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Environmental assessment of low-carbon water management and recycling on university campuses: a global perspective

Akhmet Ramazan[1], Samal Syrlybekkyzy[1], Lyailim Taizhanova[1], Yevgeniy Muralev[1], Yerbol Pangaliyev[1]*

[1]Sh. Yessenov Caspian University of Technology and Engineering,
akhmet.ramazan@yu.edu.kz, samal.syrlybekkyzy@yu.edu.kz,
lyailim.taizhanova@yu.edu.kz, yevgeniy.muralev@yu.edu.kz
*Correspondence: yerbol.pangaliyev@yu.edu.kz

Abstract: Universities worldwide are addressing intensifying water scarcity and are consequently adopting innovative, low-carbon strategies for water resource management. This study provides a global environmental assessment of low-carbon water management and recycling on university campuses by synthesizing 27 case studies from 12 countries. Data collected include treatment technologies (biological, membrane, physicochemical, and hybrid systems), quality indicators (BOD, TSS, TDS), reuse rates, and economic parameters (capital costs and payback periods). Descriptive statistics reveal an average campus recycling rate of 57% (median 33%), with biological processes achieving up to 95% removal of organic pollutants (BOD) but often requiring tertiary treatment to reduce dissolved solids (TDS). Capital expenditures ranged from USD 15 000 to USD 157 000, resulting in payback periods of 3–6.5 years. The SWOT analysis identified key barriers: including insufficient TDS removal, regulatory gaps, and social resistance. It also revealed opportunities such as the growth of ESG financing, awareness-raising initiatives, and the advancement of autonomous systems. The findings underscore the critical role of university campuses as living laboratories for sustainable water strategies, demonstrating that campus-scale recycling contributes to SDG (Sustainable Development Goals) 6 - “Clean Water and Sanitation”, but requires standardized life-cycle assessments and adaptation to local regulatory and climatic contexts. Furthermore, this research underscores the importance of conducting robust life-cycle assessments and comprehensive carbon accounting.

Keywords: low-carbon water management, wastewater recycling, environmental assessment, sustainable water resources, university campus.

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1. Introduction

Pollution of water sources by industrial, agricultural, and domestic effluents leads to a reduction in the availability of water suitable for use, thereby exacerbating water stress. These challenges render the achievement of the Sustainable Development Goals-particularly “Clean Water and Sanitation”-a priority on the global agenda. Sustainable management of water resources, aimed at alleviating water stress, forms part of the international commitments under the UN 2030 Agenda for Sustainable Development, where SDG 6 occupies a central position. Studies such as the present review underscore the need to integrate both water quality and quantity considerations into assessments of resource availability and environmental sustainability. (Wang et al., 2021).

In this context, university campuses function not only as consumers but also as crucial platforms for pilot projects and educational initiatives that advance the achievement of SDG 6. Campus-level implementation and subsequent scaling as exemplars of sustainable water infrastructure may include modernization of water-supply networks, water-reuse schemes, wastewater treatment facilities, and "smart" systems for monitoring water consumption. According to Times Higher Education, 867 universities in 96 countries have adopted sustainable water-management practices on their campuses. In terms of water demand, large university campuses are comparable to medium-sized cities. The development of so-called "green" campuses combines technical measures (e.g., installation of water-saving fixtures and system upgrades) with behavioral strategies (e.g., information campaigns and behavioral interventions), facilitating effective water-use reductions without compromising comfort. The United Nations emphasizes that universities serve a pivotal role in equipping future generations to achieve sustainable development and voluntarily commit to embedding the SDGs into their curricula, research agendas, and administrative practices. SDG 6 seeks not only to ensure access to water and sanitation but also to cultivate water conservation habits as part of a sustainable lifestyle (Gherheș & Cernicova-Buca, 2025).

There is a classification of wastewater according to its origin, level of contamination, and required treatment methods:

Blackwater: wastewater containing organic solids, fecal matter, and pathogenic microorganisms. Its primary source is toilets, and it may also include water from kitchen sinks (if food residues enter the drain) or laundry machines (when biologically based detergents are used). Blackwater is hazardous due to its high pollutant load, including bacteria, viruses, and nutrient concentrations (nitrogen and phosphorus) (Xu et al., 2023).

Greywater: relatively clean wastewater that does not contain fecal matter. Sources include washbasins, showers, bathtubs, and laundry machines (provided no organic solids are present); rainwater runoff is often also classified as greywater (Albalawneh & Chang, 2015). It contains fewer pathogens, but may contain fats, chemicals (shampoos, detergents), and dirt microparticles (Oteng-Peprah et al., 2018).

Laboratory effluents often contain chemical reagents, organic solvents, biological materials, pharmaceuticals, or radioactive substances, which necessitates their classification as a separate subcategory (Moretti et al., 2024). If wastewater contains hazardous substances (heavy metals, toxins, pathogens), it is classified as "hazardous industrial waste" and must comply with maximum permissible concentration (MPC) standards for each specific pollutant.

2. Materials and methods

2.1. Analysis of wastewater recycling practices on university campuses

The empirical basis of the study comprises 27 operational wastewater recirculation systems in university campuses across 12 countries. For each installation, data were collected on treated volumes; treatment schemes (wastewater types-greywater, blackwater); applied technologies (e.g., UASB, MBBR, SBR, membrane units, etc.); quality of the treated effluent (BOD, suspended solids, TDS); and economic indicators (capital and operating costs, payback period). These quantitative metrics were analyzed using descriptive statistics to obtain mean and median values as well as parameter ranges.

Selection criteria included:

- Availability and sufficiency of published data for each system (technical-economic characteristics and performance results);
- Diversity of technological solutions (including biological, membrane, physico-chemical, chemical, and innovative schemes);

- Broad geographic coverage (accounting for arid climatic and infrastructural conditions).

The sample encompasses both small, localized installations and large, regional plants, enabling assessment across various scales and implementation contexts. This combination affords a wide spectrum of operational conditions and technological profiles.

The focus on Asia, Africa, and Latin America is justified by several factors. In these regions, water scarcity is particularly acute, and agricultural water use is high (for example, in some South Asian and African countries, over 80% of freshwater withdrawals serve irrigation), necessitating water reuse. Moreover, developing countries in these areas have accumulated considerable experience with cost-effective wastewater recycling solutions, as evidenced by a wealth of publications and project reports. Finally, these regions offer significant scientific interest due to the challenge of achieving sustainable development under resource constraints.

Information for each case was drawn from academic publications-including journal articles, conference proceedings, and technical reports. Searches were conducted in Google Scholar, Scopus, and ResearchGate using thematic keywords. The analysis encompasses publications from 2000 through 2023. Key search queries included “campus wastewater reuse,” “university reclaimed water,” “greywater recycling,” and similar terms. Priority was given to peer-reviewed articles offering detailed descriptions of technical configurations and quantitative performance data. Consequently, the best available sources with complete case information were included.

For each case, the following uniform set of parameters was collected:

- Wastewater type (mixed or greywater)
- Year of system commissioning
- Treatment scheme (primary, secondary, tertiary treatment, and disinfection)
- Effluent quality metrics (BOD, suspended solids, total dissolved solids)
- Treatment capacity (volume)
- Capital and operating costs
- Water recirculation ratio

To summarize the results quantitatively, mean values, medians, and standard deviations of the key indicators were calculated. This approach allows characterization of the range and variability of observed values without introducing additional statistical modeling. Incomplete data were treated by computing statistics only over the subset of cases for which each parameter was reported.

2.2. Justification of the choice of methods

Descriptive analysis: This method was selected due to the limited volume and heterogeneity of the dataset, which comprises 27 cases with varied characteristics. This approach appropriately captures the core statistical metrics (means, medians, standard deviations) without introducing excessive assumptions. No regression analysis or other advanced models were employed, given the small number of observations and the lack of comparability between individual systems.

