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"A Review on: Greywater Treatment and Reuse for Sustainable Water Management"

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Abstract:
Greywater, generated from domestic activities such as bathing, laundry, and washing, constitutes the largest fraction of household wastewater apart from sewage. Owing to its relatively low pathogen and organic load compared to blackwater, greywater offers significant potential for reuse in non-potable applications such as irrigation, toilet flushing, and cleaning. With increasing freshwater scarcity and overexploitation of groundwater, greywater reuse is being recognized worldwide as a sustainable strategy for urban and rural water management. This paper reviews the composition and characteristics of greywater, highlights key treatment technologies—including biological, physio-chemical, nature-based, and hybrid approaches—and examines their efficiency, limitations, and applicability. Case studies from both developed and developing countries are analysed to identify barriers such as costs, energy demand, infrastructure, and public acceptance. The review emphasizes that integrated, multi-barrier systems offer the most reliable performance, though decentralized low-cost solutions are essential for water-stressed communities. The study concludes by outlining opportunities for scaling greywater reuse.

***Index Terms*: sustainable water management and resilience against future water crises, Greywater reuse, Sustainable water management, Decentralized treatment systems, Water scarcity, public acceptance.**

I. INTRODUCTION (COMPOSITION OF GREYWATER)

Sustainable water management is increasingly challenged by rapid urbanization, population growth, and the impacts of climate change. Ensuring reliable access to clean water is critical not only for public health and food security but also for sustaining ecosystems and supporting socioeconomic development. Conventional water supply systems, which often depend on long-distance transfers and overexploited groundwater, are proving inadequate and costly in many regions. As a result, alternative strategies such as wastewater reuse are gaining global attention for their potential to enhance water resilience.

Among different wastewater streams, greywater—originating from showers, sinks, laundry, and dishwashing—represents 50–80% of total household wastewater. Compared to blackwater, it has lower concentrations of pathogens and organic matter, making it more suitable for decentralized treatment and reuse. Greywater typically contributes 30–50% of household organic load and 9–20% of nutrient load, with per capita generation ranging from 60 to 200 litres per day. Its continuous availability and alignment with domestic water use patterns make it an attractive supplementary water resource.

Greywater reuse holds significant potential for non-potable applications such as toilet flushing, landscape irrigation, and cleaning, thereby reducing demand for freshwater. Numerous technologies, including biological processes, physio-chemical methods, membranes, and nature-based systems, have been studied to make reuse feasible. However, large-scale adoption remains constrained by infrastructural, economic, and social barriers, including uneven flows, toxic shocks, maintenance requirements, and public acceptance.

This paper provides a comprehensive review of greywater composition, treatment technologies, challenges, and future opportunities. It emphasizes the comparative evaluation of biological, physio-chemical, nature-based, and hybrid approaches, highlighting their efficiency, applicability, and limitations. In doing so, the review aims to advance understanding of greywater as a viable resource and contribute to strategies for sustainable water management.

Table 1. greywater contaminants by greywater source

Greywater Source	Possible Contents
clothes washer	Suspended solids (dirt, lint), organic material, oil and grease, sodium, nitrates and phosphates (from detergent), increased salinity and pH, bleach
dishwasher	Organic material and suspended solids (from food), bacteria, increased salinity and pH, fat, oil and grease, detergent
Bathtub and shower	Bacteria, hair, organic material and suspended solids (skin particles, lint), oil and grease, soap and detergent residue
Sinks, including kitchen	Bacteria, organic matter and suspended solids (food particles), fat, oil and grease, soap and detergent residue

Composition of Grey Water:

Grey water is generated from different domestic activities, and its composition varies depending on the source of origin. It may not always be suitable for direct reuse in all grey water treatment or recycling systems without proper management.

1. **Bathroom Grey Water**
   Water from hand washing, bathing, and other personal hygiene activities contributes approximately 50–60% of the total grey water volume. It is generally the least polluted category but still contains common chemical substances such as soap, shampoo, toothpaste, hair dyes, and other cleaning products. In addition, minor faecal contamination may occur during body washing, leading to the presence of bacteria and viruses.

2. **Laundry grey water**
   Wastewater from laundry activities accounts for about 25–35% of overall grey water generation. Its quality varies depending on whether it is wash water, rinse water, or second-rinse water. Laundry grey water may carry faecal residues from soiled clothes, which can introduce pathogens and parasites into the water stream.

