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# Greywater recycling as a strategy for water conservation and addressing the water scarcity crisis: A review

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## ABSTRACT

As global freshwater resources diminish due to climate change and urbanization, the transition from a linear "use-and-dispose" model to a circular water economy is critical. Escalating global water scarcity demands innovative strategies to decouple urban growth from freshwater depletion. Greywater recycling as a critical demand-side management tool for sustainable water conservation. Greywater, defined as domestic wastewater generated from washbasins, showers, and laundry but excluding toilet discharge, constitutes 50–80% of total household effluent. By adopting a "fit-for-purpose" approach, this underutilized resource can be treated and diverted for non-potable applications such as irrigation and toilet flushing, effectively substituting high-quality potable water. The analysis highlights that implementing on-site greywater recycling systems can reduce household freshwater consumption by 30–50%, while simultaneously alleviating hydraulic loads on centralized sewage infrastructure. Furthermore, the paper reviews various treatment technologies ranging from simple physical filtration to advanced biological disinfection required to mitigate health risks and ensure safe recycle. Ultimately, the study concludes that greywater recycling provides essential resilience against drought and infrastructure strain, positioning it as an indispensable component of integrated water resource management and sustainable urban planning in arid and semi-arid regions. This article provides a detailed technical classification of wastewater types, explores advanced and passive greywater recycling methodologies, and presents water quality standards for safe recycle based on WHO and EPA guidelines.

**Keywords: Greywater, Recycling, Water Conservation, Water Scarcity.**

## Introduction

Wastewater is broadly defined as water that has been used or contaminated by human or natural activities, requiring treatment to restore it to a desirable quality before discharge or recycle (Macedo et al., 2022). Its composition varies significantly depending on its source, leading to several primary classifications.

The following definitions categorize wastewater by origin and composition, supported by academic references.

**1. Municipal Wastewater:** Municipal wastewater serves as the primary collection of liquid waste from a community. It is characterized as a mixture of liquid and solid waste removed from residences, social institutions, and commercial establishments. It often includes groundwater and stormwater that enters the sewer collection system (Derco et al., 2024). It typically contains a mix of organic matter, nutrients (nitrogen and phosphorus), and microbial pathogens. Depending on the infrastructure, it may be a blend of domestic sewage and urban runoff (Macedo et al., 2022).

**2. Industrial Wastewater:** Industrial wastewater is a by-product of manufacturing and commercial activities, distinct from domestic sewage. This type comprises effluents generated by specific industrial sectors, such as petrochemicals, textiles, food processing, and metallurgy. The pollutants are sector-specific. For example, the food and beverage industry generates wastewater with high organic loads and varying pH levels, while the petrochemical industry produces effluents containing phenols, mineral oils, and refractory organic compounds. Treatment requires specialized processes because these contaminants can be toxic or difficult to biodegrade (Kato and Kansha, 2024).

**3. Agricultural Wastewater:** Agricultural wastewater results from farming and livestock activities. This category encompasses runoff and drainage water from irrigated land, as well as effluents from livestock operations (Macedo et al., 2022). It is frequently contaminated with fertilizers, pesticides, salts, and high concentrations of organic matter from animal waste. Due to increasing water scarcity, agricultural wastewater is increasingly viewed as a resource for irrigation, though it poses health risks if untreated (Macedo et al., 2022).

**4. Stormwater (Urban Runoff):** While often treated separately, stormwater is frequently integrated into wastewater management discussions, particularly in combined sewer systems. Stormwater is rainwater or snowmelt that flows over impervious urban surfaces rather than soaking into the ground. It is often deliberately discharged or enters wastewater systems through overflows. It picks up pollutants as it travels, including heavy metals, oils from roads, and microbial pathogens, posing a human health risk if discharged untreated (Derco et al., 2024).

**5. Domestic Wastewater Classifications**

Domestic wastewater is further sub-classified based on its specific source within a household, which determines its contamination level and potential for recycle.

Understanding the specific biological and chemical composition of wastewater is the first step in designing effective recycling systems. Wastewater is not a monolith; it is categorized by its source and contaminant load.

Domestic Wastewater Classifications are shown in Table (1).