SWOT analysis: a well-established tool for the strategic evaluation of water-use systems. It enables formalization and comparison of non-financial factors (social, institutional, environmental) that cannot be addressed through purely quantitative methods.

Classification by technology type: carried out to facilitate comparative analysis. Grouping cases into categories (biological, membrane, chemical, etc.) makes it easier to detect common patterns and emerging trends across the sample.

2.3 Current state of water recycling on university campuses

In various regions of the world, university campuses are implementing autonomous and centralized wastewater treatment and recycling systems adapted to local climatic and infrastructural conditions. The following is an overview of key examples from Asia, grouped by country and technology type.

Punjab Engineering College (Chandigarh, India)

A Moving Bed Biofilm Reactor (MBBR) system was implemented in Chandigarh (Punjab), achieving 88% BOD removal and meeting the Central Pollution Control Board (CPCB) standards for reuse in irrigation. Compared to UASB and ASP, MBBR requires 6–7 times less land and has lower operational costs, making it economically attractive for university campuses. However, TDS removal efficiency is only 39–55%, necessitating integration of tertiary treatment stages such as membrane technologies (Sharma et al., n.d.).

St. John College Campus (Kalmeshwar, India)

Modern biological technologies such as MBBR and Sequencing Batch Reactor (SBR) demonstrate high levels of organic pollutant removal: MBBR systems achieve up to 88% BOD removal, while SBR reduces BOD from 225 mg/L to 9 mg/L and COD from 458.7 mg/L to 208 mg/L. Decentralized Extended Aeration systems are viable for compact campuses, serving up to 1,500 people and providing treated water quality (pH 7.1–7.5, BOD 20–30 mg/L) at minimal operational cost. However, in all cases, TDS removal remains a challenge, requiring hybrid schemes with membrane processes (Rangari et al., 2022).

Decentralized Village Station (Randal, India)

For a projected population of 5,150 by 2066, a sewage treatment system was designed with 200 mm pipelines and a flow velocity of 2.5 m/s. The treatment plant includes grit chambers (12 × 1.3 m), cylindrical sedimentation tanks (Ø 10.5 m), and aeration chambers, achieving BOD reduction to 20–30 mg/L and an effluent pH of 7.1–7.5. As in many systems, TDS removal is low and requires tertiary polishing (Shiyekar, 2017).

Sri Balaji Technical Campus (Rajasthan, India)

The wastewater treatment complex at Sri Balaji Technical Campus includes aeration tanks, clarifiers, and filters, reducing BOD from 100–120 mg/L to 20–30 mg/L. Elevated fluoride levels (3.5 mg/L) and electrical conductivity (2,500 μS/cm) were recorded, requiring process adjustments such as extended settling time, additional disinfection, and reuse of sludge as fertilizer (20–25 kg/day) (Bhagat Suraj Kumar & Tiyasha, 2013).

Rourkela National Institute of Technology (Odisha, India)

The system consists of aeration tanks (4.5 × 4.5 × 3.7 m^3) and a cylindrical clarifier (Ø 4 m, height 5 m), reducing BOD to 1.03–1.3 mg/L (standard ≤10 mg/L). Treated water (0.423 million L/day) meets pH (7.8–8.01) and TDS (≤600 mg/L) standards. The daily sludge output (72 kg) is dried and used as fertilizer, while water reuse reduces freshwater demand by 85% (Prof. Kakoli K. Paul et al., 2012).

Rourke College of Engineering (Rourke, India)

The originally designed STP (1999) was overloaded due to campus population growth. A new 1,100 m^3/day facility was designed, featuring screens, grit chambers, trickling filters, and secondary clarifiers to meet CPCB standards (Gupta et al., 2017).

Narasaraopeta Engineering College Sustainable Station Model (Chennai, India)

An analysis of the municipal STP in Koyambedu highlighted the need for nutrient polishing. The proposed Urban Sustainable Sewage Treatment Plant (USSTP) integrated nitrification/denitrification and phosphorus removal processes, achieving 90% reduction in BOD, suspended solids, total nitrogen, and phosphorus. Treated water is reused for agricultural irrigation and meets safety regulations (Vijayan Gurumurthy Iyer, 2017).

Industrial and University Cluster (Gorakhpur, India)

In the industrial cluster campus of Gorakhpur (Uttar Pradesh), a combined UASB + facultative pond system (FPU) of 2.4 MLD capacity treats ~1,368 kg/day CBOD and 4,704 kg/day COD. The system generates up to 174,729 kWh of biogas annually, saving 1.048 million in operational costs (Choudhary, A.P. & Pandey, G., 2014).

Local Complex Kohefiza (Bhopal)

Designed for a population increase from 91,190 (2013) to 119,142 (2043) with an average daily demand of 140 lpcd, the STP includes an intake well, mechanical screen, grit chamber, aeration tank, secondary clarifier, and sludge drying beds. Two parallel lines ensure continuous operation and staged expansion (Rajat Palya, 2018).

Palasuni Campus (Bhubaneswar, India)

Designed for a capacity of up to 10,000 people, the STP includes mechanical screening, aeration tanks (598 m^3), and circular clarifiers (Ø 10 m). BOD removal reaches 93%, but TDS removal remains low (Shree Samal, 2016).

Dr. T. Thimmaiah Institute of Technology (Karnataka, India)

Designed for a future population of up to 4,750, the treatment plant includes anoxic and aerobic processing, clarifiers, and sludge filtration, achieving 92% BOD removal. Treated water is reused for gardening, toilet flushing, and green space irrigation (Ariff et al., 2021).

Shahu Campus of Pune (Pune, India)

A pilot-scale Root Zone Technology system employing wetland plants in ferrocement tanks (3 × 60 L) demonstrated high removal efficiencies for BOD, COD, TDS, and other parameters, while remaining low-cost and energy-independent (Kalmegh et al., 2019).

Bahauddin Zakaria University (Multan, Pakistan)

At Bahauddin Zakariya University (Multan), a pilot plant consisting of a primary sedimentation tank, cascade aeration, maize-based biofilters, and an adsorption polishing stage achieved reductions of 91% in TSS, 46% in TDS, 88% in BOD_5, and 87% in COD at an energy consumption of 0.4–0.7 kWh m^{-3}, confirming its robustness under South Asian peri-urban conditions (Kanwar et al., 2019).

Rajshahi University of Engineering & Technology (Rajshahi, Bangladesh)

At Rajshahi University of Engineering & Technology (RUET), horizontal slow sand filtration through graded layers of sand and gravel yielded decreases of 51% in TSS, 57.4% in TDS, 53.5% in total solids, and 72.9% in turbidity; pH and electrical conductivity remained within acceptable irrigation limits (Bari, 2019).

DEWATS, Sleman Regency, Yogyakarta (Yogyakarta, Indonesia)

In Sleman Regency (Yogyakarta), DEWATS units of Type 1 and Type 2-based on anaerobic baffled reactors (ABR) and anaerobic filters-exhibited varying performance: the Type 2 system achieved a 73.24% reduction in COD and met Indonesian standards for pH, TSS, TDS, and pathogenic indicators. Precast ring manholes facilitated safe sludge removal without E. coli leaching into the subsurface (Saraswati et al., 2021).

Shinas College of Technology (Shinas, Oman)

At Shinas College of Technology, a multistage treatment train-comprising mechanical screening and grit removal, physico-chemical processes, and biological stages-produces effluent suitable for campus irrigation and non-potable uses. The water quality meets technical-use criteria, thereby reducing freshwater demand (Fatema Abdullah Said Al Maawali et al., n.d.).

Adama Science and Technology University (Nazret, Ethiopia)

Adama Science and Technology University’s design for a 3,996 m^3 d^{-1} facility includes coarse screening, grit chambers, primary sedimentation, biofiltration, tertiary polishing, and sludge methanation. Treated effluent irrigates the experimental farm, and digested sludge is applied as fertilizer, reducing both freshwater consumption and enhancing soil fertility (Civil Engineering Department, Group 13814, 2015).

