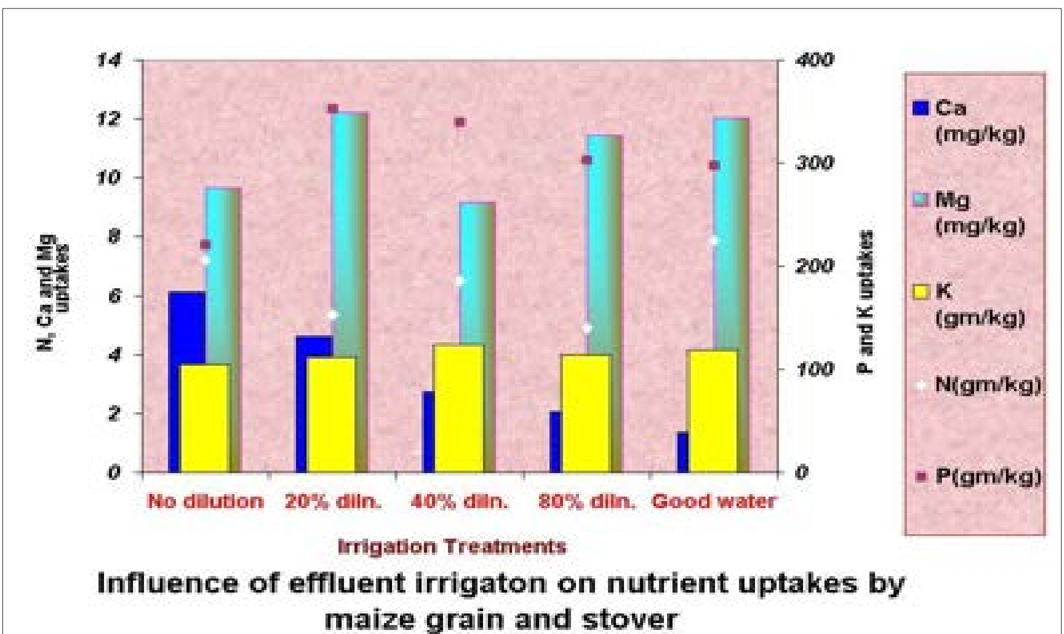

Figure 3. Effect of paper mill effluent irrigation on nutrient uptake by maize crop

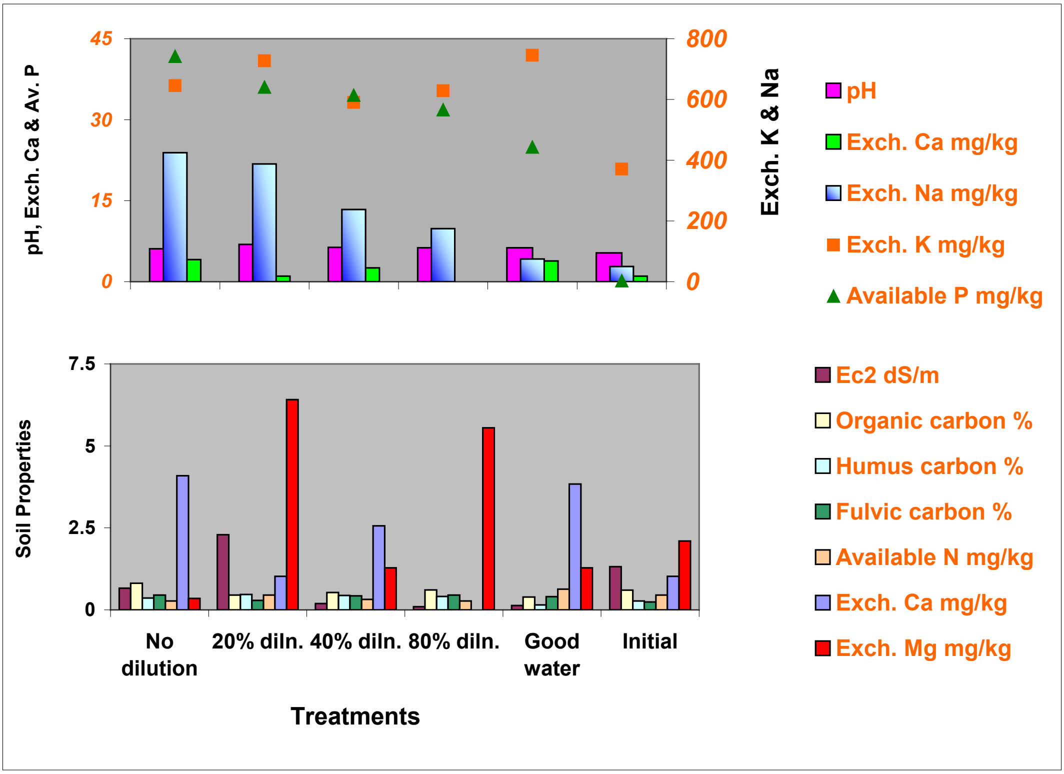

Figure 4. Impact of paper mill effluent irrigation on soil properties

and N, P and K requirements of the crop. Besides, reuse of the water @ 80–120 m^3/ha before 10 to 16 days of transplanting proved optimum to correct soil constraints and improve paddy yield in acidic (pH < 6.0) red and laterite soils. In case of sugarcane, application of wastewater @ 40 and 60 m^3/ha before 15 days of planting enhanced cane yield by 1.17 t/ha; while juice quality, sugar yield, percentage of commercial cane sugar, polarity and purity were at par with freshwater irrigation. Moreover, in light-textured upland soils, soil application of 40 m^3/ha distillery wastewater was found to be the most economical level for sugarcane production by improving soil health to the magnitude of 28% N, 27% K, 58% Ca and 87% Fe. No adverse impact of wastewater application was noted on soil and water quality in the surrounding areas. The study thus showed that by adopting appropriate management practices, effluent water could be safely utilized in crop production.

Prospects of Industrial Effluent Reuse in Crops

Effluent water reuse is a promising option, particularly during water shortage. Assessing irrigation potential and perfecting its use in a particular soil type have been proved effective in ensuring crop return without affecting the quality of resources. For example, near-neutral, saline and Ca- and Mg-salt–enriched paper mill effluent has come up as a suitable and alternative irrigation source for acidic, non-saline Ca-deficient soil. Irrigation with the effluent @ 5 cm per application has been found capable of augmenting grain yield by 3 to 6% in maize. Nutrient concentration got improved over freshwater irrigation in the order of Mg > P > Ca > K. No decline in important soil properties (pH, organic carbon, available N, P, K, exchangeable Ca and Mg) or increase of any unfavorable substance (Cd, Cr) was evident.

Again, cane molasses-based (post-methanated) distillery effluent alternated with freshwater or a 50/50 effluent/freshwater ratio was found to be the most favorable concentration to irrigate groundnut growing in non-saline, acidic red and laterite soil. Groundnut pod/kernel yield did not decrease; rather, it substantially got improved over freshwater irrigation without compromising nutrient uptake or soil properties. However, proper guidelines and management practices need to be followed for safe use of effluent water in crop production.

Guidelines for Industrial Effluent Reuse in Agriculture

Reuse of industrial effluent induces a risk to contaminate soil, water and crops, though it is imminent in agricultural perspectives. Detailed guidelines are available for safe and secure use of effluent in different perspectives. However, in effluent reuse practice, the following steps need to be taken care of to abate adverse impacts of effluents, protecting soil health and crop quality.

1. Characterization of effluent

Prior to putting it into practice, the effluent needs to be thoroughly analyzed and estimated for its constituents, which reveals the type and quality of the effluent.

2. Evaluation of effluent potential by comparing its characteristics with different irrigation water quality standards

After characterization, prioritization of effluent constituents as per their potential to cause damage is carried out in this process. Prioritization will help to eliminate the effluent if it contains hazardous substances such as heavy metals beyond their corresponding standards at the first instance. Heavy metals cause irreversible damage to living beings. Thus, this step will help to disclose the effluent's ability to be used or not used for irrigation.

3. Match the effluent characteristics with relevant properties of dominant soil types

Soils vary by their contents and characteristics. Different soils are dominant in different regions. This could be used as a yardstick for effluent selection and to improve its prospect of utilization in cropping, such as soil with acidic pH and low salinity can be used for receiving effluent of high pH and high salt content. In this way, the effluent's liabilities could be conditioned and its potential can be utilized for cropping. The soil-based effluent reuse option could be employed if the information of soil is known in various locations/regions.

4. Identification of effluent quality indicators

For surveillance of effluent quality, testing of a number of properties at regular intervals is a major burden in an effluent reuse program. Identification of salient indicator properties of effluent will help to relieve the load while monitoring its quality in an effective manner. Choosing an appropriate mechanism to screen effluent properties and select the properties as indicators is vital in this process.

5. Check the type of crops, soil and adjacent water resources

All steps are mandatory for effluent reuse practice. But for continued use of the same kind of effluent, monitoring of indicator properties (effluent quality indicators) and a strict vigil on soil/water/crop quality are highly required to promote its safe use in crop production.

Thus, planned and judicious use of wastewater increases its safe use, in addition to enriching nutrients in the soil–plant continuum wherever possible, decreases environmental nuisance and progresses towards a water–smart agriculture.

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Cost-Effective and Energy-Efficient Decentralized Wastewater Treatment Technologies for Safe and Sustainable Agricultural Use

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Relevance

Water security is an urgent concern in India. Out of 15 major river basins in India, 11 basins may face water stress in near future, with annual per capita renewable water availability falling below 1,700 cubic metres. In order to bridge the widening demand–supply gap, it is crucial to explore alternative water sources. While numerous studies highlight the potential of various water-demand management interventions, one area that has only recently gained attention is the reuse of treated wastewater. This approach is gaining increasing traction, given that India generates approximately 72,368 million litres of wastewater per day in urban areas alone. If treated to the required quality standards and effectively reused, it has the potential to significantly address the water supply-demand imbalance while simultaneously reducing pressure on freshwater resources.

