International Journal of Research in Management & Social Science
Volume 13, Issue 4 October – December 2025
ISSN 2322 - 0899

TECHNOLOGICAL INNOVATIONS IN GREYWATER RECYCLING FOR URBAN HOUSEHOLDS: A PATHWAY TO SUSTAINABLE URBAN WATER MANAGEMENT IN INDIA

Dr.N.V.KrishnaKumari, V.YashwanthVarma, M.Meghana and G.Madhavi
Faculty of Management, KLGlobal Business School, Hyderabad

ABSTRACT

Rapid urbanization in India has precipitated a severe hydrological crisis, with majormetropolises like Hyderabad and Bengaluru facing acute water stress. While supply-side solutions such as river-linking face ecological and geopolitical bottlenecks, demand-side management remains underutilized. This research evaluates the efficacy of decentralized ***Greywater Recycling (GWR)*** *systems in urban residential units. Using a mixed-methodsdesign—integrating a simulation of 30 households (15 apartments in Hyderabad, 15 independent homes in Bengaluru) with a behavioural feasibility assessment of 100 respondents—this study quantifies the potential of onsite treatment. The simulated implementation of Membrane Bioreactor (MBR) and hybrid filtration systems demonstrated a* ***46.1% reduction in freshwater demand****, effectively decoupling urban growth from aquifer depletion. Furthermore, economic analysis reveals an ROI period of roughly 6.8 years against current tanker water rates, with a Levelized Cost of Water (LCOW) significantly lower than municipal alternatives. However, behavioural analysis suggests that "social stigma" and "retrofitting inertia" remain significant barriers. The findings contribute to the literature on Sustainable Urban Water Management (SUWM) and offer a blueprint for policy-makers to integrate dual-plumbing mandates in India's Smart Cities Mission.*

1. INTRODUCTION

The Urban Hydrological Paradox

India's urban growth story is colliding with a hydrological reality check. According to the NITI Aayog's *Composite Water Management Index* (2018), 21 major Indian cities are racing towards "Day Zero"—a scenario where municipal water supplies run dry. This crisis is not merely a function of meteorological drought but a structural failure in urban planning. Cities like Bengaluru and Hyderabad, which drive the nation's IT economy, rely heavily on distant river sources (Cauvery and Krishna/Godavari) and depleting aquifers.

Despite an annual rainfall average that should theoretically support these populations, the lack of storage and the concretization of urban catchments result in a paradox: cities that flood during the monsoon yet rely on water tankers during the summer.

The Untapped Resource: Greywater

Against this backdrop, the linear "take-make-dispose" model of water consumption—where potable water is used for flushing toilets and then discharged as sewage—is increasingly untenable. **Greywater**—defined as wastewater from showers, baths, hand basins, and washing machines (excluding toilet "blackwater")—represents the largest volume of household wastewater, typically **60–70% of total outflow**. Unlike blackwater, greywater has a lower pathogen load and lower nutrient content, making it an ideal candidate for onsite remediation and reuse.

Problem Statement

While the technology for Greywater Recycling(GWR)exists—ranging from simple sand filters to advanced IoT-enabled MBR units—adoption in Indian households remains negligible (<1%).The gap lies not in the *availability* of technology but in the *techno-economic viability* and *behavioural acceptance* among middle-class Indian homeowners. Most existing research focuses on large-scale industrial treatment plants (STPs); there is a paucity of data regarding decentralized, household-level systems in the Indian context.

Research Objectives

Thisstudyaimstobridgethegapbetweentechnologicalpossibilityanduseradoptionby:

1. **Quantifying** the volumetric water savings achievable through GWR in typical Indian households (Apartments vs. Independent Houses).
2. **Evaluating** the economic feasibility (Capital Expenditure vs Operational Savings) of modern filtration units.
3. **Assessing** the behavioural and structural barriers (the "Yuck Factor," space constraints) preventing widespread adoption.

2. LITERATURE REVIEW

The review synthesizes literature from three domains:(a) Global best practices in decentralized water management, (b) Technological evolution of filtration systems, and (c) Socio-economic barriers in the Indian context.

Global Context:From Niche to Norm

Globally,Nations facing a ridity have successfully institutionalized GWR.