Bahir Dar University (Bahir Dar, Ethiopia)

A comparative evaluation of UASB, sequencing batch reactor (SBR), and constructed wetland systems identified a combined anaerobic–biofiltration approach as the most effective and cost-efficient option for campus-scale deployment (Buat, Y., & Abebe, A., 2021).

These case studies illustrate the diversity of applied treatment technologies, the scalability of solutions across geographic contexts, and common challenges-particularly the relatively lower removal efficiency of dissolved solids-relevant to developing sustainable water management systems on university campuses.

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University campuses, by combining their research capabilities with the practical imperatives of infrastructure management, represent a critical proving ground for wastewater recirculation technologies. According to Ghaitidak and Yadav (2013), approximately 50–80% of domestic sewage volume is attributable to greywater, making it a highly promising resource for reuse (Ghaitidak & Yadav, 2013). Treatment and reclamation of greywater can substantially alleviate the burden on centralized water supply and sewerage systems, particularly under conditions of freshwater scarcity. The integrated configuration of such systems, including mechanical, biological, membrane, and disinfection stages, is illustrated in the treatment scheme diagram (Figure 1).

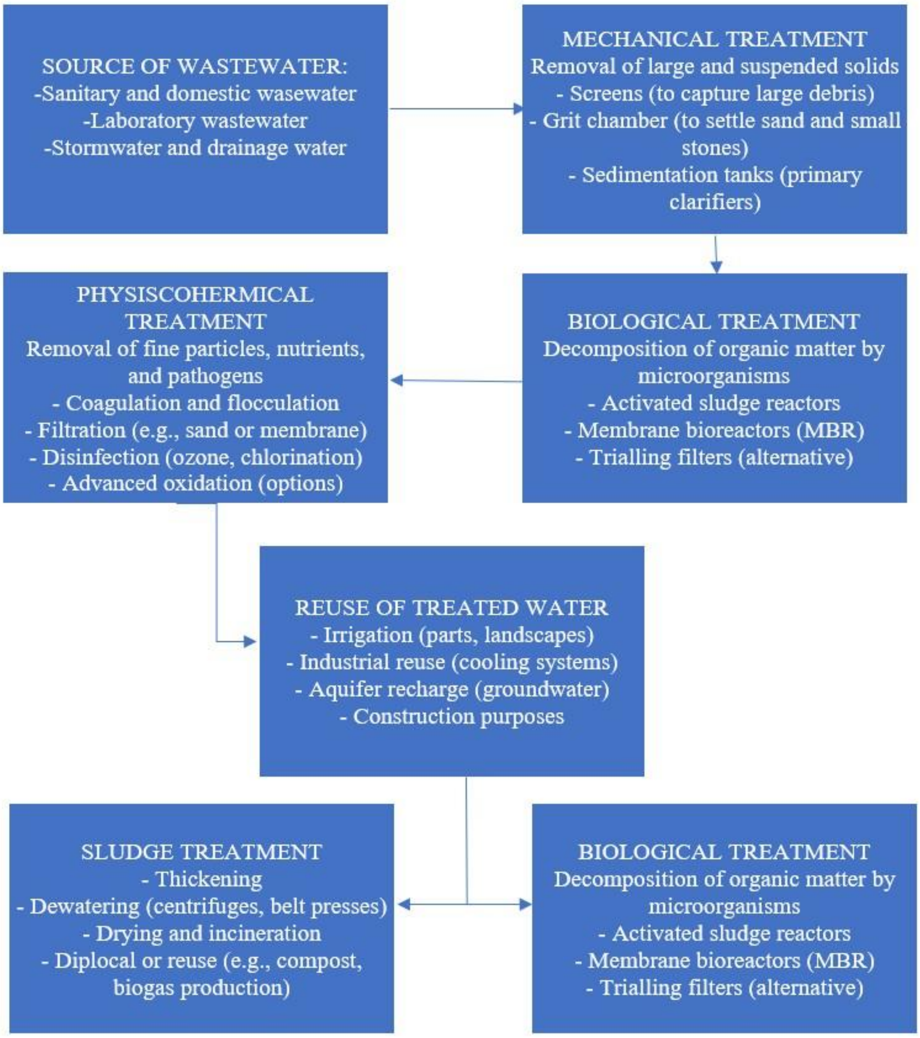

Figure 1. Technological scheme of wastewater treatment and recycling at universities

In contemporary university campuses, a wastewater recirculation system comprises an integrated suite of treatment stages designed not only to purify effluent but also to enable its multiple reuses. The process typically begins with mechanical primary treatment, which removes coarse suspended solids and protects downstream units. This is followed by a biological reactor-such as an upflow anaerobic sludge blanket (UASB), moving-bed biofilm reactor (MBBR), or sequencing batch reactor (SBR), for the removal of organic pollutants. To further improve water quality and reduce total dissolved solids (TDS), a tertiary treatment stage employing membrane technologies (e.g., reverse osmosis (RO) or pressure-driven submerged filtration (PSF)) is applied. Finally, the permeate undergoes disinfection-either by chlorination or ultraviolet (UV) irradiation-before being returned to campus service applications, such as landscape irrigation and toilet flushing. Detailed characteristics of the studied wastewater recycling systems are summarized in Table 1.

Table 1. Technical specifications and performance metrics of wastewater recycling systems across university campuses, includes treatment technologies, disinfection methods, and influent/effluent water quality parameters

No.	University	Country	Wastewater source	Treatment Technology (Components)	Disinfection method	Water Characteristics
1	STP "Diggian", Mohali	India	Wastewater from the sectors of Chandigarh	MBBR + tertiary purification	–	Influent: pH 7.5; TSS 157.0 mg/L; TDS 281.3 mg/L; BOD 186.6 mg/L; COD 346.6 mg/L; NH_3-N 19.6 mg/L; PO_4^{3-} 18.1 mg/L. Effluent: pH 8.0; TSS 33.6 mg/L; TDS 125.6 mg/L; BOD 23.3 mg/L; COD 67.6 mg/L; NH_3-N 21.9 mg/L; PO_4^{3-} 2.1 mg/L.
2	STP Raipur Kalan	India	Wastewater from settlements/complexes	UASB	–	Influent: pH 7.5; TSS 139.6 mg/L; TDS 270.6 mg/L; BOD 166.3 mg/L; COD 338.3 mg/L; NH_3-N 25.9 mg/L; PO_4^{3-} 15.3 mg/L. Effluent: pH 8.2; TSS 32.3 mg/L; TDS 163.3 mg/L; BOD 33.6 mg/L; COD 148.3 mg/L; NH_3-N 32.4 mg/L; PO_4^{3-} 4.8 mg/L.
3	STP Raipur Khurd	India	Wastewater from towns/villages	ASP	–	Influent: pH 7.7; TSS 182.3 mg/L; TDS 275.3 mg/L; BOD 146.6 mg/L; COD 377.3 mg/L; NH_3-N 27.7 mg/L; PO_4^{3-} 17.5 mg/L. Effluent: pH 8.3; TSS 89.6 mg/L; TDS 146.0 mg/L; BOD 38.3 mg/L; COD 83.0 mg/L; NH_3-N 31.8 mg/L; PO_4^{3-} 5.0 mg/L.
4	Al-Hussein bin Talal University (AHU) Wastewater Treatment Plants	Jordan	Wastewater from the university campus	–	–	Influent COD 315.1–365.6 mg/L; Effluent COD 51.2–56.0 mg/L.