India treats only 28% of the total sewage generated daily from urban centers. The vast majority of untreated wastewater is directly discharged into freshwater bodies, including rivers, posing severe environmental and public health risks. One of the key reasons for the lack of interest from the government and local bodies in reclaiming wastewater is the high cost associated with the installation, operation, and maintenance of centralized wastewater treatment plants. Other constraints include the non-availability of suitable land in and around urban areas, high energy costs, and the requirement of trained technical manpower to operate these facilities. As a result, decades-old conventional treatment plants are either dysfunctional or operating at less than 25% efficiency. Moreover, monetary returns on investment in wastewater treatment plants remain low, making them economically unviable for local bodies that already struggle with limited financial resources.

Description of Technology

A prototype with two variants—No. I without a spillway and No. II with a spillway—was designed and developed to simulate an open concrete drain. The prototype measured 3.6 meters in length, 0.2 meters in height, and 0.34 meters in width. It was fitted with three gabion walls, each placed 60 cm apart and positioned perpendicular to the longitudinal direction of the prototype. These walls were constructed using stones enclosed in gabion cages. Three different filtration materials, each measuring 20 cm × 34 cm with a thickness of 4 cm, were placed in the middle of the three stone walls. In Prototype I, two variations were introduced: one with treated gabion materials (P Ia) and the other with untreated gabion materials (P Ib). In Prototype II, approximately 10% of the gabion surfaces were left open to allow excess water to spill out in case of heavy rainfall.

The developed prototype consisted of four chambers. Raw wastewater was discharged into the first chamber and then passed through Gabions 1, 2, and 3 before reaching the fourth chamber, which contained the treated water. Key features of the designed prototype were: i) an *in situ* landless system, ii) a removable and adjustable structure, iii) no reliance on non-renewable energy, and iv) easy operation and maintenance by the local

Prototype-I without spillway

Prototype–II with spillway

community. The prototypes were tested with controlled discharge of wastewater from a tank that was continuously refilled with wastewater from the identified Chandrasekharpur drain. A valve was fitted at the bottom of the tank, and the discharge rate was set at 0.24 l/s, which was equivalent to 6 l/s in the main drain. Two prototypes were tested. In Prototype Ia (treated), the filtration materials were pre-treated to modify their surface charge characteristics.

Both the prototypes were tested with 20,000 litres of wastewater, and the water quality in different chambers was analyzed and compared. Prototype II demonstrated significantly improved performance in terms of pollutant reduction in treated wastewater. Reduction in total dissolved solids (TDS) and suspended solids (SS) increased from less than 5% and 50% to 35% and 75%, respectively. Microbial load and biological oxygen demand (BOD) reduction exceeded 98% and 60%, respectively. Heavy metal reductions were greater than 90%. Based on the results of the prototype wastewater treatment structure, an *in situ*, landless wastewater treatment system with a removable and adjustable structure, requiring no non-renewable energy, was upscaled and installed in the drain at Chandrasekharpur, Bhubaneswar, adjacent to ICAR-IIWM gate. Three gabions were placed 3.0 metre apart. A bar screen was installed between the first gabion and the wastewater discharge point in the drain to capture floating materials such as plastic bottles, sheets/bags, coconut shells, stones, etc. The gabions, measuring 1.7 metre in width, 1 metre in height, and 0.7 metre in thickness, were positioned perpendicular to wastewater flow in the drain.

Installed wastewater treament system

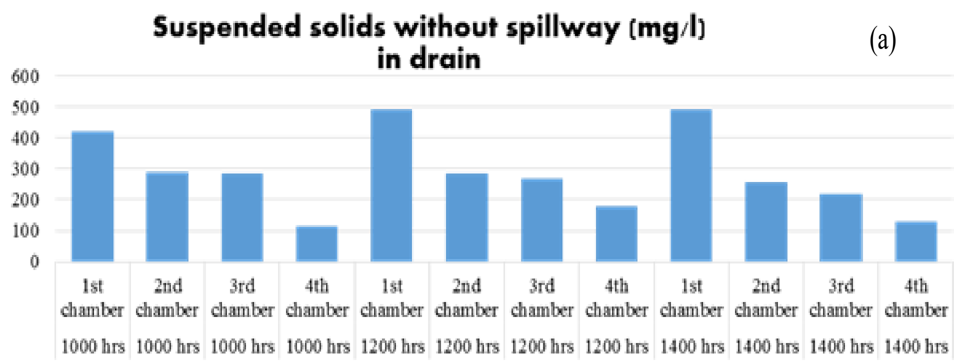
Union Minister of State for Agriculture and Farmers' Welfare visiting the waste-water treatment system

The gabions were constructed using different filtration materials like gravel, quartz sand, jute, and charcoal, each with a thickness of 20 cm, sandwiched between two layers of stones, each layer 25 cm thick. The stones were stacked in cages made of cross-linked, diamond-shaped wire with multiple dimensions to create a spillway in the gabion, allowing excess wastewater to discharge during high wastewater flow or heavy rainfall.

Performance Evaluation

The treated wastewater showed a 60% reduction in suspended solids and a 45% reduction in BOD (Figure 5 a&b). The reduction in heavy metals was 66% for chromium (Cr) and 75% for both nickel (Ni) and cadmium (Cd). No significant stagnation of wastewater in the upstream was observed during the summer months. With the spillway, the reductions in BOD, suspended solids, Cr, Ni, and Cd were 37%, 34%, 53%, 42% and 47%, respectively. The microbial reductions were 5 log without the spillway and 3 log with the spillway.

The water samples from all four chambers (compartments) of the filtration system were analyzed using Fourier Transform Infrared Spectroscopy (FTIR) after filtering 2,000 litres and 4,000 litres of wastewater to assess the removal of organic pollutants in the treated wastewater (Figure 6 a&b). The peaks at 1634 and 1384 correspond to the conjugated alkene [n(C-C=C-C=C-C)n stretch] and phenolic compounds, respectively. Phenolic compounds and other conjugated alkenes are common constituents of wastewater containing various organic compounds. The gradual reduction in peak intensity in the FTIR spectra, from the first to the fourth chamber



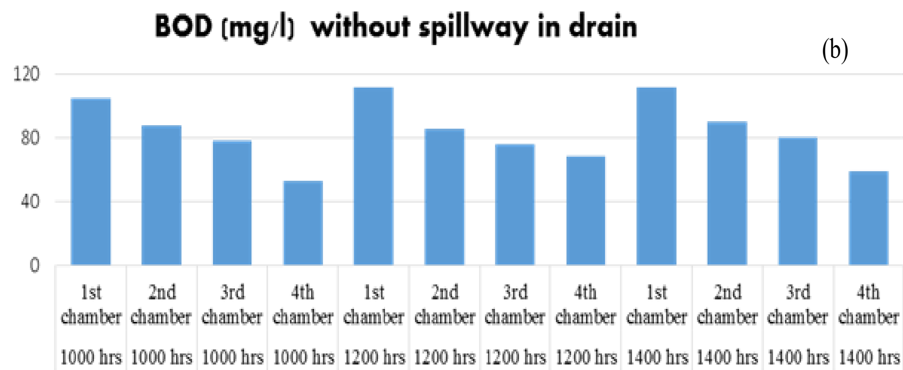


Figure 5. Temporal changes in (a) suspended solids, and (b) biological oxygen demand (BOD) in different chambers of wastewater treatment system without spillway during summer season

of the wastewater treatment system, corroborates the decrease in pollutant quantity as the wastewater flows through the system.

Visually, the treated wastewater was significantly less turbid and had a reduced odour. During the rainy season, the absence of a spillway caused flooding in the upstream, whereas with the spillway, no significant water stagnation was observed.

Design modification of filtration system

In the catchment areas of the Chandrasekharpur drain, various construction activities may have led to excessive silt deposition. The accumulation of silt before the bar screen is a concern, necessitating a silt removal system. The extent of silt deposition may also vary from place to place. The design of the filtration system was modified to address the siltation issue and to suit farmers' field conditions. A de-siltation tank was introduced between the bar screen and the first gabion, and a storage tank for treated wastewater was provided after the third gabion for further distribution.

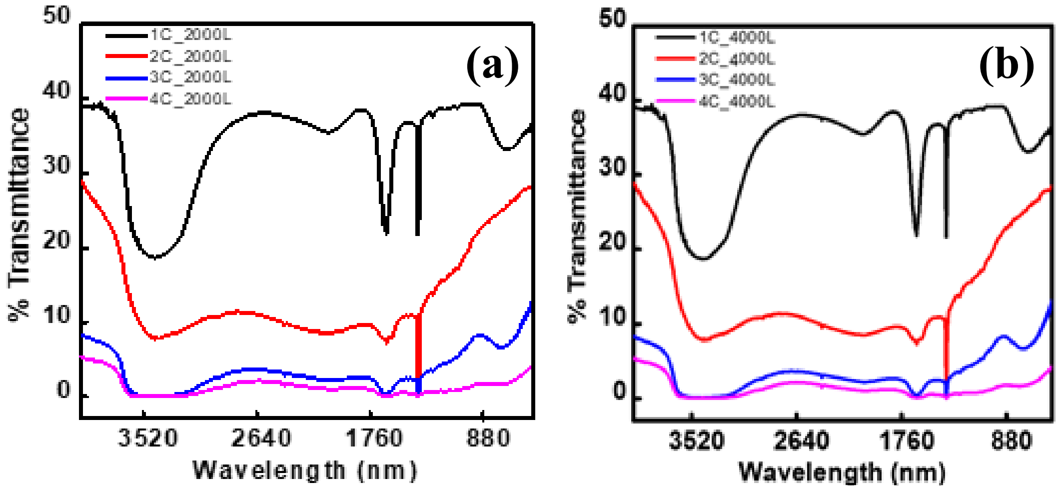


Figure 6. FTIR spectrum of water sample in different chambers after (a) 2000 litre and (b) 4000 litre of wastewater filtration

Impact of treated wastewater on crop growth

A pot culture experiment was conducted using one cereal (maize), two fruiting vegetables (okra and tomato), two root vegetables (carrot and radish), two leafy vegetables (spinach and amaranth), and one flowering plant (marigold) to study the impact of treated wastewater on crop growth and heavy metal accumulation.Plants irrigated with treated wastewater showed higher biomass production compared to those irrigated with untreated wastewater. Okra, spinach, amaranth and radish grown with treated wastewater recorded 12, 14, 8 and 4% higher biomass, respectively, than those grown with untreated wastewater. Tomato, maize and marigold also exhibited higher biomass production with treated wastewater. There was a reduction in the concentration of Cd, Cr, and Ni in the plant biomass grown with treated wastewater compared to those grown with untreated wastewater (Figure 7). The highest reduction in Cd concentration was observed in carrot, while the highest reductions in Cr and Ni concentrations were recorded in radish and maize, respectively.