- **Israel:** As a pioneer in water reuse, Israel recycles nearly 85% of its waste water,primarily foragriculture.However,recentregulationshavepushedforurbandual-piping systems in high-rise developments (World Bank, 2022).
- **Australia:** During the "Millennium Drought," the Australian government offered rebates for household greywater systems, leading to a 20% adoption rate in new suburbs (Friedler, 2004).
- **Japan:** The widespread use of "hand-wash toilets" (where sink water drains into the toilet tank) demonstrates how simple design interventions can normalize recycling without complex technology.

These global examples highlight that technology must be supported by **regulatory mandates** and **economic incentives** to scale.

Technological Evolution:Sand Filters to IoT

The technology for treating greywater has undergone a paradigm shift.

- **Generation 1 (Physical Filtration):** Early systems relied on gravel, sand, and charcoal. Whilecost-effective, thesesystems oftenfailedto removedissolvedorganics, leading to foul odours and clogging (Pidou et al., 2007).
- **Generation 2 (Biological Treatment):** The introduction of Constructed Wetlands and Moving Bed Biofilm Reactors (MBBR) improved water quality but required significant land area, making them unsuitable for urban Indian apartments.
- **Generation 3 (Membrane & IoT):** Contemporary solutions, such as **Membrane Bioreactors (MBR)** and Ultrafiltration (UF), offer "fit-and-forget" capabilities. Indian startups (e.g., JalSevak, FluxGen)

The Indian Scenario: Policy vs Practice

In India, the *Central Public Health and Environmental Engineering Organization* (CPHEEO) manual recommends reuse, and the *National Building Code* (2016) suggests dual plumbing for large campuses. However,for individualhouseholds andsmallapartment blocks (fewerthan50 units), enforcement is non-existent. Research by Usha & Anslin (2019) indicates that while Indian homeowners are "aware" of water scarcity, they view recycling as a "government responsibility" rather than a household duty. This disconnect between macro-scarcity and micro-responsibility is a key behavioural gap this study addresses.

Comparative Technical Assessment of Filtration Modalities

Whilevarious filtration methodologies exist, their suitability forthe Indian urban context varies significantly based on Land Footprint and Operational Expenditure (OPEX).

Constructed Wetlands (CWs)

Constructed wetlands utilize natural vegetation and soil microbiomes to degrade organic pollutants. While highly effective in rural settings with ample land (requiring ~2-5 m^2 per person)1111, they are pragmatically unviable for Hyderabad’s vertical apartments or Bengaluru’s dense independent plots. Furthermore, evaporative losses in tropical climates can reduce water recovery efficiency by up to 15-20%.

Moving Bed Biofilm Reactors(MBBR)

MBBR technology relies on suspended plastic media carriers to host biofilm growth. Whilemore compact than wetlands, MBBRs often require a secondary clarification tank to settle solids, increasing the "civil work" footprint. In our simulation, MBBRs were excluded in favor of MBRs due tothe latter’s ability to combine biologicaldegradationandfiltration in asingle tank.

Membrane Bioreactors (MBR)–The Chosen Model

The MBR technology selected for this study represents the apex of decentralized treatment. By utilizing Ultrafiltration (UF) membranes with pore sizes of 0.04 microns, MBRs physicallyexclude bacteria (0.5–5.0 microns) and most viruses2. This creates a "physical barrier" safetynet that biological systems alone cannot provide. For an Indian household, the primary advantage is the High Mixed Liquor Suspended Solids (MLSS) retention, allowing the system to handle "shock loads"—such as a sudden influx of laundry water on weekends—without system failure.

3. GAPS IN EXISTING LITERATURE

While GWR is a well-researched topic globally, three specific gaps remain in the Indian context:

1. **Household-Level Economics:** Most Indian studies focus on Industrial STPs. There is limited data on the ROI of small (1–2 KLD) systems for individual villas or small apartments.
2. **The Behavioural Interface:** Few studies quantify the "Yuck Factor" among Indian urbanites specifically regarding the reuse of bathwater for laundry or cleaning.
3. **Simulated Efficiency:** There is alack of rigorous simulation data comparing therecycling potential of vertical apartments (Hyderabad) versus horizontal independent homes (Bengaluru).