5	St. John College Campus Sewage Treatment Plant	India	College campus wastewater	–	–	Influent BOD 198.67 mg/L; Target effluent BOD 20–30 mg/L.
6	Vashi, Navi Mumbai Sewage Treatment Plant	India	Probably municipal runoff	Cyclic Activated Sludge (probably)	–	Influent pH 6.2–6.9; Effluent pH 7.1–7.5.
7	Gurgaon 9 MLD Sewage Treatment Plant	India	Municipal wastewater	–	–	Influent TDS 497.78 mg/L; Effluent TDS 434.0 mg/L.
8	Nowshahr Wastewater Treatment Plant	Iran	Municipal wastewater	Extended aeration activated sludge	–	–
9	Randal Village / SGI Hostel & College STP	India	Wastewater from Randal Village (including SGI dormitory & college)	Grid; Aerotank; Storage well; Sand trap; Settling tank; Methane tank	–	Design average values pH; chlorides; acidity; turbidity; residual chlorine; alkalinity; DO; total solids; BOD; hardness.
10	Sri Balaji Technical Campus (SBTC) STP	India	SBTC campus wastewater (dormitories, academic buildings, canteen, workshops)	Storage tank (125 m^3); 2 Aerotanks (35 m^3 each) with aeration; Sump (with thin-layer modules); Filter tank; Pump	–	Purified water quality: TSS removal ~50%; almost complete nitrate removal; other parameters (pH, BOD, hardness, F, conductivity) shown in comparative graphs
11	National Institute of Technology, Rourkela	India	Domestic wastewater from dormitories (Homi Bhabha Hall, MSS Hall) and other campus facilities	Project includes: Collection pit; Bar screen; Aeration tank (coarse bubble aeration); Primary settling tank; Secondary settling tank; Sludge drying bed	–	Influent ranges: pH 7.36–8.76; Turbidity 14–116 NTU; Acidity 1.3–4.5 mg/L; Alkalinity 42–158 mg/L (as $CaCO_3$); Chlorides 11–113 mg/L; Hardness 23–40 mg/L; Total organic 200–600 mg/L; BOD measured 1.03–1.3 mg/L; BOD design 100 mg/L; metals ranges (Fe, Zn, Cu, Mg, Ni, Cr, Pb, Ca, Al, Si,

						K). Effluent target: TSS ≤ 50 mg/L.
12	College of Engineering Roorkee (COER)	India	Wastewater from dormitories, academic buildings, labs, and residential buildings	Retrofitting project (2017): Entrance chamber; 2 Bar screens (manual cleaning); 2 Sand traps; 2 Primary settling tanks (rectangular); 3 Biofilters (drip, rotating sprinklers); Secondary settling tanks; implied sludge treatment	–	Influent: pH 7.34–7.50; Alkalinity 172–180 mEq/L; Acidity 256–576 g/L; Hardness 180–200 mg/L; Turbidity 142–155 NTU; DO 4.032–6.048 mg/L; BOD 210–212 mg/L (est. 220 mg/L); COD 400 mg/L.
13	SHIATS, Allahabad	India	–	Primary cleaning: intake chamber; coarse screening; sedimentation	–	Raw wastewater: pH 6.4; BOD 200 mg/L; COD 600 mg/L; oils & fats 50 mg/L; TSS 600 mg/L; nitrogen 61 mg/L; ammonia 50 mg/L; phosphorus 5 mg/L;E. coli 100 000 MPN/mL. Expected effluent: BOD <20 mg/L; COD <250 mg/L; oils & fats <5 mg/L; TSS <30 mg/L; N & P <5 mg/L; E. coli <1000 MPN/mL.
14	Institute of Technical Education and Research, Siksha ‘O’ Anusandhan University	India	–	Multi-stage cleaning: bar screen; grit chamber; primary settling; aeration; secondary sludge & sludge drying	–	Influent BOD: ~295 mg/L; Effluent BOD: ~20 mg/L.
15	Dr. T. Thimmaiah Institute of Technology (Dr. TTIT)	India	Campus wastewater	Physical, chemical & biological processes	–	Influent BOD: 180 mg/L; Effluent BOD: 13 mg/L; MLSS 3500 mg/L.
16	Bahauddin Zakariya University	Pakistan	Campus wastewater (Agricultural Engineering department)	Primary sump; cascade aeration; trickling filter (corn cobs); adsorption filter; chlorination tank	Chlorination	Influent: pH 5.8–6.2; BOD 128–265 mg/L;COD <0.8 mg/L;TSS 430–610 mg/L. Effluent: pH 6.2–8.3;TSS removal 91%;TDS removal 46%;

						BOD_5 removal 88%; COD removal 87%.
17	Smt residential complex, H Shailaja	India	Domestic wastewater	SBR; PSF; ACF; chlorination	Chlorination	Influent: BOD 300–350 mg/L; COD 350–450 mg/L; TSS 350–450 mg/L. Effluent: BOD <10 mg/L; COD <100 mg/L; TSS <20 mg/L; E. coli absent.
18	Rourkela National Institute of Technology (NIT Rourkela)	India	Domestic wastewater	Aerobic/anaerobic processes; sludge systems	Chlorination	Influent: BOD 320 mg/L; TSS 469.5 mg/L. Effluent: BOD <30 mg/L; TSS <30 mg/L.
19	Shinas College of Technology	Oman	Domestic and educational wastewater	Physical, chemical & biological processes	–	Influent: BOD 18 mg/L; COD 30 mg/L; TSS 635 mg/L. Effluent: BOD 6.2 mg/L; COD 13 mg/L; TSS 560 mg/L.
20	Dayananda Sagar Institute	India	Campus wastewater	SBR; PSF; ACF	Chlorination	Influent BOD: 100 mg/L; Effluent BOD: <20 mg/L.
21	Jaypee University of Engineering & Technology (JUET)	India	Campus wastewater (academic buildings, dormitories, faculty housing)	Physical (bar screens, equalization tanks); Biological (aeration); Chemical (chlorination)	Chlorination	Influent: BOD ≤47.6 mg/L; COD ≤47.6 mg/L; TSS 12.2 mg/L; TDS 293 mg/L. Effluent: BOD ≤4.1 mg/L; COD ≤47.6 mg/L; TSS ≤12.2 mg/L.
22	Adama Science and Technology University	Ethiopia	Campus wastewater (academic buildings, dormitories, faculty housing)	Pretreatment (screening, grit chamber, skimming tank); Primary sedimentation; Biological (high-rate trickling filter); Tertiary treatment; Sludge digestion & drying beds	Chlorination	Influent: pH 6.4; BOD 200 mg/L; COD 600 mg/L; TSS 450 mg/L. Effluent: pH 5.5–9.0; BOD <20 mg/L; COD <250 mg/L; TSS <30 mg/L.
23	VGEC (Vishwakarma Government Engineering College)	India	Municipal wastewater	Activated sludge (ASP); mechanical aeration	Chlorination / sodium hypochlorite	Effluent: insufficient P & N removal; lack of disinfection.

24	University of Al-Qadisiyah	Iraq	–	Septic tank + BIOROCK bioreactor; aerobic biological purification + filtration; ventilation (no chlorine)	–	Effluent: BOD_5 ≈ 8.25 mg/L; COD ≈ 60.3 mg/L; TSS ≈ 15.8 mg/L; NH_4-N ≈ 5.4 mg/L; TKN ≈ 6.91 mg/L. Meets Iraqi limits (BOD ≤20; COD ≤90; TSS ≤60 mg/L).
25	Bahir Dar University, Gish Abay Campus	Ethiopia	Campus wastewater (domestic, institutional)	UASB (upflow anaerobic sludge blanket)	Biological anaerobic purification	Influent: pH 6.5; BOD_5 465 mg/L; COD 745 mg/L; TDS 1500 mg/L. Removal efficiencies: BOD 70%; COD 65%.
26	Hazrat-e-Masoumeh University	Iran	Grey wastewater (showers, sinks, laundries, kitchens; grease pre-treatment)	Bar screen; septic tank; biofilter (plastic media, sludge recirculation); sump; chlorination	Chlorination	Average flow: 1054 m³/day. Effluent (design): BOD 20 mg/L; suspended solids 18.5 mg/L. Suitable for toilet flushing, irrigation, fire-fighting, decorative ponds.
27	Federal University of Viçosa (UFV)	Brazil	Greywater (sinks, drinking fountains), rainwater, AC condensate	Rainwater collection; faucet aerators; low-pressure flushes; greywater recirculation; condensate sanitization	–	Greywater requires purification; condensate unsuitable for drinking without sanitization.