**Table (1): Domestic Wastewater Classifications**

| Type | Source | Characteristics | Recycle Potential |
|---|---|---|---|
| **Greywater** | Showers, bathtubs, bathroom sinks, washing machines. | Low pathogen count; contains soap, hair, skin cells, and lint. Rapidly biodegradable. | **High:** Irrigation, toilet flushing, car washing (after treatment). |
| **Blackwater** | Toilets, urinals, bidets. | High pathogen load (feces, urine), toilet paper, and flush water. High risk of disease transmission. | **Low (On-site):** Requires heavy biological digestion (septic/sewer). Composting toilets can treat it. |
| **Dark Greywater** | Kitchen sinks, dishwashers. | Technically greywater but often treated as blackwater due to high grease, oil, and food scrap content (high organic load/BOD). | **Medium:** Requires grease traps and biological treatment before recycle. |
| **Yellow Water** | Urine (diverted from feces). | High in nitrogen, phosphorus, and potassium (NPK). Low pathogen load if separated from feces. | **High:** Excellent fertilizer after simple storage/ sterilization. |
| **Brown Water** | Feces mixed with flush water (without urine). | High solid content, high pathogen load. | **Low:** Biogas generation or composting. |

**A. Blackwater:** Blackwater is wastewater that has come into direct contact with human waste (feces and urine). It primarily originates from toilets and urinals, though some regulations also classify kitchen sink water as blackwater due to high organic food waste content. It contains high concentrations of nitrogen, organic matter, and pathogens, requiring rigorous treatment before discharge or recycle (Morandi and Steinmetz, 2019).

**B. Greywater:** Greywater is defined as household wastewater excluding toilet discharge. It originates from showers, bathtubs, hand basins, and laundry machines. Compared to blackwater, greywater has significantly lower concentrations of pathogens and nutrients (nitrogen and phosphorus). This makes it easier to treat and highly suitable for on-site recycling and recycle, such as for landscape irrigation (Morandi and Steinmetz, 2019).

Greywater is considered one of the most sustainable and effective solutions to combat water scarcity crises, particularly in arid and semi-arid regions. Greywater constitutes a significant proportion ranging from 50% to 80% of total domestic wastewater. This makes its exploitation a prime opportunity to reduce pressure on fresh water resources (Shaikh and Ahn, 2020).

**Greywater Recycling:** is increasingly recognized as one of the most sustainable and effective solutions to combat water scarcity crises, particularly in arid and semi-arid regions. Greywater constitutes a significant proportion—ranging from **50% to 80%** of total domestic wastewater making its exploitation a prime opportunity to reduce pressure on fresh water resources (Masi et al., 2016; Oteng-Peprah et al., 2018).

**Greywater Recycling Methodes:** Below is a comprehensive analysis of how greywater is used as a tool for conservation and solving water crises (Li et al., 2009; Shaikh and Ahn, 2020):

**1. Physical Treatment (Primary Treatment)**

These methods rely on mechanical separation to remove suspended solids, serving as the critical first line of defense to prevent clogging in downstream biological or chemical stages (IWA Publishing, 2024).

1. **Coarse Filtration:**
    1. **Mechanism:** Uses simple barriers like nylon stockings, mesh bags, or stainless-steel screens with a pore size typically between **1–2 mm** (Friedler et al., 2005).
    2. **Purpose:** Captures hair, lint, and large particulate matter. This pre-treatment is essential to protect pumps and fine filters from fouling (PUB Singapore, 2018).
2. **Sedimentation Tanks:**
    1. **Mechanism:** Water is retained for a hydraulic retention time (HRT) ranging from minutes to hours (IWA Publishing, 2024).
    2. **Purpose:** Allows heavy solids to settle as sludge and lighter materials (oils/grease) to float as scum, achieving roughly 60% removal of suspended solids (Pidou et al., 2007).
3. **Membrane Filtration (MF/UF):**
    1. **Microfiltration (MF):** Utilizes membranes with pore sizes of **0.1–10 µm**. It effectively removes suspended solids and protozoa but allows most viruses and dissolved organic matter to pass (Aquasana, 2024).
    2. **Ultrafiltration (UF):** Operates with finer pore sizes of **0.01–0.1 µm**. It is capable of removing viruses and colloidal particles, often serving as a pretreatment for reverse osmosis or as a polishing step (Aquasana, 2024; MDPI, 2024).