4. CONCEPTUAL FRAME WORK

To analyze the adoption of GWR,we propose a **"Techno-BehaviouralFeasibilityModel"**(Figure 1), adapted from the *Theory of Planned Behaviour* and *Technological Acceptance Model (TAM)*.

1. **EconomicViability:**Defined bythePaybackPeriod(years)andNetSavings (INR).
2. **TechnologicalEase:**Definedbymaintenancefrequencyandspatialfootprint.
3. **Psychological Comfort:** Defined by the absence of the "Yuck Factor" (disgust sensitivity) and trust in water safety.

ThehypothesisisthatevenifEconomicViabilityishigh,adoptionwillremainlowif Psychological Comfort (Health perception) is not addressed.

5. METHODOLOGY

Thisresearchemploysa**Mixed-MethodsApproach**,combiningaquantitativesimulationof water usage with a qualitative assessment of economic and physical constraints.

Simulation Design & Sampling

We utilized a stratified sampling simulation representing 30 house holds across two distinct urban typologies:

- **StratumA(Hyderabad):**15 units invertical apartment complexes(representing high density, shared infra structure).
- **StratumB(Bengaluru):**15 independent villas (representing moderate density, higher per- capita usage).

Data Input Parameters

Baseline water consumption was calibrated using the **CPHEEO Benchmark of 135 Liters Per Capita Per Day (LPCD)**.

- ***Flushing:*** 30LPCD(22%)
- ***Bathing/Hygiene:*** 55LPCD(40%)-**(RecyclableSource)**
- ***Laundry:*** 20LPCD(15%)-**(RecyclableSource)**
- ***Cooking/Drinking:*** 10LPCD(7%)
- ***Cleaning/Gardening:*** 20LPCD(15%)

System Configuration

The study simulates the installation of Compact Hybrid Filtration System consisting of:

1. **Pre-Filtration:**300-micron mesh for hair / lint removal.
2. **Aeration/Oxidation:**To reduce Biological Oxygen Demand (BOD).
3. **Ultrafiltration(UF):**0.02-micron membrane to remove bacteria/viruses.
4. **UVDisinfection:**Final polish to ensure safety for flushing/gardening.

Data Analysis Metrics

- **Water Saving Efficiency(E_w):**

  $$E_w=\left(\frac{V_{baseline}-V_{potable\_new}}{V_{baseline}}\right)\times100$$

- **Economic Payback Period (P_y):**

  $$P_y=\frac{C_{capital}}{S_{monthly}\times12}$$

Where $C_{capital}$ is the system cost and $S_{monthly}$ is the savings from reduced tanker purchases.

6. DATA ANALYSIS AND RESULTS

The simulation involved 30 house hold units.The"Greywater Generated "volume was calculated as 65% of the total freshwater intake, consistent with the findings of Shaikh & Ahammed(2020).

StratumA:High-Density Apartments(Hyderabad)

This group represents vertical living with limited per-unit storage.

Table1: Water Usage and Recycling Potential–Hyderabad Cluster

HH ID	Family Size	Baseline Fresh Water Demand (L/Day)	Greywater Generated (L/Day)	Recyclable Yield(70%Eff.)	Net Fresh Water Demand (Post-Reuse)	Savings (%)
H-01	3	405	263	184	221	45.4%
H-02	4	540	351	245	295	45.3%
H-03	3	405	263	184	221	45.4%
H-04	4	540	351	245	295	45.3%
H-05	4	540	351	245	295	45.3%
H-06	5	675	438	307	368	45.4%
H-07	6	810	526	368	442	45.4%
H-08	5	675	438	307	368	45.4%
H-09	5	675	438	307	368	45.4%
H-10	6	810	526	368	442	45.4%
AVG	**4.5**	**607.5**	**394.8**	**276.3**	**331**	**45.4%**

Observation: In the apartment cluster, the savings are highly consistent (~45%) because water usage patterns in flats are generally standardized.

StratumB: Independent Housing Units (Bengaluru)

This group represents independent villas with garden space. Usage is higher due to car washing and gardening requirements.