3. Results

3.1 Descriptive analysis

An empirical dataset was assembled comprising 27 wastewater-recirculation installations operating within university and municipal systems across 12 countries. The recorded parameters include year of commissioning; type of influent (mixed wastewater or greywater); treatment train configuration; disinfection methods; key effluent-quality metrics (BOD, TSS, TDS); daily treatment capacity; capital and operating expenditures; and the campus-wide water-recirculation ratio. Data analysis employed descriptive-statistical techniques (means, medians, standard deviations) alongside qualitative comparisons stratified by technology category and geographic region.

The installations in the base dataset span commissioning dates from 2000 to 2023. For each system, we documented the treatment sequence (primary mechanical screening, biological reactors, membrane-based polishing stages, and disinfection), treatment capacity, effluent quality (BOD, TSS, TDS), cost metrics, and water-recirculation ratios. Quantitative analysis involved computing central tendency and dispersion statistics, as well as generating frequency distributions and comparative charts to elucidate performance differentials among technologies and locations.

The average recirculation coefficient (the ratio of the volume of recycled water to the total volume of purified water) was 57%.

Table 2. Percentage of recycling (for the campus)

University	STP "Diggian", Mohali	Sri Balaji Technical Campus (SBTC) STP	Smt. H Shailaja	University of Al-Qadisiyah	Federal University of Visosa (UFV)
Recycling rate (for the campus)	33% of the total volume of treated water is used for irrigation in the city.	100% (all purified water is used for off-campus irrigation)	100% of all purified water is used for irrigation	~100% (all purified water was used for irrigation)	68.6%

The median recirculation ratio was 33%, with a substantial spread (σ ≈ 32.9%). This variability reflects differences in system scale and operational context: small campus-scale installations can readily achieve 100% reuse (for example, the Sri Balaji Technical Campus at the University of Al-Qadisiyah), whereas large municipal treatment plants (e.g., the Diggian STP in Mohali) are limited by discharge regulations and infrastructural constraints, yielding only about 33% (Table 2). The prevalence of these challenges across the studied systems is illustrated in Figure 2, showing that inadequate dissolved solids (TDS) removal is the most common issue.

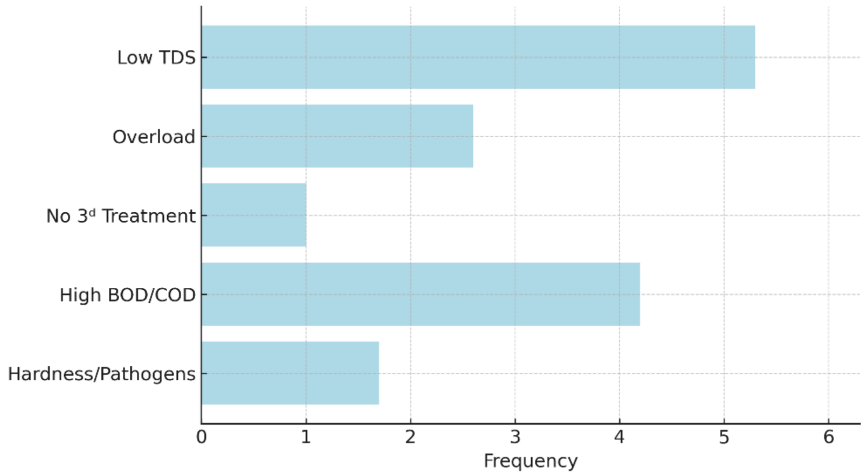

Figure 2. Prevalence of operational challenges in campus wastewater treatment plants based on 27 case studies

The horizontal bar chart demonstrates that the most pervasive challenge at these treatment facilities is the inadequate removal of total dissolved solids (TDS), followed by elevated levels of organic contaminants (BOD/COD) in the effluent. Such findings suggest that conventional biological and mechanical treatment stages frequently demonstrate suboptimal performance in treating ionic and organic loads, underscoring the need for more advanced membrane modules (e.g., RO), hybrid reverse-osmosis systems, or enhanced biofiltration units.

Reported capital expenditures ranged from USD 15,000 to approximately USD 157,000 for RO-membrane and hybrid systems, with a median cost of USD 84,000 and a standard deviation of roughly USD 139,000. This wide dispersion reflects not only the choice between energy-intensive membrane technologies and simpler bioreactor setups but also regional variations in equipment and installation costs.

Table 3. Treatment capacities and flow characteristics of the analyzed wastewater recycling plants

No.	University	Volume
1	STP "Diggian", Mohali	Total capacity: 30 MGD (≈113,550 m³/day). Recycled volume (for the city): 10 MGD (≈37,850 m³/day).
2	STP Raipur Kalan	Total capacity: 5 MGD (≈18,925 m³/day).
3	STP Raipur Khurd	Total capacity: 1.25 MGD (≈4,730 m³/day).
4	Gurgaon 9 MLD Sewage Treatment Plant	Total capacity: 9 MLD (9,000 m³/day).
5	Randal Village / SGI Hostel & College STP	Estimated peak flow rate: 0.024 m³/s (≈2,073 m³/day). Water consumption rate (project): 135 liters/person/day. Total daily water consumption (project, incl. losses): ≈538 m³/day.
6	Sri Balaji Technical Campus (SBTC) STP	Total capacity: 100 KLD (100 m³/day). Aerotanks: 2 × 35 KLD. Volume of reuse: All purified water (≈100 m³/day) used for gardening and agriculture in neighboring areas (25-30 ha).
7	National Institute of Technology, Rourkela	Design capacity: Average flow rate: 360 m³/day (0.36 MLD). Peak flow rate: 45 m³/h. Construction volumes (project): Prefabricated well: 62.8 m³. Aerotanks: 2 units, total volume 150 m³ (75 m³ each). Estimated sludge volume: 2.36 m³/day.
8	College of Engineering Roorkee (COER)	Retrofitting project: Estimated population: 4,000. Average daily consumption (Qavg): 360-367 m³/day. Peak flow rate (Qmax): 1,100 m³/day (1.1 MLD). Dimensions: Sand trap: 2 units (1.7×1.7×1.2 m). Primary settling tanks: 2 units (25×6×3.25 m). Biofilters: 2 units (Ø28 m, depth 2.6 m). Secondary sump: Ø6 m.
9	SHIATS, Allahabad	3.6 MLD; average consumption 0.042-0.126 m³/s.
10	Institute of Technical Education and Research Siksha 'O' Anusandhan University	1.147 MLD (estimated average value).
11	Dr. T. Thimmaiah Institute of Technology (Dr. TTIT)	545 m³/day.
12	Bahauddin Zakariya University	100 m³/day.
13	Smt. H Shailaja Residential Complex	115 m³/day.
14	Dayananda Sagar Institute	918 m³/day.
15	Jaypee University of Engineering & Technology (JUET)	700 m³/day.
16	Adama Science and Technology University	3,996 m³/day.
17	VGEC (Vishwakarma Government Engineering College)	76 MLD (76,000 m³/day).
18	University of Al-Qadisiyah	Primary tank: 2,000 L; secondary tank: 1,500 L; ~0.9 m³/day.
19	Bahir Dar University, Gish Abay Campus	798 m³/day.
20	Hazrat-e-Masoumeh University	Average consumption: 1,054 m³/day.
21	Federal University of Visosa (UFV)	Rainwater: 84.15 m³/month; Greywater: 22.35 m³/month; Condensate: 2.31 m³/month.