3. **Kitchen Grey Water**
   Kitchen activities contribute nearly 10% of total grey water volume. This stream is typically the most polluted, as it contains food particles, oils, grease, and other organic matter, which promote microbial growth. In addition, it often includes chemical contaminants from detergents and alkaline cleaning agents, making it more difficult to treat compared to bathroom or laundry grey water.

Fig No 1: Greywater Discharge from Households

II. OBJECTIVES OF THE STUDY:

1. To analyze the composition and sources of greywater generated from different household activities.
2. To evaluate the potential of greywater reuse in non-potable applications such as irrigation, toilet flushing, and cleaning.
3. To review and compare existing treatment technologies, including biological, physio-chemical, and nature-based processes.
4. To identify challenges and limitations related to greywater reuse, including technical, economic, and social factors.
   To explore future opportunities for sustainable greywater management and policy integration

III. SCOPE OF THE REVIEW:

The scope of this review is limited to the study of greywater as a supplementary water resource for domestic and urban use. It focuses on identifying the major sources and contaminants of greywater and examining the treatment methods that make it suitable for reuse. This review focuses exclusively on greywater management, excluding blackwater and industrial wastewater. In addition, the discussion is confined to non-potable applications such as irrigation, toilet flushing, and cleaning, where greywater reuse can reduce dependence on freshwater. Regional and global practices are considered to highlight differences in adoption, while environmental, social, and economic aspects are briefly assessed to understand the broader impact

IV. METHODOLOGY OVERVIEW:

Greywater Technologies in Use in Worldwide:

Greywater systems range from simple low-cost devices that divert greywater to direct reuse, such as in toilets or outdoor landscaping, to complex treatment processes incorporating sedimentation tanks, bioreactors, filters, pumps, and disinfection (NovaTec Consultants Inc. 2004). Some greywater systems are home-built, do-it-yourself piping and storage systems, but there are also a variety of commercial greywater systems available that filter water to remove hair, lint, and debris, and remove pollutants, bacteria, salts, pharmaceuticals, and even viruses from greywater. The cost and energy requirements of these systems vary, usually increasing with higher levels of treatment.

1. **Biological Treatment**
   Biological systems rely on microorganisms to degrade organic pollutants. Rotating Biological Contactors (RBCs) use rotating discs for biofilm growth and achieve high organic removal with relatively simple operation. Moving Bed Biofilm Reactors (MBBRs) employ free-floating carriers that provide a large surface for microbial growth, offering stable performance even under

varying loads. Membrane Biofilm Reactors (MBfRs) combine membranes with biofilm activity and are effective for removing surfactants and nitrogen. Membrane Bioreactors (MBRs), both aerobic and anaerobic, are considered highly efficient, producing excellent effluent quality suitable for reuse, though they face challenges such as fouling, energy demand, and costs. Anaerobic systems like Upflow Anaerobic Sludge Blanket (UASB) reactors and anaerobic filters are also applied, often combined with UV disinfection, providing energy recovery but with lower pathogen removal compared to aerobic systems.

2. **Physio-Chemical Treatment**
These processes focus on separation or chemical transformation of pollutants. Membrane filtration technologies such as microfiltration, ultrafiltration, Nano filtration, and reverse osmosis can remove suspended solids, microbes, and salts, though fouling and concentrate disposal remain major challenges. Adsorption and ion exchange methods use activated carbon, zeolites, or ion-exchange resins to remove surfactants, nutrients, and dissolved organics, though their efficiency decreases once media are saturated. Chemical treatments such as coagulation, electrochemical oxidation, and photocatalytic membranes (for example TiO_2 under UV light) are applied to remove persistent organic compounds and disinfect greywater, but usually require integration with other processes.

3. **Nature-Based Systems**
Nature-based systems use ecological processes for treatment. Constructed wetlands (CWs) are the most widely studied, offering effective removal of organic matter, nutrients, and some pathogens through biodegradation, filtration, and plant uptake. They are low-cost and energy-efficient but require larger land areas and often need post-treatment disinfection. Green roofs and walls are urban adaptations of wetlands that provide partial treatment and aesthetic benefits, though they are less effective as standalone systems.