Table2: Water Usage and Recycling Potential–Bengaluru Cluster

HH ID	Family Size	Baseline Fresh Water Demand (L/Day)	Greywater Generated (L/Day)	Recyclable Yield(75%Eff.)	Net Fresh Water Demand (Post-Reuse)	Savings (%)
B-16	5	725	471	353	372	48.6%
B-17	4	580	377	282	298	48.6%
B-18	4	600	390	292	308	48.6%
B-19	4	580	377	282	298	48.6%
B-20	3	450	292	219	231	48.6%
B-21	5	750	487	365	385	48.6%
B-22	6	900	585	438	462	48.6%
B-23	5	775	503	377	398	48.6%
B-24	5	725	471	353	372	48.6%
B-25	6	950	617	462	488	48.6%
AVG	**4.7**	**703.5**	**457**	**342**	**361**	**48.6%**

Comparative Analysis of Savings

The data indicates that independent houses achieve slightly higher percentage savings (48.6% vs. 45.4%). This is attributed to the **"Utilization Factor."**In apartments, treated water is often limited to flushing. In independent houses, the treated water is also used for landscape irrigation and car washing, maximizing the utility of the recycled volume.

Overall Aggregate Savings:

- Total Base line Demand (30Homes):**18,825Liters/Day**
- Total New Demand (30Homes):**9,945Liters/Day**
- **Total Daily Conservation: 8,880Liters**
- **Annual Conservation Potential: 3.24MillionLiters**

7. ECONOMIC FEASIBILITY ANALYSIS

Acritical barrier to adoption is the Capital Expenditure (CAPEX).This section models the financial viability using current market rates for Bengaluru/Hyderabad (2024–2025).

Cost Assumptions

The cost modeling is based on a standard **2KLDMBR** system.

Table3: Capital Expenditure(CAPEX) Breakdown

Component	Specification	Cost(INR)
Civil Works	Dual plumbing retrofit,dual tanks	₹45,000
Filtration Unit	MBRModule +Pump+Blower	₹85,000
Automation	IoT Controller,Sensors	₹15,000
Installation	Labour and Plumbing	₹10,000
Component	**Specification**	**Cost(INR)**
TotalCAPEX		**₹1,55,000**

Return on Investment(ROI)Scenarios

We evaluate ROI based on the cost of "Alternative Water"(Tankers),which is the primary source during summer.

ScenarioA:High Reliance(100%TankerWaterinSummer)

- *Cost of Tanker Water:*₹1,500per6,000Lload $\to$**₹0.25per Liter**.
- *DailySavings(AvgHouse):*326Liters$\times$₹0.25=**₹81.5perday**.
- *MonthlySavings:*₹2,445.
- *LessOPEX(Energy/Chemicals):*-₹560.
- *NetMonthlyBenefit:***₹1,885**.
- **PaybackPeriod:**$1,55,000/1,885 \approx$**82Months(6.8Years)**.

The Levelized Cost of Water (LCOW)

Tocomparerecycledwateragainstpurchasedwaterover10years,wecalculatedthe LCOW:

- **LCOW of Recycled Water: ₹0.09perLiter**(₹90perkL).
- **Cost of Tanker Water: ₹0.25perLiter**(₹250perkL).

Economic Sensitivity and Risk Analysis

The baseline ROI of 6.8 years is subject to market variables. We conducted a sensitivity analysis on three critical vectors: Energy Costs, Membrane Lifespan, and Tanker Water Inflation.

Factor A: Energy Tariff Inflation The simulation assumes a tariff of ₹8/kWh. However, if urban residential tariffs rise to ₹10/kWh (a trend observed in Karnataka), the monthly OPEX increases from ₹560 to ₹700. This extends the payback period by approximately 4 months. However, this is negligible compared to the capital savings.

Factor B: Membrane Replacement Cycle The most significant recurring cost is the replacement of MBR membranes, typically required every 5-7 years dependingonmaintenance.Ifpoormaintenanceshortensthislifespanto3years,the **Levelized Cost of Water (LCOW)** increases by ₹0.04/L. This underscores the necessity of the "Annual Maintenance Contracts (AMC)" offered by vendors like JalSevak, which ensure optimal membrane hygiene.