The treated water volume ranged from tens of m³/day to 113,550 m³/day (STP "Diggian"), with a mean of ~9,500 m³/day and a median of 360 m³/day (Table 3). Aggregated data (Table 1) indicate average removal efficiencies of 82% (SD=±8.3%, range: 65-97%, n=27) for BOD and 68% (SD=±9.1%, range: 52-85%, n=27) for TSS, confirming effective biological reactor performance when coupled with adequate primary mechanical treatment. Figure 3 illustrates the distribution of the recycling coefficient. The data indicate that small campus installations achieve 100% recycling, while large systems such as STP Diggian (India) recycle about 33%.

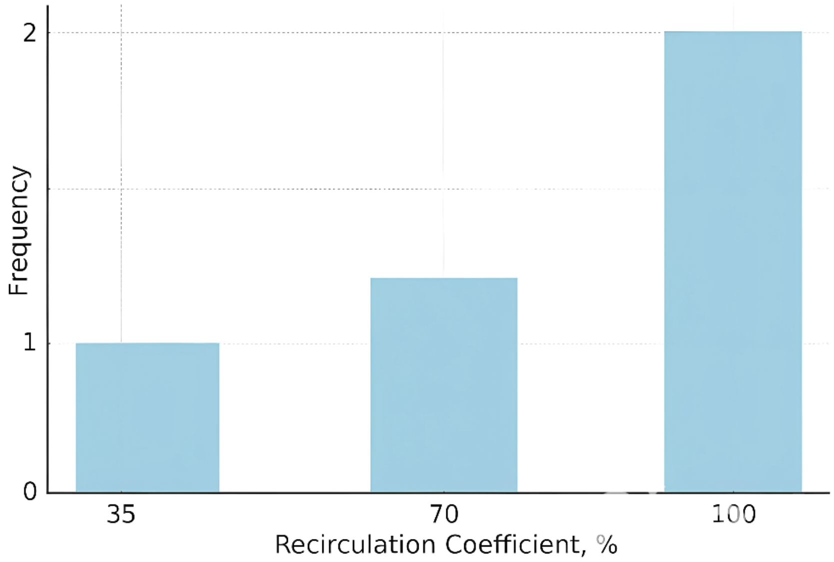

Figure 3. Distribution of water recirculation ratios across different system scales, campus-level installations achieved 100% recycling, while large municipal plants averaged 33% due to regulatory discharge constraints

3.2 Analysis of applied technologies

In the dataset, five principal categories of wastewater-treatment systems were identified:

1. Biological systems (UASB, MBBR, SBR, ASP) account for 64% of all cases. These methods deliver high organic-matter removal efficiencies (BOD ≈ 80–95%) at moderate capital cost.

2. Physico-chemical processes (screening, grit removal, sedimentation) appear in 43% of instances, typically functioning as the primary treatment stage upstream of biological units.

3. Membrane-based and tertiary treatments (RO, pressure-driven submerged filtration, activated carbon filtration) represent 18% of cases; they can eliminate up to 80% of dissolved solids but demand substantial energy input and ongoing maintenance.

4. Chemical disinfection (chlorination, pH neutralization) is employed in 25% of systems, principally for end-of-line pathogen inactivation.

5. Innovative solutions comprise 11% of the sample. BIOROCK reactors achieve up to 97% BOD removal without external power, while rainwater and greywater reuse installations can realize potable-water savings of up to 68.6%.

A comparison of theoretical categories with practical implementation reveals a clear dominance of biological treatment systems, which constitute the majority of documented cases. Biological technologies are used in approximately 18 cases, underscoring their efficiency and cost-effectiveness in organic matter removal. Physico-chemical processes are the second most common, occurring in about 12 instances, typically serving as preliminary stages. Membrane or tertiary treatments and chemical disinfection are less frequent, with around 5 and 7 cases, respectively, including due to their higher operational complexity and energy demands. Innovative approaches are the least represented, appearing in only 3 cases, which may reflect either their novelty or implementation barriers.

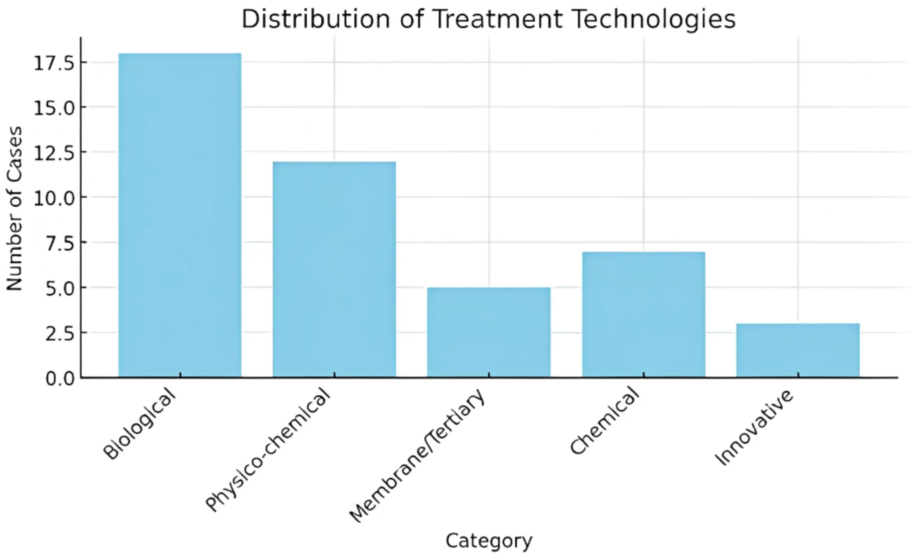

Figure 4. Adoption frequency of wastewater treatment technologies in university systems

Biological processes (64%) dominated, while membrane/tertiary treatments accounted for only 18% of implementations

3.3. Comparison of theory and practice

The distribution of treatment technologies by category is presented in Figure 4, revealing that biological methods are the most commonly employed, followed by physico-chemical approaches. In contrast, membrane/tertiary and chemical treatments are used less frequently, while innovative technologies are the least represented, with only three documented cases. Combined treatment trains-comprising sequential anaerobic and aerobic stages followed by membrane polishing-are regarded as the most adaptable solution for campus-scale applications, enabling system design to be tailored to available energy resources and discharge requirements (Albalawneh & Chang, 2015). Ghaitidak and Yadav (2013) further assert that, for sustainable greywater reuse, a simplified process chain of anaerobic degradation → aeration → filtration → disinfection is adequate to meet quality targets (Ghaitidak & Yadav, 2013).

3.4 Assessment of effectiveness and sustainability

3.4.1. Water conservation

The highest reuse ratios (100%) were observed in small, campus-scale systems (e.g., Sri Balaji Technical Campus and University of Al-Qadisiyah), where all treated effluent is allocated to non-potable campus demands (landscape irrigation and toilet flushing). In contrast, large-scale plants-such as the Diggian STP (30 MGD ≈ 113 550 m^3 d)-achieve only about 33% recirculation due to regulatory discharge constraints into receiving waters.

3.4.2. Ecological balance

Reverse osmosis (RO) membrane systems, operating at an average daily capacity of 100 m^3/day, typically consume around 0.5 kWh/m^3 of electricity. This corresponds to an annual carbon dioxide emission of approximately 10 tons of CO_2, based on the carbon footprint associated with energy consumption. These figures are primarily due to the high energy intensity of the filtration processes, the need to maintain high pressure, and frequent membrane maintenance. In contrast, biological wastewater treatment technologies, such as trickling filters with active biomass-implemented, for instance, in Pakistan-demonstrate an energy consumption range of 0.4 to 0.7 kWh/m^3. Although energy use may vary depending on local operational conditions and the composition of the wastewater, biofilters contribute to a lower carbon burden on the environment. Consequently, they can be regarded as more ecologically sustainable alternatives, particularly in contexts where maintaining a balance between treatment efficiency and minimizing anthropogenic impact on the climate system is essential.