Impact of treated wastewater on aquaculture

The impact of treated wastewater (TWW) in various proportions with freshwater (FW)—T1 (100% FW), T2 (75% FW + 25% TWW), T3 (50% FW + 50% TWW), T4 (25% FW + 75% TWW), and T5 (100% TWW) on the length and weight of

Indian major carps was assessed under laboratory conditions. Untreated wastewater was used as Control. The results indicated that highest increase in body weight (34.19%) and length (14.3%) was recorded with treated wastewater, followed by the combinations of freshwater and treated wastewater in the sequence of T4, T3, T2 and T1 (Figure 8). No diseases were detected in any aquarium, regardless of treatment, except for fin and tail rot. Tail disintegration was observed in fish during

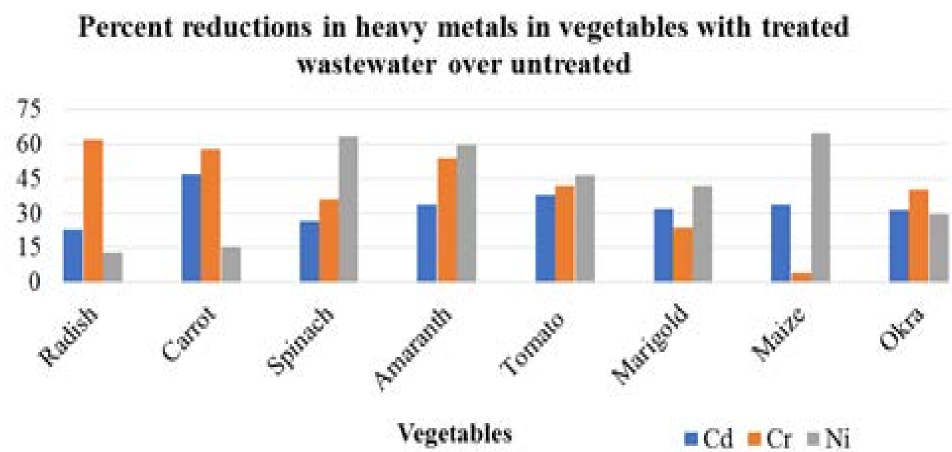


Figure 7. Reduction in concentration of Cd, Cr and Ni in plant biomass under treated wastewater in comparison to crop grown with untreated wastewater

the growth stage (60–75 days) in 2 to 3 specimens in 100% and 50% freshwater treatments (T1 and T3). Application of a medicinal treatment comprising copper sulfate and tetracycline effectively cured the affected fish.

Fish grown in wastewater accumulated heavy metals in the order of Cr (0.54 mg/kg) > Ni (0.31 mg/kg) > Pb (0.27 mg/kg) > Cd (0.25 mg/kg) in different tissues, all within permissible limits. Accumulation of heavy metals in different fish parts decreased significantly (p<0.01) in treated wastewater and further diluted treatments (Figure 9). Results of the present study revealed that concentration of all the heavy metals like Cd, Cr, Pb and Ni was lowest in the muscles, the part most commonly consumed, and remained within the permissible limits by FAO, 1983. No heavy metal accumulation was detected in fish grown in freshwater.

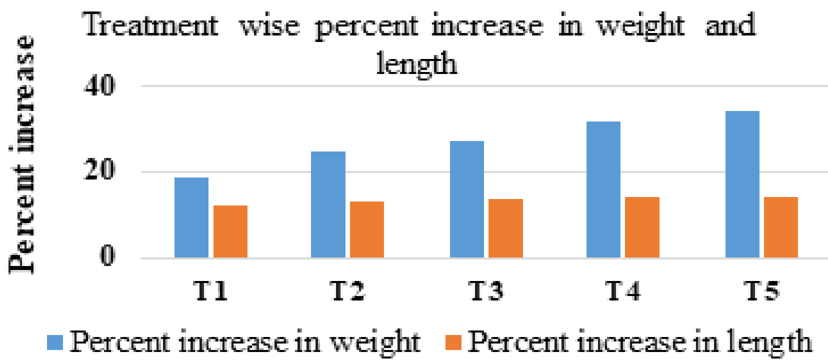


Figure 8. Effect of treated wastewater and its combination with freshwater on the growth of Indian major carps

Human Health Risk Assessment

Potential health risk to humans due to prolonged exposure to chemicals was assessed using Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI), as introduced by EPA in the United States. The results revealed that females have a higher risk due to their lower body weight.The maximum daily intake of Cr was 0.0957 and 0.081 mg/kg body weight per day for females and males, respectively, followed by Ni > Cd > Pb from fish grown in wastewater. EDIs were several times higher than their respective reference doses. Daily intake of

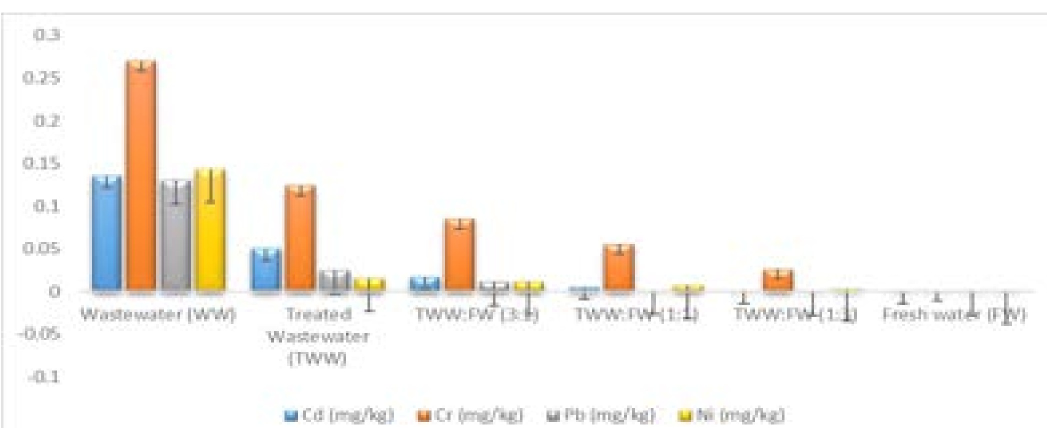


Figure 9. Heavy metal content in muscle of fish

Cd, Cr, Pb, and Ni was reduced by 63.0, 54.1, 80.8 and 89.5%, respectively in both males and females from fish grown in treated wastewater. Upon further dilution of treated wastewater with freshwater [TWW:FW (1:3)], the daily intake of Cd, Cr, Pb, and Ni was reduced by 100, 90.4, 100 and 97.9%, respectively, in both males and females. The THQ for heavy metals followed the order Cd > Cr > Pb > Ni for both males and females. The maximum HI was 0.095477 and 0.080788 for the intake of fish grown in wastewater, which was reduced to 0.03518 and 0.029768 for females and males, respectively for fish grown in treated wastewater. The HI was further reduced to a minimum of 0.003126 and 0.002645 for females and males, respectively when treated wastewater was diluted with freshwater [TWW:FW (1:3)]. The THQ for all the heavy metals studied did not exceed 1, even for fish grown in untreated wastewater, indicating a lower potential for non-carcinogenic risks to the exposed population. However, the level of concern increases as the THQ approaches or exceeds 1.

Biological Filter for Safe Wastewater Irrigation Utilising Microbial Bioremediation Traits

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Relevance

About 72,368 million liters per day (MLD) of urban wastewater is generated in India, while the developed centralized sewage treatment plant (STP) facilities have a maximum treatment capacity of 31,841 MLD. Various technologies, such as activated sludge, trickling filters, and stabilization ponds are used for wastewater treatment.However, these systems are cost-intensive, require significant land for installation, and have low efficiency. As a result, more than 70% of the wastewater is discharged untreated into the environment. This untreated wastewater contains varying amounts of metals and heavy metals of diverse compositions. Due to the lack of sufficient freshwater resources, farmers often use this untreated wastewater for irrigation, posing risks to human health through heavy metal accumulation and pathogenic infections. Among pollutants, volatile organic compounds (VOCs) and heavy metals are of particular concern. Some of these are classified as carcinogens and toxic substances, leading to environmental deterioration and serious health hazards. Consequently, there is an increasing demand for technologies that can restore natural water resources and ensure safe water use. Currently, implementation of eco-friendly green technologies is being considered to remove various contaminants from water. Developing a biological tool utilizing microbial activity to improve water quality is both eco-friendly and cost-effective approach. Traditional wetland systems are constrained by high land requirements, whereas in-line filtration systems offer better potential for wastewater treatment. Microorganisms, whether indigenous or introduced, serve as primary agents for bioremediation. Several bacterial species have demonstrated biosorption potential for heavy metals, including *Rhodobacter sphaeroides* for Cr, Pb, and Cd, *Staphylococcus saprophyticus* for Cr, Pb, and Cu, *Pseudomonas* sp., *Zoogloea ramigera*, and *Streptomyces* for Pb, Cr, Cu, and Cd. Selection and application of microorganisms depend on the chemical nature of the pollutants, as these microbes thrive within specific environmental limits.

Since various types of pollutants are encountered at contaminated sites, a diverse range of microorganisms is required for effective remediation. This process is further supported by the creation of a congenial environment within a suitable matrix. However, free microbial cells are not suitable for commercial or industrial applications in column packing due to their low mechanical strength, small particle size, and susceptibility to hostile conditions. Additionally, the high hydrostatic pressure required to generate suitable flow rates can cause disintegration of free biomass. To overcome these challenges, physical confinement or localization of microbial cells within a defined space is a viable approach. This restriction prevents their free migration, allowing for the development of a biological filter suitable for wastewater treatment and its subsequent use in crop irrigation.

