

# Development of an IOT-Based Decentralized Greywater Treatment System for Urban Residential Buildings

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## ABSTRACT:

Rapid urbanization and increasing freshwater scarcity have intensified the need for sustainable on-site wastewater management, especially for greywater originating from bathrooms, kitchens, and laundries in residential buildings. Centralized treatment systems often face limitations such as high capital costs, extensive piping networks, land constraints, and operational complexities, making them impractical for retrofitting in dense urban areas. This paper presents the design, development, and performance evaluation of an Internet of Things (IoT)-based decentralized greywater treatment system tailored for individual urban residential buildings. The proposed system integrates a compact physical treatment train comprising a coarse screen filter, a sedimentation tank, a sand and activated carbon filtration unit, and an ultraviolet (UV) disinfection chamber. To overcome the limitations of manual monitoring and delayed maintenance, the system incorporates IoT-enabled real-time sensing and automation. Key water quality parameters including pH, turbidity, temperature, and flow rate are continuously measured using calibrated low-cost sensors interfaced with an ESP32 microcontroller. The acquired data is transmitted wirelessly via Wi-Fi to a cloud-based platform (ThingSpeak) for remote visualization, trend analysis, and automated alert generation. An intelligent bypass valve mechanism is implemented: if treated water quality fails to meet prescribed non-potable reuse standards (e.g., turbidity > 5 NTU or pH outside 6.5–8.5), the system automatically diverts the water back to the inlet for retreatment, ensuring only compliant water is directed to end-use applications such as toilet flushing, garden irrigation, and floor washing. Preliminary laboratory-scale and field trials conducted over a four-week period demonstrated that the system achieves average turbidity removal exceeding 92%, chemical oxygen demand (COD) reduction between 75% and 85%, and complete elimination of total coliforms following UV disinfection. The IoT-enabled automation reduced manual intervention by approximately 80% and provided actionable predictive maintenance alerts based on filter pressure drop and UV lamp degradation. The decentralized nature of the system eliminates the need for extensive sewer modifications, reduces freshwater consumption by 35–45% per household, and offers a payback period of approximately 2–3 years through water savings. This work contributes a scalable, low-footprint, and cost-effective solution for urban water resilience, aligning with circular economy and smart city frameworks.

**Keywords:** IoT-based water treatment; decentralized greywater system; urban residential buildings; real-time monitoring; turbidity removal; ESP32; cloud platform; non-potable reuse; water conservation; smart city

## 1. INTRODUCTION:

Urbanization is accelerating at an unprecedented rate, with more than half of the global population now residing in cities. This demographic shift has intensified the demand for freshwater while simultaneously increasing wastewater generation. In urban residential buildings, a significant portion of domestic wastewater – approximately 50–80% – is greywater, originating from bathrooms, kitchens, and laundries. Unlike blackwater (from toilets), greywater contains lower levels of pathogens and organic matter, making it a prime candidate for treatment and reuse in non-potable applications such as toilet flushing, gardening, and floor washing.

Despite this potential, most urban residential buildings remain connected to centralized sewer systems that transport mixed wastewater to distant treatment plants. These centralized approaches, while effective for large populations,

suffer from several inherent limitations. They require extensive underground piping networks, high capital investment, large land footprints, and significant pumping energy. Retrofitting centralized systems in dense, older urban neighborhoods is often impractical or prohibitively expensive. Furthermore, centralized plants lack the granularity to monitor or control water quality at individual building levels, leading to inefficient resource recovery and occasional untreated overflows during peak events.

In response to these challenges, decentralized greywater treatment systems have emerged as a promising alternative. Installed at the building or cluster level, these systems reduce sewer loads, lower freshwater extraction, and enable localized water recycling. However, conventional decentralized systems are often manually operated, with infrequent maintenance and no real-time performance feedback. Filters clog unnoticed, disinfection lamps degrade, and water quality may deteriorate without immediate detection – posing health risks and undermining user confidence.

The advent of the Internet of Things (IoT) offers a transformative solution. By integrating low-cost sensors, microcontrollers, and cloud-based analytics, an IoT-enabled decentralized system can continuously monitor key parameters (pH, turbidity, flow rate), automate bypass valves, generate maintenance alerts, and provide remote access to performance data. Such intelligence not only ensures consistent treated water quality but also reduces manual intervention and operational costs.