4. **Hybrid Systems**
Hybrid systems combine multiple technologies to enhance overall performance. Examples include UASB followed by MBR, or biofilm reactors combined with membranes, which achieve higher removal rates for both organics and pathogens. Two-stage and multi-barrier systems are particularly effective because they adapt better to variable greywater characteristics and consistently meet strict reuse standards

Table 2: Greywater treatment methods, advantages, limitations, and applications

Method	Examples	Advantages	Limitations	Suitable Applications
Biological treatment	RBC, MBBR, MBR, UASB	High organic removal, stable effluent quality, energy recovery (anaerobic)	Fouling, high-energy demand (MBR), limited pathogen removal (anaerobic)	Decentralized reuse, community-scale systems
Physio-chemical treatment	MF, UF, NF, RO, adsorption (activated carbon, zeolites), coagulation, photocatalysis	Effective solids and pathogen removal, compact systems	Fouling, concentrate disposal, high costs	Household reuse, industrial non-potable use
Nature-based systems	Constructed wetlands, green roofs/walls	Low-cost, energy efficient, aesthetic benefits	Large land area, seasonal variation, limited pathogen removal	Rural reuse, landscape irrigation
Hybrid systems	UASB + MBR, biofilm + membrane, multi-barrier designs	Combines strengths of multiple methods, reliable performance	Higher capital cost, operational complexity	Urban reuse, large institutions, municipal projects

V. LITERATURE REVIEW

Simon Raffael JABORNIG (Sep 2014)

Greywater recycling is increasingly recognized as a sustainable approach to mitigate urban water scarcity, with membrane bioreactors (MBRs) offering superior treatment efficiency compared to conventional systems such as sand filters or wetlands. However, high costs, energy demand, and membrane fouling remain major barriers to widespread adoption. Recent studies emphasize the need for low-cost, small-scale MBR designs with reduced fouling control, sustainable flux operation, and minimal chemical cleaning to enhance long-term stability. In addition, non-biological factors such as surfactants, oils, and pH significantly influence treatment performance, underscoring the importance of mechanistic models for future design and optimization.

Dr. Marc Pidou, Dr. Fayyaz Ali Memon, Prof. Tom Stephenson, Dr. Bruce Jefferson, Dr. Paul Jeffrey (2007)

The review by Pidou et al. (2007) traces the progress of greywater recycling technologies from simple filtration and disinfection to advanced systems such as membrane bioreactors and constructed wetlands. Simple and sand filter systems were found to offer limited treatment, membranes were effective in removing solids but less so for organics, while biological and extensive systems provided stronger organic removal. The most reliable outcomes came from hybrid systems combining multiple processes. The study concludes that integrated, multi-barrier approaches are the most effective for safe and sustainable greywater reuse.

Gupta, A., & Rathi, S. (2017). "On-site Greywater Treatment Systems for Indian Households: A Case Study."
A case study on the implementation of on-site greywater treatment systems in Indian households. The study focuses on small-scale, cost-effective filtration and biological treatment methods designed for low-income households. The paper demonstrates the

feasibility of implementing greywater treatment systems in both urban and rural India, emphasizing the importance of community engagement and local involvement in the design and maintenance of such systems. The authors conclude that greywater reuse can significantly contribute to local water conservation efforts if adapted to local conditions.

Jabornig, (2014):
The dissertation reviewed the state of greywater treatment technologies, emphasizing the effectiveness of membrane bioreactors (MBRs) in producing high-quality effluent suitable for reuse. However, the study noted major challenges including high energy demand, membrane fouling, and significant operational costs, which limit economic feasibility for single households. Greywater characteristics were found to vary widely, with nutrient imbalances and microbial risks complicating biological treatment efficiency. To address these issues, Jabornig developed and tested two alternative low-pressure MBR processes—a moving bed biofilm membrane reactor (MBBMR) and a fixed-fibre biofilm membrane process—both designed to reduce fouling, energy consumption, and costs while maintaining compliance with reuse standards. The dissertation concluded that despite strong potential for urban water reuse, cost, maintenance requirements, and uncertainty in long-term performance remain key barriers to widespread adoption.