Description of Technology

i. Identification of effective bacterial strains

The strains *Pseudomonas aeruginosa*, *Acinetobacter baumannii*, and *Bacillus cereus* have proven effective in removing heavy metals and pharmaceutical products. *P. aeruginosa* exhibited highest chromium absorption (85%) at 5 ppm, followed by *B. cereus* and *A. baumannii*. For cadmium sorption, *P. aeruginosa* demonstrated highest efficiency, followed by *B. cereus* (54%) and *A. baumannii* (37%) at pH 7. Additionally, *P. aeruginosa* capable of degrading 72% of paracetamol within 2 minutes.

ii. Structural supports to the selected bacterial strains

Performance of immobilized cells was found to be superior to that of free cells. Hydrogel-based immobilization demonstrated better efficiency compared to Ca-alginate beads. A three-fold increase in metal sorption was observed with immobilized cells compared to free cells. A novel consortium of immobilized axenic microbial hydrogel beads was used to house the bacterial isolates, minimizing antagonism among strains. This consortium exhibited higher metal absorption, with 43% more Cr, 62% more Cd, and 19% more Ni than axenic beads.

iii. Effective packing material

The packing material in biofilters plays a crucial role in treatment efficiency. The same materials exhibited different performances in batch and continuous processes, affecting microbial anchorage on the packing surfaces. Microbial biofilms were developed in all the filters; however, in electro-conductive graphite, the biofilm was more compact and resistant to washout under hydraulic pressure. However, restricted electron movement in batch processes limited the efficiency of the graphite biofilter, making it no more effective than Fiber Reinforced Plastic (FRP) or gravel. The order of manganese (Mn) removal efficiency was: Gravel > Graphite > FRP.

iv. Design of biofilter

Four novel biofilters were fabricated namely, (i) Biobed, (ii) Tunnel, (iii) Gabion, and (iv) Column biofilters, using specific packing materials as shown in Figure 10-12.

Figure 10. Designs of different biofilters

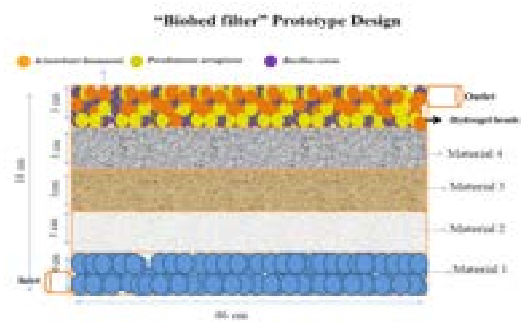

Figure 11. Prototype design of Biobed filter

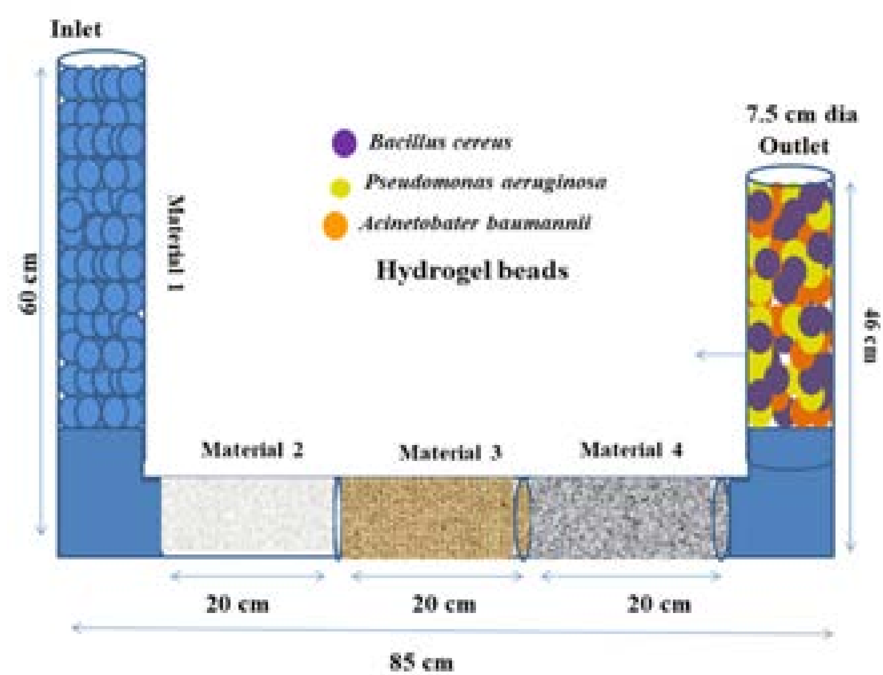

Figure 12. Prototype design of Biobed filter

Performance Evaluation

- The biofilters demonstrated metal reduction efficiency of 65% for Cr, 48% for Cd, and 43% for Ni when treating synthetic wastewater (Figure 13). Also, paracetamol and ibuprofen were reduced by 39% and 25%, respectively.
- Higher Cr removal was observed with all the biofilters. These biofilters reduced Cr concentration from 1.0 mg to a range of 0.07–0.03 mg. The graphite biofilter exhibited greater performance stability for Cr removal from wastewater.
- Interestingly, the biofilters performed better in reducing pollutants from actual wastewater over synthetic wastewater. The presence of organic pollutants in actual wastewater may have facilitated metal retention on material surfaces.
- The reduction of heavy metals increased by approximately 10% with industrial wastewater and by 9% for pharmaceuticals in hospital wastewater.
- Evidence of heavy metal adsorption and precipitation on the packing materials was confirmed by shifts in X-ray diffraction peaks and field emission scanning electron microscopy (FE-SEM) images.

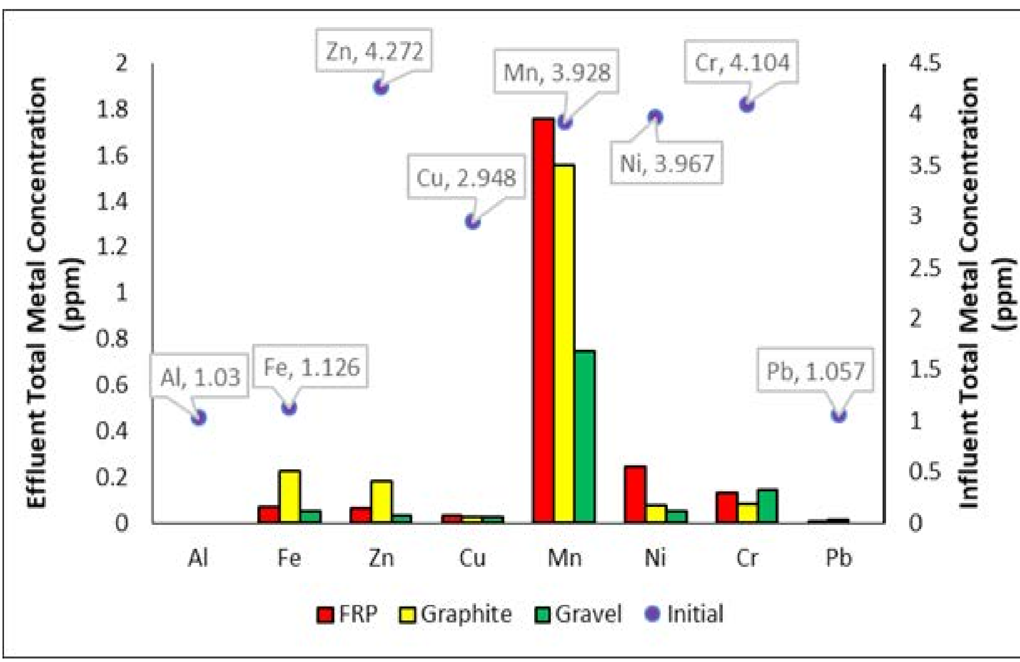

Figure 13. Prototype design of Gabion based biofilter

- Energy Dispersive X-ray (EDX) analysis of the packing materials revealed heavy metal accumulation on biofilms, highlighting the role of biofilms in metal removal (Figure 14).

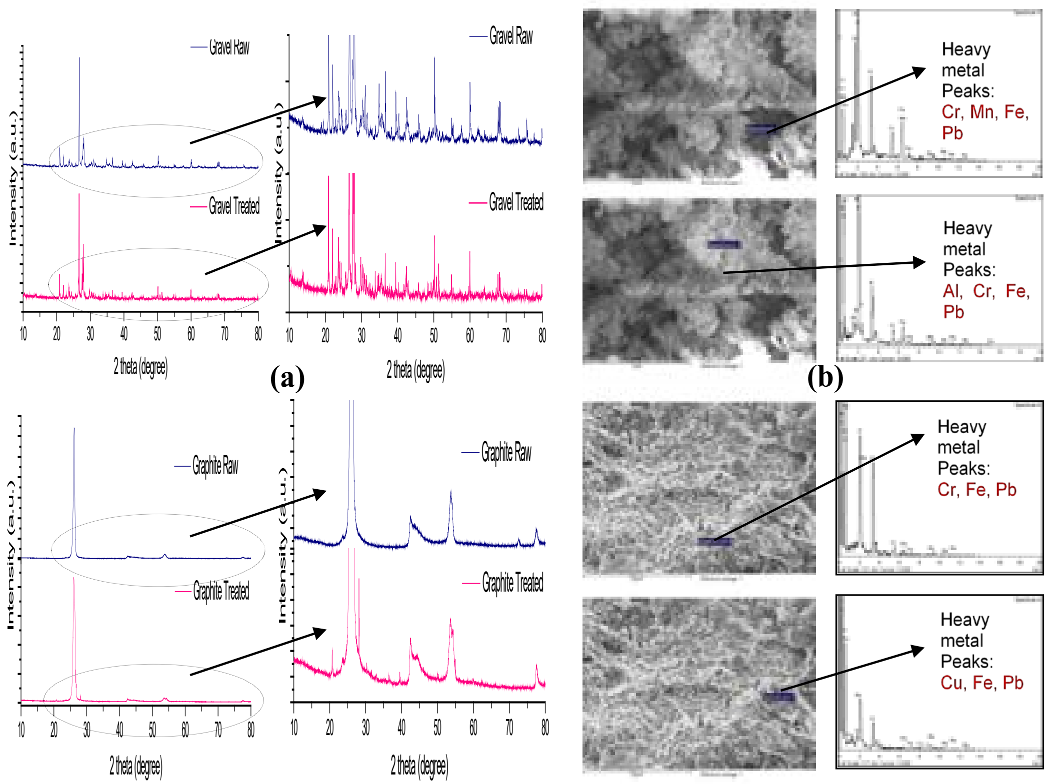

Figure 14. Shift in X-ray diffraction peak observed in (a) field emission scanning electron microscopic images indicating (b) heavy metal adsorption and precipitation on packing materials like gravel and graphite

- The 16S rRNA metagenomic analysis of the developed biofilms on gravel surfaces treated with actual wastewater revealed dominant abundance of the following phyla: *Proteobacteria* (44.78%), *Bacteroidetes* (18%), *Verrucomicrobia* (8%), *Acidobacteria* (6.5%), *Chloroflexi* (4.23%), *Actinobacteria* (3.9%), *Patescibacteria* (2.7%), *Gemmatimonadetes* (1.5%), *Nitrospirae* (1%), *Planctomycetes* (1.2%), and *Firmicutes* (1.2%) (Figure 15).