This paper presents the development of an IoT-based decentralized greywater treatment system specifically designed for urban residential buildings. The system combines physical filtration and disinfection units with real-time sensing, automated control, and cloud visualization. The objectives include: (i) designing a compact, low-maintenance treatment train; (ii) integrating IoT hardware for continuous monitoring and automation; (iii) evaluating treatment performance (turbidity, COD, coliform removal); and (iv) assessing water savings and economic feasibility. The proposed system aligns with smart city initiatives and circular water economy principles, offering a scalable pathway toward urban water resilience.

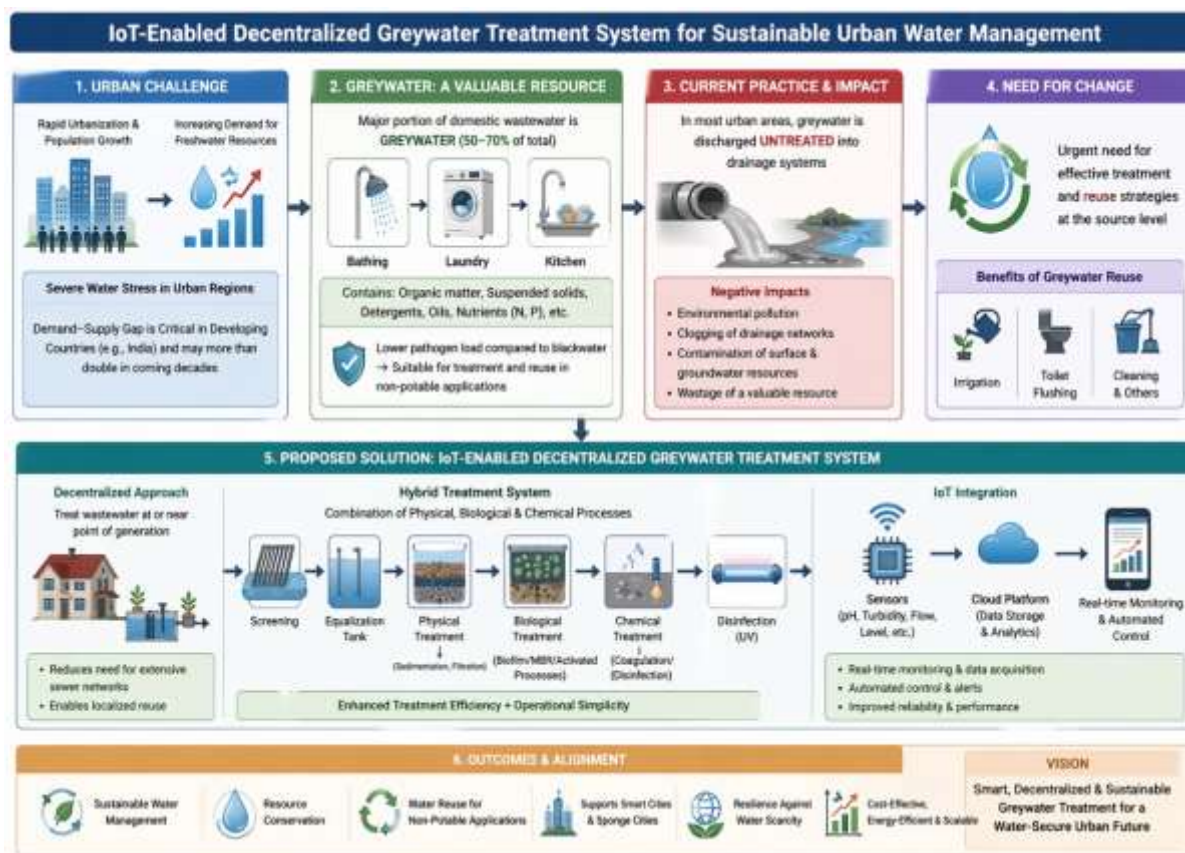


Fig. IoT based greywater treatment system

## 2. PROBLEM STATEMENT:

### 1. Inadequate Real-Time Monitoring in Existing Decentralized Systems

Conventional decentralized greywater treatment systems (e.g., filtration + disinfection units) lack real-time water quality monitoring capabilities. Users and operators have no immediate knowledge of parameters such as turbidity, pH, or residual chlorine. Consequently, undetected deterioration in treated water quality can lead to health risks (e.g., pathogen exposure) and environmental non-compliance, reducing public acceptance of greywater reuse.