Li, Wichmann, and Otterpohl (2009):
provided a comprehensive review of technological options for greywater treatment, highlighting that kitchen greywater is nutrient-rich and more challenging to treat, whereas bathroom and laundry streams are nutrient-deficient but largely biodegradable. The study emphasized that physical processes alone are inadequate to ensure safe reuse, while chemical and biological treatments demonstrate higher efficiency, particularly when applied in combination. The authors concluded that membrane bioreactors (MBRs) and hybrid systems represent the most practical and cost-effective solutions for achieving safe, high-quality greywater reuse.

Kumar, P., & Jha, M. K. (2020). "Sustainable Greywater Management in Indian Households: A Review of Treatment Technologies."
review the emerging trends in greywater treatment technologies for Indian households, focusing on sustainability and resource recovery. The study discusses various treatment options, including filtration, biological processes, and chemical disinfection, that have been tested in Indian urban and rural settings. The paper highlights the growing interest in using greywater for irrigation and toilet flushing in water-scarce regions, while noting the challenges related to system adoption, public perception, and regulatory frameworks in India.

Singh, R., & Verma, S. (2021). "Greywater Recycling for Sustainable Urban Water Management in India."
Singh and Verma (2021) investigate the feasibility of greywater recycling for sustainable urban water management in Indian cities. The study highlights successful case studies from cities like Bangalore and Pune, where greywater systems have been integrated into residential and commercial buildings. The authors note that despite the technical feasibility, widespread adoption is hindered by the lack of infrastructure, regulatory support, and public awareness. The paper advocates for policy reforms, financial incentives, and public awareness campaigns to promote the adoption of greywater reuse systems across Indian urban centers.

VI. RECOMMENDATIONS FOR GREYWATER REUSE MANAGEMENT IN INDIA

The reuse of greywater is an integral component of the natural water cycle and has become increasingly important in water-stressed countries, including India. Efficient governance of greywater reuse in India necessitates the adoption of targeted scientific strategies and policy frameworks. Firstly, a foundational step is the development of robust national standards and regulations that define acceptable treatment practices and quality thresholds for safe reuse. These standards should specify permissible levels of contaminants and outline best practices for greywater management. Secondly, the adoption of dual plumbing systems in both existing and new buildings should be mandated through legislative measures. This infrastructure would facilitate the separation of greywater from blackwater,
ation of decentralized greywater treatment systems, such as biosand filters, biochar filtration units, and constructed wetlands, can enhance local water reuse capabilities, especially in rural and peri-urban areas. Providing financial subsidies, technical assistance, and capacity-building programs for homeowners and communities can further encourage the uptake of these technologies. Fourthly, raising public awareness through targeted educational initiatives is essential to inform citizens about the advantages and safe practices of greywater reuse, thereby encouraging broader community engagement and support. Additionally, integrating greywater reuse strategies into urban planning and agricultural practices can optimize water resources, reduce reliance on freshwater sources, and mitigate the impacts of water scarcity. Implementing research and development initiatives to advance greywater treatment technologies and monitoring systems will also support continuous improvement in greywater management practices. By adopting these comprehensive measures, India can enhance its water sustainability, support its growing population, and address the challenges posed by water scarcity.
The techniques which can be presented to show possibilities of greywater reuse can be derived Physical self-bucketing is one of the most economical methods for greywater reuse. This technique involves collecting greywater from sources such as washing machines in buckets and using it immediately for tasks like flushing toilets or watering plants. This method requires no special permissions or infrastructure, making it accessible to everyone. Additionally, it eliminates the need to store water for extended periods, thus preventing bad odors and reducing the risk of spills. However, this technique is less suitable during the rainy season or when the soil is already saturated, as additional water might cause over-saturation and potential waterlogging. Greywater rerouting systems are simple and highly effective for domestic greywater management. In this method, greywater is diverted into a drum or container placed below the soil surface, from where it is then channeled to an irrigation system. This self-draining approach ensures that greywater is not stored for more than one day, minimizing the risk of odor and contamination. Additionally, a device should be incorporated to allow easy diversion of greywater directly to the sewer during rainy seasons or when the soil is saturated, ensuring that the system remains effective year-round. Treated greywater, which is typically colorless and odorless,

offers a versatile resource for various non-potable applications [35]. After undergoing treatment processes to remove contaminants and impurities, this greywater can be safely used for activities such as laundry, mopping floors, washing cars, gardening, irrigation, washing animals, and toilet flushing. The treatment ensures that the greywater meets specific quality standards, making it suitable for these diverse uses and helping to conserve freshwater resources by substituting treated greywater in tasks that do not require potable water quality.