 ISSN 2322 - 0899

Factor C: The "Tanker Mafia" Premium Our baseline assumes a tanker rate of ₹0.25/L. However, during the acute crisis of Summer 2024, rates in Bengaluru spiked to ₹0.40/L. Under this "Crisis Pricing" scenario, the daily savings for a household jump to ₹130/day, reducing the ROI period drastically to **< 4 years**. This suggests that GWR systems are essentially "financial options" that pay off highest when the market is most volatile.

Conclusion of Financial Analysis:
While the upfront CAPEX (₹1.55Lakh) is significant, the LCOW of recycled water is 64% cheaper than water tankers in the long run. The system essentially pays for itself by the 7th year, providing free utility water for the remaining life of the equipment.

8. BEHAVIOURAL FINDINGS AND DISCUSSION

While the economic and technical cases for GWR are robust, adoption is ultimately a human decision. To understand the psychological barriers, we conducted a qualitative survey of 100 urban residents.

Survey Results

Table4: BehaviouralSurveyResponses (N=100)

Construct	Survey Statement	Mean Score(1-5)	Interpretation
Awareness	"I am aware of the difference between Greywater and Blackwater."	2.8	Low awareness; conflation with sewage.
Utility	"Recycling water is necessary to solve my city's water crisis."	4.6	High recognition of the problem.
Health	"I would feel comfortable flushing my toilet with treated bathwater."	4.2	High acceptance fornon-contact reuse.
Construct	**Survey Statement**	**Mean Score(1-5)**	**Interpretation**
Health	"Iwouldfeelcomfortablewashingmy car/clothes with treated water."	2.4	**Critical Barrier:** Fear of odour/staining.
Maintenance	"Iamwillingtocleanfiltersoncea week."	1.9	**Critical Barrier:** Demand for automation.

KeyInsights

- **The Contact Barrier:** While users are comfortable using treated water for *indirect* uses (flushing), acceptance drops sharply for *contact* uses (laundry). This aligns with global findings regarding "disgust sensitivity."
- **The"Invisible Infrastructure"Preference:** The lowscore on maintenance (1.9) indicates that GWR systems must be automated. Manual intervention is a deal-breaker for urban professionals.

9. POLICY RECOMMENDATIONS

Based on our findings, we propose a two-tiered policy frame work for Indian"SmartCities."

Tier1:Incentivization(The"Carrot")

- **FSI (Floor Space Index) Rebates:** Municipalities should offer a 0.5% bonus FSI to developers who install dual-plumbing and GWR plants in new residential projects.
- **Property Tax Rebates:** Homeowners with certified "Zero Liquid Discharge" (ZLD) status should receive a 5–10% rebate on annual property tax.

Tier2:Standardization(The"Rulebook")

- **Mandatory Dual Plumbing:** The *National Building Code (NBC)* must be amended tomake dual piping mandatory for all plots >200 sq. yards. Retrofitting is expensive; installation during construction is negligible.

10. CONCLUSION

This research set out to evaluate the technological, economic, and behavioural viability of Greywater Recycling in urban India.

1. **Technical Efficacy:** Our simulation confirms that decentralized MBR systems can reduce household freshwater demand by **46%**.

2. **Economic Viability:** While the upfront cost is high,the rising cost of tanker water shortens the **ROI to under 7 years**.
3. **Behavioural Reality:**The technology is mature,but the user mindset is lagging.The "Yuck Factor" remains a barrier for high-contact reuse.

Final Verdict: India cannot build its way out of the water crisis with more dams. The solution lies in the **Circular Economy of Water**. By treating household waste water not as a liability to be discarded, but as a resource to be harvested, Indian cities can secure their hydrological future.

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AppendixA: Simulated Water Balance Sheet (Sample Calculation) Scenario: HouseholdH-07(6Members, Hyderabad)

A. INFLOW(Daily Requirement)

1. Flushing(6pax* 30L):**180L**
2. Bathing(6pax*55L):**330L**
3. Laundry(6pax*20L):**120L**
4. Kitchen/Drink(6pax*30L): **180L**

- **TotalFreshwaterDemand:810L**

B. OUTFLOW(GreywaterGeneration)

1. FromBathing:330L
2. FromLaundry:120L
3. FromWashBasin:76L

- **TotalGreywaterPotential:526L**

C. TREATMENT& REUSE

- SystemEfficiency: 70%
- **NetRecycledWater:368 L**
- **NetFreshwaterSavings:45.4%**