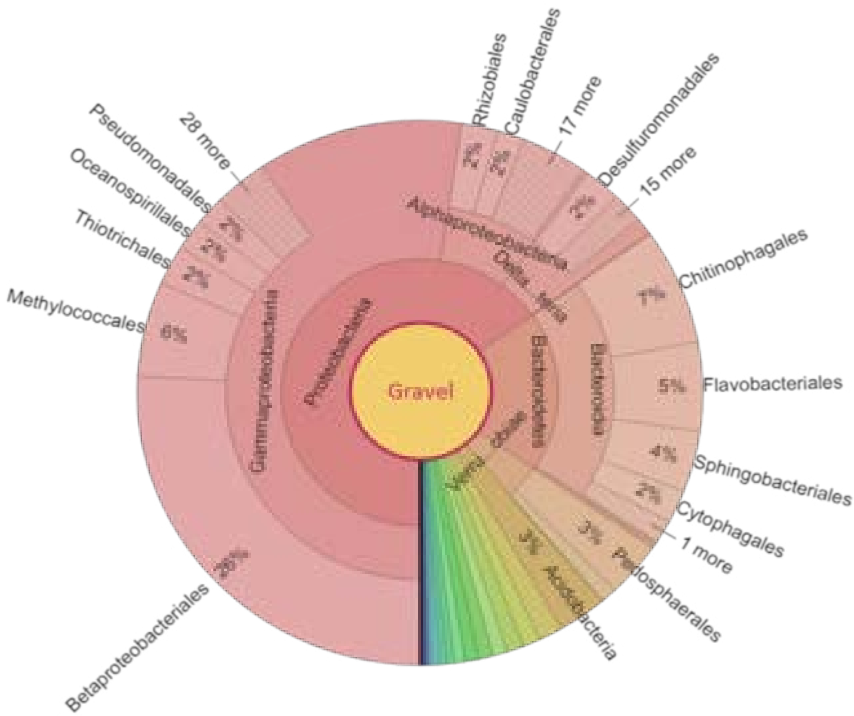

Figure 15. Microbial community on gravel biofilter

Impact / Merits of the technology

This technology directly addresses wastewater management challenges, such as the high treatment costs of conventional methods, lack of available land for treatment system installation, and high energy requirements of the existing processes. Its primary advantage lies in providing a low-cost, green technology capable of treating large volumes of wastewater with minimal training and skill requirements for users. Peri-urban farmers will benefit from the ability to use treated wastewater through the developed biological treatment options. During the non-rainy season, when irrigation water availability is limited, treated wastewater will serve as an alternative source of irrigation. Additionally, the improved quality of treated wastewater, compared to raw wastewater, will help in reducing accumulation of metal pollutants in edible parts of crops, thereby minimizing the risk of contaminated food consumption by consumers.

Development of a Suitable Filtering Technique for Reusing Household Wastewater for Irrigation

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Relevance

Water scarcity is a significant challenge, particularly during summer months. Reusing household wastewater presents a viable solution for irrigation in both urban and rural areas. Household wastewater, rich in nutrients like phosphorus and sulphates, can be a resource for homestead irrigation if treated effectively. However, untreated wastewater may contain impurities such as heavy metals and high salinity, making it unsuitable for direct use. Due to their complexity, existing methods like constructed wetlands are effective but impractical for homestead use. Therefore, a simple and cost-effective filtration system can provide a sustainable way to reuse household wastewater, benefitting agriculture and aquaculture.

Description of Technology

A sand filter (Figure 16) was designed for treating laundry wastewater, consisting of:

- A fibre tank (60 litres, 0.6 m height, 0.3 m diameter)
- Multi-layered filter media:
  - Charcoal (5 cm thickness)
  - Clay balls (10 cm thickness, 8-10 mm size)
  - Fine sand (10 cm thickness, 0.25-0.125 mm size)
  - Fine gravel (10 cm thickness, 2-4 mm size)

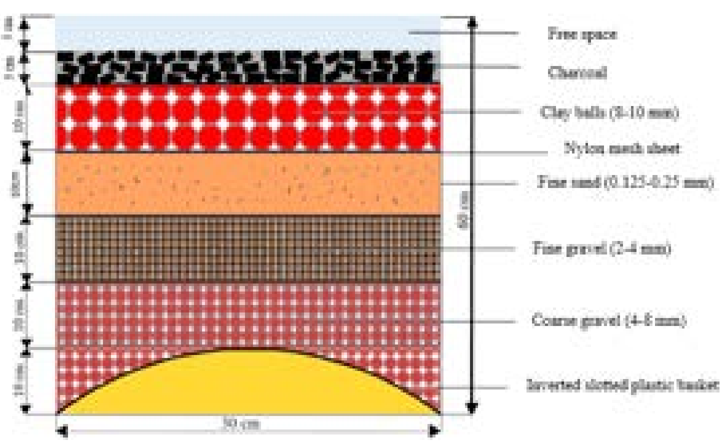

Figure 16. Cross-sectional view of laundry wastewater sand filter

- Coarse gravel (10 cm thickness, 4-8 mm size)

- A nylon mesh sheet for layer separation and ease of cleaning
- An inverted plastic net basket at the base for water flow
- A tap at the bottom for collecting filtered water

Cost of the filter system is Rs. 3000. A 200-litre settling tank is incorporated to pre-treat the wastewater by allowing suspended solids to settle before filtration.

Top view of filter

Settling tank and filters

Methodology

1. Household wastewater was collected, bulked, and analysed for physio-chemical parameters such as pH, Electrical Conductivity (EC), Sodium Adsorption Ratio (SAR), Residual sodium carbonate (RSC), and heavy metals.
2. The sand filter was tested with wastewater collected from two locations.
3. During 2021-23, field trials were conducted at Agronomic Research Station, Chalakudy on okra plants (*var. Arka Anamika*) and fish under rain shelter conditions using:
   - Untreated wastewater (T_1)
   - Treated wastewater (T_2)
   - Normal irrigation water (T_3)
   - Mixed water in the ratio 1:1 of treated and untreated wastewater (T_4)

Filtration procedure

The wastewater was retained for 24 hours in the settling tank before being filtered. Filtered water was analysed for impurities and its suitability for irrigation and aquaculture.

Performance Evaluation

Laboratory analysis

- Initial analysis revealed laundry wastewater's unsuitability for irrigation due to high pH, EC, SAR, and RSC.
- The sand filter was effective in bringing these parameters to within permissible limits (Table 1).
- Heavy metals were below detectable levels in both untreated and treated wastewater.

Table 1. Characteristics of laundry wastewater before and after filtration

Sl. No	Parameters	Before filtration		After filtration		Safe limit value in irrigation water
		Sample I	Sample II	Sample I	Sample II	
1	pH	8.40	9.40	7.80	6.90	6.50-8.50*
2	EC (dS/m)	1.10	1.40	0.70	1.00	1.50*
3	CO_3^{2-} (meq/l)	0.00	0.00	0.00	0.00	-
4	HCO_3^- (meq/l)	4.80	3.60	2.40	2.40	-
5	Na^+ (meq/l)	9.30	13.50	3.50	6.50	-
6	K^+ (mg/l)	7.80	12.00	6.10	7.40	-
7	Ca^{2+} (mg/l)	1.60	8.10	29.40	26.50	-
8	Mg^{2+} (mg/l)	1.40	1.20	1.80	7.40	-
9	B (mg/l)	0.25	0.30	0.18	0.16	<1*
10	SAR (meq/l)	29.80	26.90	3.90	6.50	10.00*
11	RSC (meq/l)	4.60	3.10	0.80	0.50	1.25*
12	Ni (mg/l)	BDL#	BDL	BDL	BDL	0.20**
13	Cd (mg/l)	BDL	BDL	BDL	BDL	0.01**
14	Cr (mg/l)	0.00307	0.00308	0.00108	0.00109	0.10**
15	Pb (mg/l)	BDL	BDL	BDL	BDL	5.00**

Note: *Bureau of Indian Standards (1986); **FAO (1985); #BDL (below detectable level)

Field trials

Effects on crop growth and yield are as follows:

- The yield of okra from the treated wastewater was found to be equivalent to that of irrigation water of normal quality (Table 2).
- However, a 1:1 mixture of treated and untreated wastewater produced the best output (2.25 kg/plant).
- There were no discernible adverse effects or variations in plant height or leaf count across treatments.