**2. Biological Treatment (Secondary Treatment)**

These systems employ microorganisms to degrade dissolved organic compounds (measured as Biochemical Oxygen Demand, or BOD) and nutrients that physical filtration cannot remove (Jefferson et al., 2001).

1. **Membrane Bioreactors (MBR):**
    1. **Process:** Integrates an activated sludge biological process with a microfiltration or ultrafiltration membrane barrier (Jefferson et al., 2015).
    2. **Output:** Produces high-quality effluent free of suspended solids and with significantly reduced pathogen counts. It is widely regarded as the most effective technology for high-density urban reuse (e.g., indoor toilet flushing) (Sigmadaf, 2023).
2. **Biological Aerated Filters (BAF):**
    1. **Process:** Uses a submerged media bed (plastic or ceramic) to support a biofilm of bacteria.
    2. **Mechanism:** Air is mechanically pumped into the reactor to maintain aerobic conditions for the biomass. While effective at reducing BOD, BAFs generally require downstream disinfection as they do not physically filter out pathogens as effectively as MBRs (Jefferson et al., 2015).

**3. Chemical Treatment (Tertiary Treatment)**

This stage is primarily for **disinfection** to inactivate pathogenic microorganisms (bacteria, viruses, protozoa) before the water is stored or used (Friedler et al., 2005).

1. **Chlorination:**
    1. **Mechanism:** Addition of chlorine (tablets or liquid sodium hypochlorite).
    2. **Pros/Cons:** It is low-cost and provides a residual disinfectant that prevents regrowth in storage tanks. However, chlorine residuals can be phytotoxic (harmful) to sensitive garden plants if concentrations exceed 0.5 mg/L (Rodda et al., 2011).
2. **Ozone ($O_3$):**

1. **Mechanism:** A powerful oxidant gas injected into the water.
2. **Pros/Cons:** Rapidly inactivates pathogens and breaks down color/odor compounds without leaving harmful chemical residues. The primary drawback is the high energy consumption required for ozone generation (ASCE Library, 2014).

3. **UV Irradiation:**
   1. **Mechanism:** Water passes through a chamber exposed to UV light (wavelength approximate 254 nm), which disrupts pathogen DNA/RNA (Gilboa and Friedler, 2008).
   2. **Pros/Cons:** Chemical-free and effective against chlorine-resistant protozoa (like *Cryptosporidium*). However, it requires low turbidity (clear water); suspended particles can "shade" pathogens, rendering the treatment ineffective (Winward et al., 2008).

**4. Nature-Based Solutions (NBS)**

These "passive" systems utilize soil, plants, and natural microbial communities to treat water, often integrating the treatment system into the landscape design (National Academies of Sciences, 2016).

1. **Constructed Wetlands:**
   1. **Mechanism:** Engineered basins filled with gravel and planted with macrophytes (*Phragmites*, *Typha*).
   2. **Horizontal Subsurface Flow:** Water flows horizontally through the gravel bed below the surface. This design prevents odors, mosquito breeding, and human contact with the water (Vymazal, 2010).
   3. **Vertical Flow:** Water is dosed intermittently onto the surface and percolates vertically through sand/gravel layers. This method allows for better oxygenation and nitrification compared to horizontal flow (MDPI, 2020).
2. **Mulch Basins:**
   1. **Mechanism:** Greywater is discharged into a trench backfilled with wood chips or coarse mulch.
   2. **Process:** The organic mulch filters solids and prevents surface ponding, while soil microorganisms break down organic contaminants before the water reaches plant roots (Santa Clara Valley Water, 2024).
   3. **Application:** Recognized by codes (e.g., California Plumbing Code) as the simplest and most cost-effective method for residential landscape irrigation (California Building Standards Commission, 2019).