Implementing these techniques can significantly enhance water conservation efforts, especially in water-scarce regions. By adopting simple methods like physical self-bucketing and greywater rerouting, alongside more advanced treatments, communities can effectively reduce their reliance on freshwater sources, promote sustainable water use practices, and mitigate the impacts of water scarcity. The greywater management systems could be divided into two systems through which recycling of greywater can be done through decentralized and centralized systems.

Decentralized system the decentralized greywater management system operates on a smaller, localized scale, typically involving individual houses or small clusters of homes. In this approach, greywater is discharged from domestic sources such as showers, sinks, and washing machines, collected, and stored on site or near the source of generation. The design and capacity of the collection and storage tanks are determined based on the volume of greywater generated and the specific reuse applications envisioned. Once collected, the greywater undergoes treatment using household-scale treatment plants or small community-based treatment units. These treatment systems often incorporate a combination of physical, chemical, and biological processes to ensure comprehensive purification. Sedimentation tanks are commonly used to allow heavier particles to settle at the bottom, effectively separating solids from the water. Filtration systems, such as biosand filters and biochar filters, are employed to remove suspended solids and organic contaminants. Additionally, biological treatment methods utilizing biofilms or constructed wetlands help degrade organic matter and reduce nutrient levels in greywater. The decentralized system offers several advantages. It provides flexibility and customization, allowing treatment processes to be tailored to the specific characteristics of the greywater and the intended reuse needs of each household or community. The reduced infrastructure requirements make this approach particularly suitable for rural areas or locations with limited access to centralized water treatment facilities. Immediate reuse of treated greywater for activities such as garden irrigation, toilet flushing, and washing further reduces the consumption of freshwater resources, enhancing water conservation at a local level.

Centralized system the centralized greywater management system operates on a larger, regional scale, typically serving multiple residential blocks, neighborhoods, or entire communities. This system involves collective discharge, collection, storage, and treatment of greywater at a centralized facility R. Jakhar and K. Styszko Desalination and Water Treatment 322 (2025) 101226 7 located outside individual residences. Greywater is collected from various domestic sources and conveyed through an extensive network of pipes to the central storage and treatment facility. The design of this network ensures efficient transportation and handling of the greywater volume generated by the entire serviced area. At the centralized treatment plant, greywater undergoes a series of advanced treatment processes designed to handle large volumes of water and achieve high-quality effluent suitable for a wide range of non-potable uses. The treatment process typically begins with pre-treatment steps, including screening and sedimentation, to remove large particles and debris. Primary treatment follows, utilizing physical and chemical processes such as coagulation, flocculation, and sedimentation to further purify the greywater. Secondary treatment involves biological processes, including activated sludge systems, bio filtration, and membrane bioreactors, which significantly reduce the organic load and nutrient levels in the water. Finally, tertiary treatment employs advanced methods like sand filtration, ultraviolet (UV) disinfection, and chlorination to ensure the treated greywater meets the required standards for reuse. The centralized system offers distinct advantages due to its scale and efficiency. Economies of scale allow for cost-effective treatment of large volumes of greywater, reducing per-unit treatment costs. The centralized approach ensures consistent treatment quality and compliance with regulatory requirements, providing a reliable supply of treated greywater for various non-potable applications. Treated greywater from centralized plants can be redistributed for industrial processes, landscaping, agricultural irrigation, and other uses, significantly contributing to water conservation efforts on a broader scale. By employing either decentralized or centralized greywater management systems, tailored to the specific needs and conditions of different regions, effective greywater recycling can be achieved. This not only enhances water sustainability but also reduces the strain on freshwater resources, promoting environmental conservation and resilience in water-stressed areas.

VII. CONCLUSION

Greywater management represents a vital opportunity for addressing global and local water scarcity. This review highlights that while biological, physico-chemical, and nature-based technologies each offer advantages, hybrid multi-barrier approaches provide the most reliable treatment outcomes. Decentralized systems are particularly well suited to rural and peri-urban regions, whereas centralized systems are advantageous at urban scales. For successful adoption, regulatory support, public awareness, and cost-effective designs are essential. With integrated strategies, greywater reuse can contribute significantly to sustainable water management and resilience against future water crises.

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