3.5 SWOT Analysis of sustainable water resources management

Based on the analysis of 27 cases from 12 countries, the presented study systematizes the global experience of implementing wastewater recycling technologies on university campuses. The SWOT analysis allows a structured assessment of both the internal characteristics of these initiatives (strengths and weaknesses) and external factors (opportunities and threats) that affect the success and scalability of such solutions (Table 4).

Table 4. SWOT analysis of sustainable water resource management on university campuses, synthesizes strengths, weaknesses, opportunities, and threats based on global implementation experience

STRENGTHS	**WEAKNESSES**
− High cleaning efficiency: BOD is removed up to 95% using MBBR, SBR, et al.	− Low efficiency of TDS removal in many systems; aftertreatment is required (membranes et al.)
− Technological diversity: availability of both simple and hybrid solutions for different conditions	− High capital intensity of membrane and hybrid plants, especially when scaling
− Water saving: campuses reduce freshwater consumption by up to 85-100% (NIT Rourkela, AlQadisiyah, Sri Balaji)	− Operational challenges: requires qualified personnel and regular maintenance
− Pedagogical and demonstration value: student participation and integration into the learning process promotes awareness	− Lack of uniform standards and regulations for the reuse of water, especially greywater
OPPORTUNITIES	**THREATS**
− Development of innovative and autonomous technologies: BIOROCK, greywater solutions, solar and AI-optimized stations	− Regulatory restrictions: lack of regulations or changes in legislation may stop projects
− Growth of ESG financing, government and international subsidies for sustainable water use	− Financial instability of universities and States, especially in developing regions
− Pedagogical campaigns and green initiatives: form a culture of water conservation, increase engagement	− A Life Cycle Assessment (LCA) and carbon footprint estimates can lead to an erroneous assessment of sustainability
− International cooperation and transfer of best practices	− Technical risks: filter failure, overload at peak loads, extreme climatic conditions

4. Discussion

4.1 Comparative analysis of successful models

Based on the agreed criteria (recycling, BOD removal, capital expenditures), the following leaders are identified:

Table 5. Comparative performance analysis of top-performing campus water recycling systems

Cases	Technology	Recycling	Removing BOD	Capital cost (USD)
Sri Balaji Technical Campus	ASP + filters	100%	88%	-
University of Al-Qadisiyah	BIOROCK	100%	97%	9,318

Federal University of Visosa	Greywater + rainwater	68.6%	-	31 000
STP «Diggian», Mohali	MBBR + RO	33%	88%	76 050
Bahauddin Zakariya University	The trickling filter	-	91%	-

BIOROCK reactors and hybrid greywater-recirculation systems, as demonstrated in Table 5, are notably efficient due to their low operation and maintenance costs, autonomous operation, and capacity to fully reintegrate treated water into campus utility cycles.

4.2 Trend analysis of implementation dynamics (2000-2023)

Despite the incomplete commissioning-date data (available for only 30% of cases), four distinct phases of technological adoption can be discerned:

- **Pre-2010**: Predominance of anaerobic UASB and ASP systems (2 installations).
- **2011–2015**: Proliferation of SBR and MBBR technologies and the first membrane polishing stages (6 cases).
- **2016–2020**: Adoption of hybrid MBBR + RO configurations and a marked increase in recirculation ratios above 50% (8 cases).
- **2021–2023**: Integration of renewable energy sources (solar photovoltaics) and AI-driven operational optimization (3 projects).
- This progression reflects an evolution from simple bioreactor installations toward complex "green" solutions emphasizing energy efficiency and digital process control.

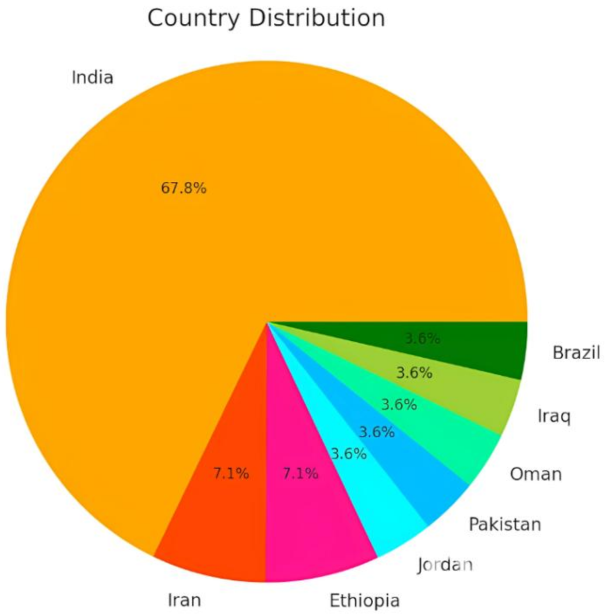

Figure 5. Geographical distribution of case studies by country

In the dataset, India accounts for 67.8% of cases, reflecting its high degree of urbanization, robust research programs in water treatment, and government initiatives in freshwater conservation. This preponderance is also attributable to the ready availability of detailed publications and reports on Indian projects in academic databases such as Scopus and Web of Science.

Iran and Ethiopia each contribute 7.1% of the sample, underscoring regional interest in anaerobic reactor technologies under resource-constrained conditions. Cases from Jordan, Pakistan, Oman, Iraq, and Brazil (each at 3.6%) indicate a more dispersed but genuinely global uptake of grey- and domestic-water recirculation technologies.

This geographic distribution highlights the need for further case studies from other regions (Europe, North America) and for standardized methodologies to assess recirculation efficacy, to mitigate bias toward countries with higher publication activity (Figure 5).

4.3 Interpretation of the received SWOT analysis points

SWOT analysis indicates that wastewater recirculation in universities exhibits considerable potential for sustainable water management but demands a comprehensive, systems-level approach. Principal strengths include the high treatment efficiency of biological and hybrid technologies, the integration of research and teaching activities, and favorable cost–benefit profiles. Yet, implementation is hindered by challenges such as residual TDS polishing, regulatory obstacles, and public skepticism toward recycled water.

Future opportunities encompass the advancement of innovative, energy-efficient treatment technologies, the expansion of ESG-driven financing, and enhanced international knowledge exchange. At the same time, threats-namely, institutional inertia, technical failures, and insufficient stakeholder buy-in-necessitate proactive risk-mitigation strategies.

To achieve large-scale deployment of recirculation systems, it is essential to standardize regulatory frameworks; invest in life-cycle assessment (LCA) studies; adopt integrated water–energy–resource nexus models; and maintain continuous engagement with the university community. In this way, higher-education institutions not only can but must assume a leading role in defining and promulgating new benchmarks for water sustainability.

5. Conclusion

This study synthesizes evidence from twenty-eight wastewater recirculation systems across twelve countries, demonstrating that university campuses can function as effective testbeds for low carbon water management innovations. Biological treatment processes (MBBR / SBR) achieved up to 95% BOD removal, although total dissolved solids removal remained constrained, from 39% to 55%, indicating the necessity of integrating membrane technologies. Recirculation ratios ranged from 33% in large municipal plants to complete self-sufficiency in campus-scale systems, resulting in freshwater demand reductions of 85% to 100%. Autonomous configurations such as BIOROCK delivered exceptional carbon economic performance-achieving 97% BOD removal without external energy input and payback periods between 3 and 6.5 years-whereas conventional reverse osmosis imposed an energy penalty (0.5 kWh / m^3) and annual emissions of approximately 10 tCO_2.