Okra crop grown with treated wasterwater

Table 2. Effect of irrigation water quality on growth and yield of okra

Sl. No.	Parameters	Laundry wastewater (T_1)	Treated laundry wastewater (T_2)	Normal irrigation water (T_3)	Mixed water (T_4)
1	Plant height (m) 35 days after planting	0.44a*	0.41a	0.42a	0.42a
2	Number of leaves 35 days after planting	7.00a	6.00a	7.00a	8.00a
3	Yield (kg/plant)	1.97a	1.72a	2.19a	2.25a

*Numbers followed by same letters are not significantly different in a column at $p \leq 0.05$ as per DMRT test

Effect on soil properties

- Soil irrigated with treated wastewater showed improved nutrient levels (P, K, Ca, Mg) compared to untreated wastewater (Table 3)
- Heavy metal concentrations remained within safe limits

Table 3. Effect of different types of irrigation water on soil chemical properties

SN	Parameters	Laundry wastewater (T_1)	Treated laundry wastewater (T_2)	Normal irrigation water (T_3)	Mixed water (T_4)	CD ($p \leq 0.05$)	Safe limit value in soil
1	pH	7.02^a	6.85^b	6.39^d	6.50^c	0.06	-
2	EC (dS/m)	1.51	1.44	1.33	1.71	NS	-

3	OC (%)	1.74	2.27	1.74	2.00	NS	-
4	P (kg/ha)	957.25^{a}	844.49^{a}	569.66^{b}	862.16^{a}	157.86	-
5	K (kg/ha)	1256.15^{a}	1066.20^{c}	1190.15^{b}	1305.48^{a}	53.50	-
6	Ca (mg/kg)	1240.65^{a}	1262.40^{a}	1039.11^{b}	1264.24^{a}	59.12	-
7	Mg (mg/kg)	274.43^{a}	256.38^{a}	205.31^{b}	271.15^{a}	18.51	-
8	S (mg/kg)	130.10	101.56	94.32	112.26	NS	-
9	Fe (mg/kg)	24.62	23.02	22.70	23.33	NS	-
10	B (mg/kg)	0.31	0.34	0.35	0.39	NS	-
11	Mn (mg/kg)	21.75	21.11	18.54	20.64	NS	-
12	Zn (mg/kg)	6.76	5.95	4.09	7.08	NS	300*
13	Cu (mg/kg)	2.21	2.29	1.86	3.36	NS	140*
14	Ni (mg/kg)	0.019^{a}	0.017^{b}	0.014^{c}	0.011^{d}	0.001	75*
15	Cd (mg/kg)	BDL	BDL	BDL	BDL	NS	3-6*
16	Cr (mg/kg)	0.012^{a}	0.005^{c}	0.003^{d}	0.008^{b}	0.001	150*
17	Pb (mg/kg)	0.072^{a}	0.066^{b}	0.052^{c}	0.053^{c}	0.002	300*

Note: *European Union standards (EU 2002); *Numbers followed by same letters are not significantly different in a column at $p \leq 0.05$ as per DMRT test

Effect on chemical composition of plant

- Treated wastewater-irrigated crops had nutrient levels within safe limits and negligible heavy metal content.
- Chromium levels in edible parts were significantly below the permissible threshold.

Conclusion

Treated wastewater was found suitable for irrigation purposes, and the filter effectively reduced the pH, EC, SAR, and RSC of the wastewater to acceptable limits. The filter encourages water reuse and sustainability and is cost-effective and user-friendly, making it suitable for homesteads.

Treated Domestic Sewage Water as an Alternate Irrigation Source in Cotton-Wheat Cropping System

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Relevance

The availability of good quality fresh water is diminishing day by day, so it becomes imperative to explore alternative irrigation sources, such as treated sewage water, to sustain agricultural productivity. Therefore, reuse of treated sewage water in agriculture has become increasingly essential due to the growing scarcity of water resources for irrigation. However, using untreated wastewater can negatively impact soil properties, including increased salinity, SAR, organic matter content, bulk density and microbial population of the soil. In Punjab, sewage treatment plants (STPs) equipped with advanced technologies have been established in major cities to address this need. Punjab, a predominantly agricultural state, has 85% of its land under cultivation, with a cropping intensity exceeding 200%. Approximately 98% of the net sown area is irrigated, with 27% reliant on canals and 73% on groundwater, primarily extracted through tubewells. Excessive groundwater extraction has led to a significant decline in the water table across over 80% of Punjab's regions, particularly in areas with fresh and good quality groundwater located in the north-west, central, and south-eastern parts of the state. Conversely, in the south-western region, poor-quality groundwater causes salinity and alkalinity issues. To overcome freshwater shortage, application of wastewater as a low-quality irrigation resource has been explored in recent years. Hence, a field study was conducted on loamy sand soil to assess the impact of treated domestic urban sewage water on crop yield, produce quality and soil properties in a cotton–wheat cropping system. Thus, the study highlights the potential of wastewater reuse in addressing irrigation challenges while ensuring sustainable agricultural practices.

Description of Technology

A field experiment was conducted at Punjab Agricultural University, Regional Research Station, Bathinda on loamy sand soil in permanent plots to explore the possibility of using treated domestic sewage water alone or in combination with canal water in cotton-wheat cropping system for three years from 2016 to 2019. In canal water, the pH, EC, RSC, calcium & magnesium (Ca^{2+}+ Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^{-}), chloride (Cl^{-}) and sulphate (SO_4^{2-}) were 8.02, 0.298 dS/m, 0.92, 2.13, 0.38, 0.065, 1.21, 0.70 and 0.59 mg/l, respectively. The experimental soil was low in organic carbon, medium in available phosphorus and high in available potash. Initial pH, EC and organic carbon status of surface layer (0-15 cm) of soil were 8.28, 0.173 dS/m and 0.28%, respectively. The experiment comprised six treatments of irrigation combinations with four replications in randomized block design. Treatments included T_1, irrigations with canal water (CW); T_2, irrigations with treated domestic urban sewage water (TSW), T_3, pre-sowing irrigation (PSI) with TSW_{psi} and subsequent irrigations with CW; T_4, PSI with CW_{psi} and subsequent irrigations with TSW; T_5, two irrigations with TSW followed by two irrigations with CW (in rotation) and T_6, two irrigations with CW followed by two irrigations with TSW (in rotation). American cotton was grown during *kharif* season (May-October) and wheat in *rabi* season (November-April). The composition of treated urban sewage water used for the experiment is given in Table 4.

Table 4. Composition of treated city sewage water used for irrigation in Bathinda municipal corporation

Parameter	Content	Critical limit for irrigation	Parameter	Contents	Critical limit for irrigation
As (mg/l)	0.0072-0.0082	0.10**	Ca (mg/l)	35.16-36.96	400.0***
Cd (mg/l)	0.0009-0.0011	0.01**	Mg (mg/l)	12.99-14.48	60.0***
Cr (mg/l)	0.0057-0.0063	0.10**	S (mg/l)	72.32-73.92	-
Pb (mg/l)	0.0	5.0**	P (mg/l)	2.09-2.83	-

Ni (mg/l)	0.0028-0.0032	0.20**	K (mg/l)	34.36-35.9	-
BOD (mg/l)	4.99-5.23	10.0*	Zn (mg/l)	0.031-0.038	2.0**
COD (mg/l)	59.93-71.92	90.0	Fe (mg/l)	0.157-0.169	5.0**
RSC (meq/l)	0.4-0.5	< 2.5**	Mn (mg/l)	0.018-0.020	0.20**
EC (dS/m)	1.4-1.6	3.0***	Cu (mg/l)	0.002	0.20**
			E. coli	Present	-

Note: *United States Environmental Protection Agency (USEPA, 2012); **Bureau of Indian Standards (BIS, 2019); ***Food and Agriculture Organization (FAO, 2015)

Performance Evaluation

Effects on crop yield

Cotton: A comprehensive analysis of three years pooled data (Table 5) revealed that seed cotton yield was highest with treated domestic urban sewage water for irrigation. This treatment, along with T_4 (CW_{psi}–TSW) and T_5 (2 TSW–2 CW), consistently outperformed treatments relying more heavily on canal water. Parameters such as the number of bolls and sympods per plant were also significantly higher in TSW-based treatments. Total water use efficiency (TWUE) was highest in T_2 and lowest in T_1.

Wheat: Similar trends were observed in wheat cultivation (Table 6). Grain yield, plant height, the number of effective tillers, and spike length were significantly higher in treatments using TSW (T_2, T_4, T_5) compared to those using primarily CW (T_1, T_3, T_6). Total water use efficiency (TWUE) was also highest in T_2, followed by T_4, and was lowest in T_1.

The study thus highlights the substantial benefits of treated sewage water for irrigation in both cotton and wheat cultivation. Treatments incorporating higher proportions of treated sewage water (T_2, T_4, and T_5) consistently outperformed those with greater reliance on canal water (T_1, T_3, and T_6) across the parameters such as yield, plant growth attributes, and water-use efficiency in both the crops.

Cotton and wheat crops grown with treated urban sewage water

Table 5. Seed cotton yield (SCY) and total water use efficiency (TWUE) of cotton as influenced by treated sewage water treatments (pooled mean 2016-18)

Treatments	Plant height (cm)	Sympods (No.)	Bolls/ plant (no.)	SCY (kg/ha)	TWUE (kg/ha-cm)	B:C
CW 149.7		20.9	43.5	2967	38.5	1.00
TSW	161.0	24.4	51.0	3497	44.3	1.10
TSW_{ps} – CW	151.9	21.9	44.8	3061	39.2	1.02
CW_{psi} – TSW	159.5	24.2	50.4	3422	43.7	1.09
2 TSW – 2 CW	158.3	23.7	49.0	3325	43.0	1.07
2 CW – 2 TSW	151.9	22.4	45.7	3119	39.9	1.03
CD ($p \leq 0.05$)	5.1	1.1	2.7	204	-	-

Table 6. Grain yield and total water use efficiency (TWUE) of wheat as influenced by treated sewage water treatments (pooled mean 2016-17 to 2018-19)

Treatments	Plant height (cm)	Spike length (cm)	Yield (kg/ha)	TWU (cm)	TWUE (kg/ha-cm)	B:C
CW	93.9	9.86	4142	40.99	100.9	1.62
TSW	99.0	10.54	4714	40.88	115.4	1.93
TSW_{psi} – CW	94.8	9.97	4209	41.50	101.3	1.66
CW_{psi} – TSW	97.6	10.38	4577	41.22	110.9	1.86
2 TSW – 2 CW	96.9	10.21	4511	41.00	110.1	1.82
2 CW – 2 TSW	95.7	10.01	4272	42.20	101.1	1.69
CD ($p \leq 0.05$)	1.5	0.21	195	-	-	-

Extension and Adoption

To promote the careful adoption of treated urban sewage water in agriculture, the following strategies and precautions were followed:

Research and Monitoring

In this three-year-long field experiment on permanent plots, the increased productivity of cotton and wheat crops with treated sewage water (TSW) has been recorded. Accumulation of heavy metals was within the permissible limits in surface soil (0–15 cm), seed cotton, and wheat grains. The positive effect of treated sewage water was noted on the chemical properties of soil. *Escherichia coli* was not detected in dry seed cotton and dry wheat grains, but the presence of *E. coli* in the soil even in the non-TSW treatments rendered it unfit for use in edible crops. Although TSW enhanced cotton and wheat productivity, the heavy metal accumulation in soil, seed cotton and wheat grains was within the permissible range. This critical observation makes the researchers cautious about not recommending TSW for edible crops. However, continuous research on the long-term impacts of TSW on soil health and crop productivity is being carried out on floriculture crops to know its potential use in non-edible crops. Regular monitoring of treated sewage water quality is being done along with analysis of soil and plants to study the accumulation of heavy metals after the completion of the experiment.