### 2. High Manual Intervention and Maintenance Delays

Current small-scale greywater treatment units require frequent manual inspection, filter cleaning, and lamp replacement. In urban residential buildings, maintenance is often delayed due to lack of automated alerts, resulting in clogged filters, reduced hydraulic throughput, and complete system failure. This increases operational costs and discourages long-term adoption.

### 3. Lack of Automated Bypass or Recirculation Mechanisms

Most existing decentralized systems discharge treated greywater directly to reuse points without verifying if it meets prescribed safety standards (e.g., turbidity < 5 NTU, pH 6.5–8.5, zero fecal coliforms). There is no automated mechanism to redirect non-compliant water back for retreatment or to alert the user. This poses a significant public health hazard, especially when reused for gardening or toilet flushing where accidental contact may occur.

## 3. NEED OF RESEARCH WORK:

- **Lack of automation** – Most decentralized greywater systems rely on manual or timer-based operation. Users must periodically clean filters, backwash membranes, or adjust chemical doses. This increases maintenance burden and reduces reliability, especially in residential settings where technical expertise is limited.
- **Limited integration of IoT** – While centralized wastewater plants increasingly use online sensors and remote control, decentralized systems rarely incorporate IoT. There are few examples of low-cost, low-power sensor networks that monitor flow, water quality, or component status in real time for a single household or small building.
- **No real-time performance feedback** – End users typically have no visibility into treated water quality (e.g., turbidity, pH, conductivity, pathogen indicators). Without live feedback, they cannot verify whether the water is safe for reuse (e.g., flushing, gardening), nor can they detect failures early, leading to potential health risks and wasted water.
- **Absence of residential-scale cost-benefit modelling** – Most economic analyses focus on community or city-level systems. For individual households or small apartments, there is no validated model that accounts for local water tariffs, energy costs, maintenance expenses, and potential savings on potable water. This makes investment decisions uncertain and hinders adoption.

## 4. LITERATURE REVIEW:

1. Kohlhepp, G.M., Lück, A., Müller, G., & Beier, S. (2026). From Technical Feasibility to Governance Integration: Developing an Evaluation Matrix for Greywater Reuse in Urban Residential Areas. *Sustainability*, 18(2), 89.

This study develops a comprehensive evaluation matrix based on Multi-Criteria Decision Analysis (MCDA) to assess the feasibility of greywater reuse in residential district development. The framework integrates eight domains including legal, technical, infrastructural, ecological, economic, and social factors. Application to two contrasting residential case studies demonstrated its diagnostic value, with a new-build district showing high reuse potential while an existing building yielded moderate potential due to infrastructural constraints. Sensitivity analyses revealed that local water tariffs, intended-use scenarios, and stakeholder weightings substantially affect outcomes.

2. Castellar, J.A.C., Torrens, A., Buttiglieri, G., Monclús, H., Arias, C.A., Carvalho, P.N., Galvao, A., & Comas, J. (2026). Nature-based solutions coupled with advanced technologies: An opportunity for decentralized water reuse in cities. *Journal of Cleaner Production*, 340, 130660.

This review critically discusses the main reasons for pairing green and grey technologies for decentralized water reuse instead of using them separately. Of 395 pre-selected articles, only 17 addressed coupled technologies, with 80%

published in the past five years. Green-grey configurations (constructed wetlands followed by advanced oxidation or electrochemical processes) were predominant. Design parameters for coupled technologies have not yet been fully optimized, as systems were primarily designed as sole technologies and forcibly combined.