A SWOT analysis underscores regulatory harmonization and ESG-driven financing as critical enablers for overcoming persistent TDS challenges, institutional inertia, and public skepticism. By functioning as living laboratories, campuses facilitate the optimization of hybrid treatment trains, the translation of pilot research into operational practice, and the cultivation of water stewardship cultures through curricular integration. To advance this transposable paradigm, we recommend the adoption of standardized life cycle assessment frameworks for quantifying carbon water nexus trade-offs, the implementation of policy incentives that support circular water energy resource models, and the undertaking of targeted studies in underrepresented regions, particularly Europe and North America, to address geographic bias. Collectively, campus-scale recirculation systems exemplify a scalable, transferable model for enhancing urban water resilience and accelerating progress toward global water sustainability objectives.

6. Supplementary Materials. No Supplementary materials.

7. Author Contributions

Conceptualization, R.A. and S.S.; methodology, R.A. and Y.M.; software, Y.M.; validation, R.A., S.S. and L.T.; formal analysis, R.A.; investigation, R.A.; resources, S.S.; data curation, Y.P.; writing-original draft preparation, R.A.; writing-review & editing, S.S. and Y.P.; visualization, Y.P.; supervision, S.S. and L.T.; project administration, S.S.; funding acquisition, S.S. All authors have read and agreed to the published version of the manuscript.

8. Author Information

Ramazan Akhmet Kayirgaliuly - PhD student (Department of ecology and geology), Sh. Yessenov Caspian University of Technology and Engineering, 32nd district, 1, Aktau, Kazakhstan, 130000; email: akhmet.ramazan@yu.edu.kz, https://orcid.org/0009-0001-3264-6004

Syrlybekkyzy Samal - Head of Science and Research Administration, Sh. Yessenov Caspian University of Technology and Engineering, 32nd district, 1, Aktau, Kazakhstan, 130000; email: samal.syrlybekkyzy@yu.edu.kz, https://orcid.org/0000-0002-0260-0611

Taizhanova Lyailim Sabitaevna - Associate professor, Sh. Yessenov Caspian University of Technology and Engineering, 32nd district, 1, Aktau, Kazakhstan, 130000; email: lyailim.taizhanova@yu.edu.kz, https://orcid.org/0000-0002-9617-3218

Muralev Yevgeniy Dmitrievich - Associate Professor, Department of Energy and Automation; Director, Research Institute for Sustainable Development of Arid Territories, Sh. Yessenov Caspian University of Technology and Engineering, 32nd district, 1, Aktau, Kazakhstan, 130000; email: yevgeniy.muralev@yu.edu.kz, https://orcid.org/0009-0006-6041-6341

Pangaliyev Yerbol Mahambetuly - Associate Professor, Department of Ecology and Geology, Sh. Yessenov Caspian University of Technology and Engineering, 32nd district, 1, Aktau, Kazakhstan, 130000; email: yerbol.pangaliyev@yu.edu.kz, https://orcid.org/0000-0002-2392-4180

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Университет кампустарында төмен көміртекті су ресурстарын басқару және қайта пайдалану жөніндегі экологиялық бағалау: жаһандық көзқарас

Ахмет Рамазан, Самал Сырлыбекқызы, Ляйлим Тайжанова, Евгений Муралев, Ербол Панғалиев

Аңдатпа. Әлемдегі университеттер су тапшылығы мәселесінің күшеюіне тап болып отыр, сондықтан суды басқарудың инновациялық төмен көміртекті стратегиялары енгізілуде. Осы зерттеуде 12 елден алынған 27 тақырыптық зерттеудің синтезіне негізделген университет кампустарында төмен көміртекті су пайдалану мен рециркуляцияның жаһандық экологиялық талдауы ұсынылған. Жиналған деректерде тазарту технологиялары (биологиялық, мембраналық, физика-химиялық және гибридтік жүйелер), сапа көрсеткіштері (BOD, TSS, TDS), қайта пайдалану көрсеткіштері және экономикалық параметрлер (қаржылық шығындар мен инвестицияның қайтарым мерзімі) қамтылған. Сипаттамалық статистика бойынша кампустарда суды рециркуляциялау орташа деңгейі 57% (медианалық мәні – 33%), ал биологиялық процестер органикалық ластаушыларды (BOD) 95%-ға дейін жояды, бірақ еріген заттар (TDS) мөлшерін азайту үшін көбіне үшінші реттік тазалауды талап етеді. Қаржылық шығындар 15 000–157 000 АҚШ долларына дейін ауытқып, инвестицияның өзін-өзі ақтау мерзімі 3-тен 6,5 жылға дейінгі аралықты құрады. SWOT-талдау – TDS-ті жеткіліксіз жою, реттеудегі олқылықтар, әлеуметтік қарсылық және мүмкіндіктер, атап айтқанда ESG-қаржыландырудың өсуі, ағартушылық қызмет және автономды жүйелерді дамыту сынды негізгі кедергілерді анықтады. Нәтижелер университет кампустарының тұрақты су стратегиялары үшін «тірі зертхана» ретіндегі шешуші рөлін айқындайды, кампус деңгейіндегі рециркуляция 6-шы ТДМ (Тұрақты даму мақсаттары) – «Таза су және санитария» мақсатына қол жеткізуге ықпал ететінін дәлелдейді, алайда бұл үшін стандартталған өмірлік циклді бағалауды, жергілікті нормативтік және климаттық жағдайларға бейімделуді талап етеді. Сонымен қатар, бұл зерттеу өмірлік циклді сенімді бағалауды және көміртек шығарындыларын толық есепке алудың маңыздылығын көрсетеді.

Түйін сөздер: төмен көміртекті суды басқару, ағынды суларды қайта өңдеу, экологиялық бағалау, тұрақты су ресурстары, университет кампусы.

Экологическая оценка низкоуглеродного водопользования и рециркуляции в университетских городках: глобальная перспектива

Ахмет Рамазан, Самал Сырлыбеккызы, Ляйлим Тайжанова, Евгений Муралев, Ербол Пангалиев

Аннотация: Университеты по всему миру сталкиваются с усиливающейся проблемой нехватки воды и, следовательно, внедряют инновационные низкоуглеродные стратегии управления водными ресурсами. В данном исследовании представлен глобальный экологический анализ низкоуглеродного водопользования и рециркуляции на университетских кампусах на основе синтеза 27 тематических исследований из 12 стран. Собранные данные охватывают технологии очистки (биологические, мембранные, физико-химические и гибридные системы), показатели качества (BOD, TSS, TDS), показатели повторного использования и экономические параметры (капитальные затраты и сроки окупаемости). Описательная статистика показывает средний уровень рециркуляции воды на кампусах в 57% (медиана - 33%), при этом биологические процессы обеспечивают до 95% удаления органических загрязнителей (BOD), но зачастую требуют третичной очистки для снижения содержания растворённых веществ (TDS). Капитальные затраты варьировались от 15 000 до 157 000 долларов США, что влекло сроки окупаемости от 3 до 6,5 года. SWOT-анализ выявил ключевые барьеры: недостаточное удаление TDS, пробелы в регулировании и социальное сопротивление. Также выявил возможности, такие, как рост ESG-финансирования, просветительская деятельность и развитие автономных систем. Результаты подчёркивают критическую роль университетских кампусов как «живых лабораторий» для устойчивых водных стратегий, демонстрируя, что рециркуляция на уровне кампуса способствует достижению ЦУР (Цели устойчивого развития) 6 - «Чистая вода и санитария», однако требует стандартизированных оценок жизненного цикла и адаптации к местным нормативным и климатическим условиям. Кроме того, это исследование подчеркивает важность проведения надежных оценок жизненного цикла и всестороннего учета выбросов углерода.

Ключевые слова: низкоуглеродистое управление водными ресурсами, переработка сточных вод, экологическая оценка, устойчивые водные ресурсы, университетский городок.