Awareness and Training

Farmers are educated through lectures and trainings regarding the use of treated sewage water with utmost care and caution in field and horticulture crops. They were also made aware of the harmful effects of indiscriminate use of treated sewage water without proper monitoring.

Conclusion

These findings suggest that treated urban sewage water can serve as a sustainable and efficient alternative irrigation source, particularly in water-stressed regions by adopting strict water quality guidelines for irrigation purpose. Its use can enhance crop productivity while reducing dependency on diminishing freshwater resources. Future studies could focus on long-term soil health impacts, optimal sewage water treatment standards, presence of harmful microbial population and scalability for widespread agricultural adoption. The research highlights the capability of TSW to enhance yields, optimize water use, and provide nutritional benefits to crops.

Safe Use of Polluted Well Water for Wheat Cultivation in Medium Deep Soils of Maharashtra

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Relevance

In Ahmednagar district of Maharashtra near Rahuri, the untreated effluents from sugar factory distilleries and paper mills are often disposed into different lagoons. These effluents leak into the wells of nearby lagoons and contaminate them. There are many levels of contamination in well water, ranging from low to extreme. The well water used for irrigation has also contaminated the soils adjoining the lagoon. Depending on the concentration of different anions and cations in the effluents, the crop productivity in those areas is affected. Hence, a field study was conducted to assess the impact of contaminated well water on crop yield and soil properties in wheat-growing belt of Rahuri, Maharashtra. Consequently, the study underscores the potential of wastewater reuse to address irrigation challenges while upholding sustainable agricultural practices.

Description of Technology

Field experiments were carried out at farmers' fields of Chinchvihire and Deolali Pravara villages, Rahuri, Ahmednagar, Maharashtra during 2013-2015 to study the effect of polluted well water (due to sugar factory effluent) on crop production and soil properties in wheat. Recommended package and practices were followed during the crop-growing season. The experiment was laid out in a randomized block design with four replications having five treatments *viz.*, T_1, irrigation with polluted groundwater due to sugar factory effluent; T_2, irrigation with normal well water; T_3, one irrigation with normal well water followed by two irrigations with polluted groundwater; T_4, one irrigation with polluted groundwater followed by two irrigations with normal well water; and T_5, alternate irrigation of polluted groundwater and normal well water. The water requirement of the wheat crop was calculated based on field capacity, permanent wilting point, bulk density of soil and the root zone depth (75 cm) throughout the growing season. The irrigation was applied at 50% soil moisture depletion level.

Performance Evaluation

The water samples from the polluted and normal well were collected and analyzed for physical parameters *viz.*, total dissolved salts (TDS), EC and temperature; and chemical parameters *viz.*, pH, concentration of cations, concentration of anions, SAR and heavy metals by adapting standard analytical procedures (Table 7). The results showed that the medium polluted groundwater was of C_3S_1 class indicating high conductivity and saline water with low sodium content can be used in soils with restricted drainage. The normal well water was of C_2S_1 class indicating medium saline water with low sodium and can be used for irrigation on all crops. Initial soil properties before sowing of the wheat crop showed that the average EC of soil was 0.58 dS/m indicating non-saline soil and pH was 8.35 indicating high alkalinity. The cation and anion concentrations in medium polluted well water and normal well water were found in the sequence of $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$ while the anions were found in the sequence of $Cl^{-} > SO_4^{2-} > HCO_3^{-} > CO_3^{2-}$. The average SAR of soil was 2.61.

Experimental view of wheat crop grown with medium polluted groundwater due to sugar factory effluent

Maximum grain yield (2764 kg/ha) of wheat was recorded in the treatment T_2 (Irrigation with normal well water) followed by treatment T_4 (One irrigation with polluted groundwater followed by two irrigations with normal well water). The minimum yield of 2388 kg/ha was recorded in treatment T_1 (Irrigation with polluted groundwater due to sugar factory effluent). The treatment T_2 was at par with the treatments T_4 & T_5 and significantly superior over the treatments T_1 and T_3 (Table 8). The uptake of nitrogen by wheat crop was maximum in treatment T_2 (78.36 kg/ha) and minimum in treatment T_1 (44.50 kg/ha). The phosphorous uptake was maximum in treatment T_4 (22.15 kg/ha) and minimum in treatment T_3 (15.72 kg/ha) and potassium uptake was maximum in treatment T_2 (35.47 kg/ha) and minimum in treatment T_1 (29.09 kg/ha).

After harvesting of wheat crop, the soil properties (pH, EC, concentration of cations, concentration of anions and micronutrients) were analyzed by adopting standard procedures. It was observed that EC and TDS of soils were increased in all the treatments (Table 9). The pH of soil was decreased from 8.35 to 8.12, 8.09, 8.16, 8.07 and 8.22 in treatment T_1, T_2, T_3, T_4 and T_5, respectively. The concentration of Ca, Mg and K increased in all the treatments. The concentration of Na was found to decrease in all the treatments. The concentration of bicarbonates was found to increase in T_1 and decrease in T_2, T_3, T_4 and T_5. The concentration of chlorine was found to increase in all the treatments while the concentration of sulphate increased in all the treatments, except T_2. The concentration of heavy metals was within the safe limits in all the treatments.

Table 7. Chemical properties of normal well water and polluted groundwater

Parameter	Water quality							
	Normal well water				Polluted groundwater			
	2012-13	2013-14	2014-15	Average	2012-13	2013-14	2014-15	Average
pH	7.19	7.19	7.32	7.23	7.82	7.50	7.75	7.69
EC (dS/m)	0.53	0.53	0.57	0.54	0.73	1.61	2.38	1.57
SAR	0.60	0.60	1.03	0.74	10.68	4.66	8.18	7.84
Irrigation class	C_2S_1	C_2S_1	C_2S_1	C_2S_1	C_2S_2	C_3S_1	C_4S_1	C_3S_1

Table 8. Effect of irrigation practice on grain yield of wheat

Treatments	Grain yield (kg/ha)			Pooled
	2011-12	2012-13	2013-14	
T_1- Irrigation with polluted groundwater due to sugar factory effluent	2379	2744	2327	2388
T_2- Irrigation with normal well water	2723	3427	3523	2764
T_3- One irrigation with normal well water *fb* two irrigations with polluted groundwater	2557	3171	2006	2560
T_4- One irrigation with polluted groundwater *fb* two irrigations with normal well water	2664	3240	2889	2686
T_5- Alternate irrigation of polluted groundwater and normal well water	2599	3117	2286	2606
CD ($p \leq 0.05$)	205	1185	1230	199

Table 9. Effect of irrigation practices on soil properties

Parameters	Soil properties						Unit
	Before sowing	After harvesting					
		T_1	T_2	T_3	T_4	T_5	
Physical parameters							
Total dissolved salts	371	851	527	597	826	751	mg/l
Electrical conductivity	0.58	1.33	0.82	0.93	1.29	1.17	dS/m
Chemical parameters							
pH	8.35	8.12	8.09	8.16	8.07	8.22	-
Type and concentration of cations							
Calcium	9.33	11.45	10.70	9.25	10.60	8.70	meq/l
Magnesium	4.50	3.20	5.95	2.45	2.10	3.95	meq/l
Sodium	3.52	2.65	1.45	2.00	2.00	1.70	meq/l
Potassium	0.77	1.50	1.25	1.45	1.30	0.95	meq/l
Types and concentration of anions							
Carbonate	0.40	-	-	-	-	-	meq/l
Bicarbonate	1.71	2.37	1.47	1.49	1.67	1.24	meq/l
Chloride	4.26	7.35	5.95	6.10	6.40	5.95	meq/l
Sulphate	2.69	3.36	2.23	2.90	2.76	2.83	meq/l

SAR		1.32	0.94	0.51	0.79	0.78	0.68	-
Heavy elements	Safe limit* (mg/kg)							
Fe	-	3.39	4.65	4.42	2.25	2.19	4.44	mg/kg
Mn	-	11.22	11.07	11.51	10.12	9.62	14.16	mg/kg
Zn	300-600	1.18	1.14	0.98	1.51	1.10	1.13	mg/kg
Cu	135-270	2.84	2.54	2.72	2.18	2.54	3.09	mg/kg

Note: *Source- Awashthi (2000) and WHO (2007)

Extension and Adoption

Three field experiments were conducted at farmers' fields of Chinchvihire and Deolali Pravara villages, Rahuri, Ahmednagar, Maharashtra during 2013-2015 to study the effect of high [C_4S_2 (EC>2.25 dS/m, <10 SAR, 17)], medium [C_3S_1] and low [C_2S_1] polluted well water on crop productivity and soil properties in wheat-growing belt of Rahuri, Maharashtra. Highly polluted groundwater with very high salinity and medium sodium content was not suitable for wheat crop under medium deep soil. However, in the other two experiments, medium [C_3S_1] and low [C_2S_1] polluted well water can be used for irrigation in wheat.