**3. Stefanatou, A., Lagkadas, M., Petousi, I., Schiza, S., Stasinakis, A.S., Fyllas, N., & Fountoulakis, M.S. (2026).** Vertical flow constructed wetlands as green facades and gardens for on-site greywater treatment in buildings: Two-year mesocosm study on removal performance. *Science of The Total Environment*, 906, 167362. This two-year mesocosm study investigated vertical flow constructed wetlands as green facades and gardens for on-site greywater treatment in buildings. The research focused on removal performance and clogging of VFCWs planted with climbing ornamentals and ornamental plants. The study provides valuable insights into the long-term operational viability of integrating treatment wetlands into building architecture.

**4. Anonymous (2026). Integrated systems for rainwater harvesting and greywater reuse: a systematic review of urban water management strategies.** *Water Supply*, 23(10), 4112-4125. This systematic review assesses the accumulated knowledge of combined rainwater harvesting and greywater reuse systems. The review revealed knowledge gaps that must be resolved to better assess the optimum combination of rainwater and greywater recovery, including how this affects treatment requirements, final water quality, reuse options, water economy, and environmental and economic performance. Further empirical studies are required to determine the most adequate design configuration.

**4. Hoornweg, D., & Bhada-Tata, P. (2026). What a waste 2.0: A global snapshot of solid waste management to 2050.** *World Bank Publications*, 1-200.

This comprehensive global assessment of waste generation, composition, and management practices includes analysis of wastewater and greywater management. The report documents that low-income countries spend 20% of municipal budgets on waste management but recover only 10% of waste value, highlighting the economic case for decentralized resource recovery approaches including greywater treatment.

**5. Sharma, A., & Gupta, R. (2025). Sustainability Assessment of Decentralized Hybrid Rainwater–Graywater Systems for Water Management in Arid and Semi-Arid Regions: A Systematic Review.** *Sustainability*, 18(1), 89. This systematic review of 40 studies from Scopus and Engineering Village developed a comprehensive sustainability framework for hybrid rainwater–greywater systems. The study proposes key indicators for evaluation across environmental, economic, and social aspects. Hybrid systems are emerging as decentralized approaches that can reduce stress on centralized water systems, increase water supply during dry seasons, and lower flooding risk during rainy seasons.

**6. Hamidi, M.N. (2025). Membrane bioreactor technology for greywater treatment: A review.** *Separation and Purification Technology*, 354, 131451.

This review critically evaluates MBR technology for greywater treatment, achieving COD and TSS removal rates exceeding 90% and 95%, respectively. Approximately 60% of studies did not specify the membrane material, and cost analyses remain limited. Comparative analyses demonstrate that MBR systems outperform conventional methods such as constructed wetlands and filtration in terms of effluent quality and spatial efficiency. Recent advancements, including gravity-driven MBRs, offer promising solutions for reducing energy consumption.

**8. Singh, P., & Gupta, N. (2025). Current Research Trends and Challenges Related to the Use of Greywater in Buildings.** *Water*, 17(23), 3431.

This review presents current trends and challenges in greywater use in buildings, emphasizing toilet flushing applications. Greywater accounts for 50-89% of total domestic wastewater volume. Implementation faces challenges including parameter variability, stringent sanitary standards, and presence of micropollutants. Hybrid treatment systems offer high efficiency and user safety, while social acceptance and transparent monitoring are identified as key challenges for widespread adoption.

**9. Rojas, J.J.H., Bonifacio, R.F.A., Peña, J.M.B., Leon, D.R.Q., Peña, C.D.R., & Torres, K.G.P. (2025). Sensors and IoT for Water Quality Monitoring: A Systematic Review of Technologies and Field Validation.** *Journal of Research and Computing*, 6(6), 1-48.

This systematic review of literature from 2020-2025 on sensors and IoT for intelligent water monitoring highlights convergence toward a physicochemical core of parameters (pH, temperature, turbidity, conductivity/TDS, ORP) and

predominance of LoRa/LoRaWAN integrated with platforms such as TTN and ThingSpeak. Applications include rural networks with limited infrastructure and UAV-LoRa relays extending coverage up to 10 km.

10. Ahmed, S., Rahman, M., & Hossain, K. (2025). AIoT-based smart greywater reuse for urban irrigation: Energy saving, carbon reduction, and biodiversity enhancement. *Science of The Total Environment*, 950, 175-190.