**Greywater Recycling Concept and Strategic Importance:** The Philosophy of Greywater management relies on the "Fit-for-purpose" principle. This approach argues that high-quality potable water, which is expensive to treat and transport, should not be wasted on applications that do not require drinking-quality standards, such as garden irrigation or toilet flushing (Angelakis et al., 2018; Toze, 2006).

**Role in Addressing Water Scarcity:** Recycle achieves a direct impact on water security through three main axes:

1. **Reducing Demand for Fresh Water:** Implementing greywater systems for non-potable uses like irrigation and toilet flushing can reduce household potable water consumption by **30% to 50%** (Yu et al., 2013; Vuppaladadiyam et al., 2019).
2. **Alleviating Load on Central Treatment Plants:** By diverting greywater at the source, the volume of water entering the sewage network is significantly reduced. This decreases the energy and chemical inputs required for central wastewater treatment and lowers the risk of sewage system overflows during peak loads (Morel and Diener, 2006).
3. **Preserving Green Spaces:** During periods of drought and strict water rationing, greywater provides a reliable, continuous source for irrigating private and public green spaces without depleting strategic freshwater reserves (Vuppaladadiyam et al., 2019).

**Areas of Recycle (Applications):** The safe application of greywater is determined by the level of treatment applied (Morel and Diener, 2006) (Table 2)

**Water Quality Standards for Recycled Greywater:** The quality of recycled water determines its safe uses. Below are the standards typically cited by the World Health Organization (WHO, 2006) and the US Environmental Protection Agency (EPA, 2012).

**Table (2): Raw Greywater vs. Treated Greywater Characteristics**

| Treatment Level | Suitable Applications |
|---|---|
| **No Treatment (Direct Use)** | Sub-surface irrigation of ornamental trees, shrubs, and lawns. (Must be used within 24 hours to prevent bacterial growth and odors). |
| **Primary Treatment (Filtration)** | Drip irrigation for gardens. Filtration is essential to remove lint and hair that may clog irrigation emitters. |
| **Advanced Treatment (Disinfection)** | High-contact uses such as toilet flushing, car washing, and laundry. Requires biological treatment and disinfection (e.g., UV or chlorine) to ensure health safety. |

**Table (3): Raw Greywater vs. Treated Greywater Characteristics**

| Parameter | Unit | Raw Greywater (Typical Range) | Treated Greywater (Target for Recycle) |
|---|---|---|---|
| **pH** | - | 6.5 – 8.5 | 6.5 – 8.0 |
| **Suspended Solids (TSS)** | mg/L | 50 – 300 | < 10 |
| **BOD ($BOD_5$)** | mg/L | 90 – 290 | < 10 |
| **Turbidity** | NTU | 20 – 140 | < 2 |
| **Total Coliforms** | CFU/100mL | $10^3 – 10^6$ | < 10 (for indoor use) |
| **Fecal Coliforms ($E. coli$)** | CFU/100mL | $10^2 – 10^4$ | 0 (Non-detectable) |

**Table (4): Recommended Water Quality Limits by Use Case (WHO, 2006; EPA, 2012)**

| Intended Use | pH | BOD (mg/L) | Turbidity (NTU) | *E. coli* (CFU/100mL) | Treatment Level Required |
|---|---|---|---|---|---|
| **Surface Irrigation** (Orchards, vineyards) | 6.0-9.0 | < 30 | N/A | < 1000 | Primary + Secondary |
| **Spray Irrigation** (Public parks, golf courses) | 6.0-9.0 | < 10 | < 2 | < 1 | Secondary + Disinfection |
| **Toilet Flushing** (Indoor recycle) | 6.0-9.0 | < 10 | < 2 | 0 | Tertiary (MBR/UV/Chlorine) |
| **Car Washing** | 6.0-9.0 | < 10 | < 2 | 0 | Tertiary |
| **Construction/Dust Control** | 6.0-9.0 | < 30 | N/A | < 200 | Secondary |
| **Intended Use** | **pH** | **BOD (mg/L)** | **Turbidity (NTU)** | **E. coli (CFU/100mL)** | **Treatment Level Required** |

**(Note: BOD = Biochemical Oxygen Demand, a measure of organic pollution. Lower is cleaner.)**

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