Conclusion

Based on the above results, it is recommended that one irrigation with medium [C_3S_1] and low [C_2S_1] polluted water, followed by two irrigations of normal water, can be used to increase wheat production in medium-deep soils of Maharashtra.

Impact Assessment of Wastewater Irrigation on Soil, Groundwater, and Crop Health across Agroclimatic Regions of Bihar

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Relevance

The increasing population, industries, and agricultural activities require a great amount of water, resulting in depletion of groundwater day by day. Hence, farmers are now opting to use wastewater for irrigation of forest trees, agricultural crops, and also for other industrial works, only after processing. The primary goals of wastewater irrigation are to offer a dependable water source for farmers and to enhance soil quality by adding essential plant nutrients. However, wastewater application can solve many problems related to water scarcity and will lead to saving of financial resources, which in turn support the economy. Hence, based on the importance and all these facts, such types of studies have been conducted to assess the safe use of wastewater on agricultural crops by conducting a field experiment.

Description of Technology

An experiment was conducted at research farm of RPCAU, Pusa, Bihar with different treatment of wastewater and fresh water. The experimental soil was Entisol in order and taxonomically characterized as Calciorthents. Tomato crop was grown in split-plot design with three irrigation treatments [100% fresh water, 50% fresh water + 50% wastewater and 100% wastewater] as main factor and levels of boron (B) [0.0,0.5, 1.0 and 1.5 kg/ha] as sub-factor with three replications. All the standard crop management practices had been followed during the experimentation. The present study was conducted to investigate the nutrient content of wastewater and the relationship of wastewater with different B levels to find out the best recommended dose of B in tomato under calcareous soils of Bihar.

Performance Evaluation

Characteristics of wastewater

The value of turbidity, pH, EC, TDS was found to be higher in wastewater than that of groundwater. Similarly, concentration of Cl^-, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, RSC, Na^+, K^+, SAR are depicted in (Figure 17). The concentration of B, Zn, Fe, Cu and Mn were also found to be highest in 100% wastewater application where all the parameters were found within permissible range.

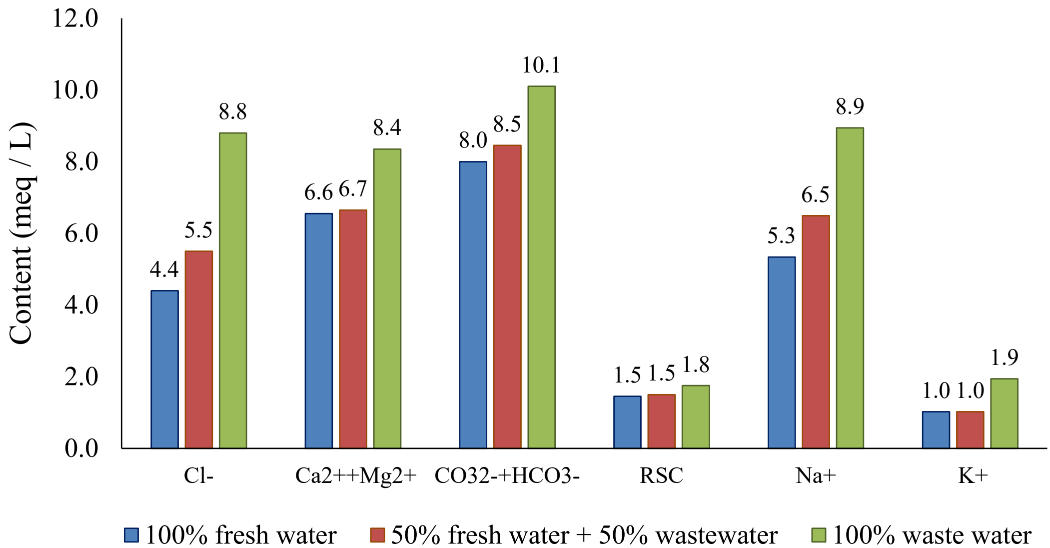

Figure 17. Nutrients in different water samples

Characteristics of experimental soils

The soil of the experimental field was sandy loam in texture with alkaline pH, low in organic carbon, rich in free $CaCO_3$(41.47 %) and medium in available N, P and K. Similarly, sulphur and B contents in soils were recorded in lower range i.e. 9.86 and 0.43 ppm, respectively. The concentrations of micronutrients Cu, Fe and Mn was higher, except Zn.

Characteristics of post-harvest soils

Results showed that pH, EC, organic carbon and sodium content were significantly higher in soils treated with 100% wastewater and also resulted in higher amount of available N, P and K in soil after harvest. Similarly, concentration of all the micronutrients among different irrigation levels were found significantly higher in soils treated with 100% wastewater.

Concentration in plants

The N, P and K contents of plant varied among different irrigation levels where all the parameters were found highest in 100% application of wastewater. The total Zn, Fe, Cu, Mn and B contents of plant were found highest with the same treatment.

Corp yield and uptake

The highest fruit yield and dry matter yield of tomato were recorded with combined application of 50% wastewater along with 50% fresh water (Figure 18). The results also showed that fruit and dry matter yields were significantly superior with addition of B at 1.0 kg/ha in comparison to other treatments (Figure 19). Maximum uptake of N, P, K and micronutrients were observed with the application of 50% wastewater in combination with 50% fresh water along with addition of B at 1.0 kg/ha in tomato.

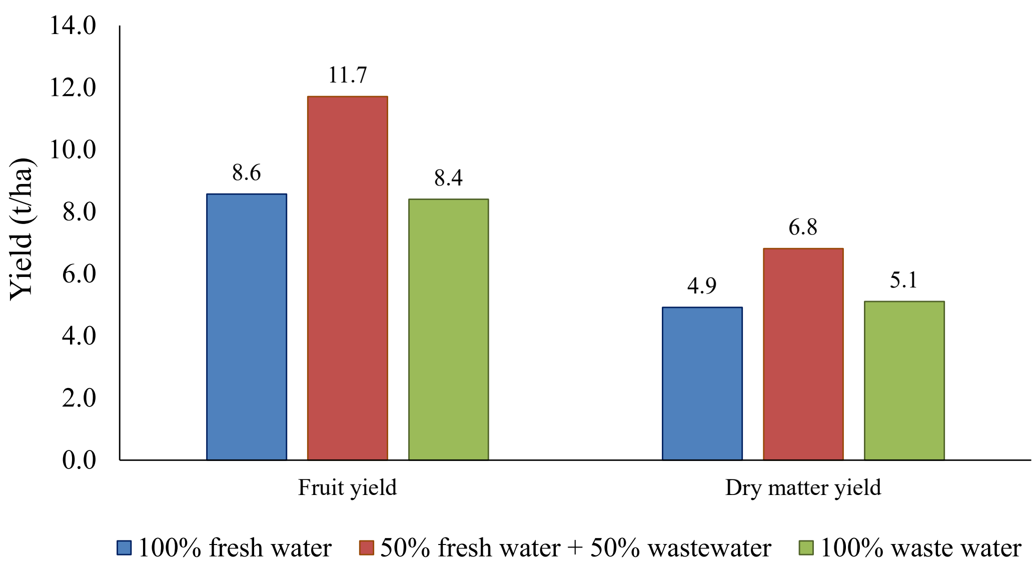

Figure 18. Effect of greywater on fruit and dry matter yields in post-harvest soil

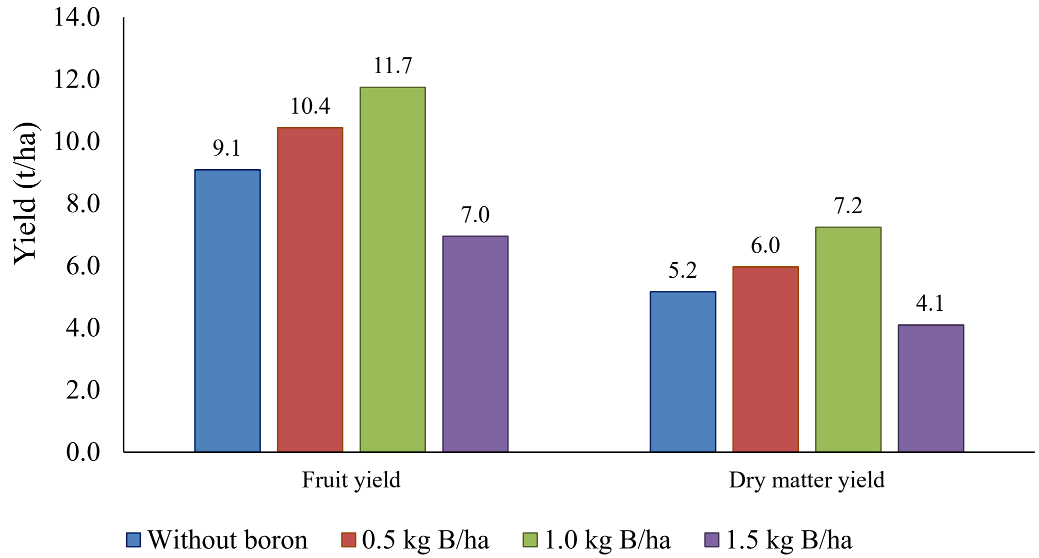

Figure 19. Effect of graded doses of boron on fruit and dry matter yields in post-harvest soil

Conclusion

In addition to the evaluation of the effect of wastewater irrigation, the type of crop to be grown, irrigation methods, and agronomic practices will determine the quality and suitability of irrigation water for sustainable crop production. Owing to global changes like population growth, increasing industrialization, rapid urbanization, and climate change, among others, which add pressure on freshwater resources, millions of farmers are driven to make use of wastewater. Hence, based on the performance of the crop, farmers may be suggested to grow cereal crops preferably rather than leafy vegetables, as they are high accumulators of pollutants. In case of wastewater, the present investigation reflected that an application of 50% wastewater in combination with 50% fresh water with 1.0 kg/ha boron emerged as the best among all the treatments and produced better yield of tomato crop as well as uptake of nutrients in B-deficient calcareous soils of Bihar.

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