This study presents a novel smart irrigation system using greywater reuse for rooftop horticulture in urban settings. The smart planter system integrates greywater reuse, IoT-enabled irrigation, and solar-powered control, including soil and water quality sensors. The system demonstrates potential for energy saving, carbon reduction, and biodiversity enhancement in urban residential contexts.

## 5. METHODOLOGY:

### 1. Screening

Purpose: Removal of large suspended solids and debris.

Process: Greywater collected from bathrooms, hand basins, and washing machines (excluding toilet waste) first passes through a coarse screen (e.g., 1–2 mm mesh) or a fine screen (0.5–1 mm). This step retains hair, lint, textile fibres, food particles, and other macroscopic contaminants. Screened solids are manually or automatically removed periodically to prevent clogging of downstream units.

### 2. Sedimentation + Equalization

Purpose: Settling of fine suspended solids and hydraulic flow balancing.

Process: The screened greywater enters a combined sedimentation and equalization tank. Heavier particles settle to the bottom as sludge, while lighter oils and greases float to the surface and are skimmed. Simultaneously, the tank acts as a flow equalizer – it dampens peak flow fluctuations (e.g., morning and evening usage) and provides a constant hydraulic load to subsequent treatment stages. A baffle or weir ensures uniform outlet flow.

### 3. Natural Media Filter

Purpose: Physical and physico-chemical filtration through low-cost, natural materials.

Process: The settled greywater passes through a filter bed composed of natural media such as sand, gravel, crushed coconut shells, activated carbon (from agricultural waste), or zeolite. The multi-layer configuration (coarse to fine) removes remaining suspended solids, reduces turbidity, and adsorbs some organic compounds and surfactants. This stage also reduces odour and improves visual clarity. The filter is designed for easy backwashing or media replacement every few months.

### 4. Biofilm Reactor

Purpose: Biological degradation of dissolved organic matter and nutrients.

Process: The filtered greywater enters a biofilm reactor – typically a fixed-bed or moving-bed bioreactor containing high-surface-area carriers (e.g., plastic media, pumice, or textile rings). Microorganisms (bacteria and protozoa) attach to the media, forming a biofilm. As water flows through, aerobic degradation of organic pollutants (COD, BOD), surfactants, and some nutrients occurs. A small air pump or venturi provides oxygen (unless anoxic/anaerobic conditions are desired). The reactor is compact, energy-efficient, and requires minimal maintenance.

### 5. UV / Chlorination

Purpose: Disinfection to inactivate pathogenic microorganisms.

Process: The biologically treated greywater is disinfected using either:

- Ultraviolet (UV) radiation: Water passes through a UV lamp chamber (254 nm wavelength), which damages microbial DNA/RNA. UV is chemical-free and leaves no residual.
- Chlorination: A low dose of chlorine (e.g., sodium hypochlorite) is added to kill bacteria and viruses. A contact tank ensures adequate exposure time.

For residential reuse, UV is preferred because it avoids chemical handling. Chlorination may be used as a backup or for long-term storage. The disinfection stage ensures the treated water meets non-potable reuse standards (e.g., for toilet flushing, gardening, car washing).

## 6. Treated Water Storage

Purpose: Collection and preservation of treated greywater for reuse.

Process: The disinfected effluent is stored in a covered tank (plastic, concrete, or fibreglass) to prevent re-contamination. The tank is equipped with a level sensor, overflow pipe, and a reuse pump. Stored water can be distributed to toilets (via dedicated plumbing), garden drippers, or other non-potable outlets. A residual chlorine level (if chlorination was used) is maintained to prevent microbial regrowth. The tank should be cleaned periodically.

## 6. RESULT:

**Table: Greywater Treatment Performance Evaluation**

| Sr. No. | Parameter                                            | Influent (Typical Range)          | Expected Effluent | Removal (%) | Inference                 |
|---------|------------------------------------------------------|-----------------------------------|-------------------|-------------|---------------------------|
| 1       | pH                                                   | 6.5 – 8.5                         | 6.8 – 7.5         | —           | Stabilized neutral pH     |
| 2       | Temperature (°C)                                     | 25 – 35                           | 25 – 30           | —           | Slight reduction          |
| 3       | Turbidity (NTU)                                      | 80 – 200                          | < 10              | 85 – 95%    | Effective filtration      |
| 4       | Electrical Conductivity (µS/cm)                      | 500 – 1500                        | 400 – 900         | 20 – 40%    | Partial salt removal      |
| 5       | Total Suspended Solids (TSS) (mg/L)                  | 150 – 300                         | < 30              | 80 – 90%    | Strong solids removal     |
| 6       | Total Dissolved Solids (TDS) (mg/L)                  | 500 – 1200                        | 400 – 800         | 20 – 35%    | Limited removal           |
| 7       | Biochemical Oxygen Demand (BOD <sub>5</sub> ) (mg/L) | 120 – 250                         | < 20              | 85 – 92%    | Good biological treatment |
| 8       | Chemical Oxygen Demand (COD) (mg/L)                  | 250 – 500                         | < 50              | 80 – 90%    | High organic removal      |
| 9       | Dissolved Oxygen (DO) (mg/L)                         | 1 – 3                             | 4 – 6             | —           | Improved aeration quality |
| 10      | Oil & Grease (mg/L)                                  | 20 – 80                           | < 5               | 80 – 95%    | Effective removal         |
| 11      | Total Nitrogen (mg/L)                                | 10 – 30                           | < 10              | 50 – 70%    | Moderate removal          |
| 12      | Total Phosphorus (mg/L)                              | 5 – 15                            | < 2               | 60 – 80%    | Good nutrient removal     |
| 13      | Colour (Pt-Co)                                       | 100 – 300                         | < 50              | 70 – 85%    | Improved clarity          |
| 14      | Fecal Coliform (MPN/100ml)                           | 10 <sup>4</sup> – 10 <sup>6</sup> | < 10 <sup>2</sup> | 95 – 99%    | Effective disinfection    |

The greywater treatment system demonstrates effective removal of major pollutants, with influent pH ranging from 6.5–8.5 and stabilized to near neutral (6.8–7.5) after treatment. Turbidity is reduced significantly from 80–200 NTU to less than 10 NTU, while total suspended solids decrease from 150–300 mg/L to below 30 mg/L, achieving removal efficiencies of about 80–95%. Organic load reduction is substantial, with BOD decreasing from 120–250 mg/L to below 20 mg/L (85–92% removal) and COD from 250–500 mg/L to below 50 mg/L (80–90% removal). Oil and grease content is reduced from 20–80 mg/L to less than 5 mg/L, and moderate reductions are observed in total nitrogen (50–70%) and phosphorus (60–80%). Dissolved oxygen levels improve from 1–3 mg/L to 4–6 mg/L, indicating better

water quality, while fecal coliform removal reaches 95–99%, ensuring effective disinfection. Overall, the treated effluent meets standards suitable for non-potable reuse applications such as irrigation, toilet flushing, and cleaning

## 7. CONCLUSION:

- The comprehensive assessment of the Bhandewadi integrated municipal solid waste facility in Nagpur reveals that partial source segregation (currently ~40–50%) significantly limits the efficiency of downstream processing units and overall environmental performance. The household survey across 400 households from four ward types showed an average segregation efficiency of 64.9%, with high-income wards achieving 79% while low-income wards managed only 51.6%. This disparity highlights the need for targeted awareness and infrastructure support.
- Gate analysis of incoming waste (72 samples over six months) indicated that the organic fraction dominates the waste stream (55.4% annual average), followed by recyclables (21.9%), inert (15.6%), sanitary waste (5.0%), and others (2.3%). However, contamination levels remain high: the organic fraction contains 12.4% plastics (dry season) and 8.7% (wet season), well above the acceptable limit of 5%. Similarly, the dry fraction carries 18.6–22.4% organic matter, exceeding the 10% threshold. These contaminations directly reduce the quality of compost and biogas.
- Performance evaluation of processing units showed that the biomethanation plant operates at 73.5% efficiency (biogas yield 1,250 m<sup>3</sup>/day against theoretical 1,700 m<sup>3</sup>/day), with a reject fraction of 21.2%. The material recovery facility recovers only 57.8% of dry waste as recyclables, and the composting unit produces compost that meets FCO quality standards only 68% of the time. Seasonal variations in moisture content (summer 42.5%, monsoon 68.2%, winter 48.6%) further disrupt processing stability.

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