Innovative Integration of Ecological Sanitation and Constructed Wetlands for Decentralized Greywater Treatment: Evaluation of a Sustainable Sanitation Module in Peru

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Abstract*– Limited access to safely managed sanitation services in vulnerable areas generates severe water pollution and public health risks, creating the need for sustainable innovations for decentralized sanitation. This study proposes and experimentally evaluates an innovative Sustainable Sanitation Module (SSM) integrating a urine-diverting dry toilet with a horizontal subsurface-flow constructed wetland for greywater treatment and resource recovery. To position this technological innovation within the current scientific landscape, a bibliometric analysis identified only 16 publications worldwide, revealing that integrating dry toilets and constructed wetlands remains an underexplored research field, particularly in Latin America. The pilot system, installed at Universidad Nacional Agraria La Molina (Lima, Peru), was evaluated under real operating conditions. During 20 weeks of continuous operation, the SSM recovered 242.65 L of urine and 170.60 L of dry material with potential for agricultural valorization, while the constructed wetland achieved removal efficiencies of 95.0% ± 3.4% for BOD_5, 66.0% for turbidity, and 99.2% ± 1.6% for fecal coliforms. These findings demonstrate that the proposed SSM is a technically feasible sustainable innovation for decentralized greywater treatment and circular resource recovery, with strong potential for rural and peri-urban communities lacking conventional sanitation infrastructure.

Keywords*-- Sustainable innovation, Circular economy, Ecological sanitation, Constructed wetlands, Greywater treatment.

I. Introduction

Universal access to safe water supply and sanitation services remains one of the major challenges for sustainable development, public health, and ecosystem protection [1]. The World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) estimate that millions of people still lack safely managed sanitation services [2], [3], a situation that increases the incidence of waterborne diseases and contributes to the contamination of water resources. In response to this challenge, Sustainable Development Goal 6 (SDG 6) seeks to ensure the availability and sustainable management of water and sanitation for all by promoting adequate wastewater treatment, safe water reuse, and the implementation of sustainable solutions aimed at reducing pollution and improving resource-use efficiency [1].

In Peru, significant gaps in access to drinking water and sanitation persist, particularly in rural and peri-urban areas. According to the National Institute of Statistics and Informatics [4], although piped water supply coverage exceeds 90% in urban areas, sewerage coverage remains limited in many rural communities, forcing a large proportion of the population to rely on on-site sanitation systems for excreta disposal. This situation is further exacerbated by increasing pressure on water resources, especially along the Peruvian coast, where limited water availability highlights the need to promote decentralized technologies capable of reducing potable water consumption while facilitating resource recovery [4].

Within this context, Ecological Sanitation (EcoSan) has emerged as a sustainable innovation grounded in circular economy principles, promoting source separation of urine, feces, and greywater to facilitate the recovery of water, nutrients, and organic matter [5], [6]. Several studies have demonstrated that urine-diverting sanitation systems reduce potable water consumption [7], [8], enhance the recovery of nitrogen, phosphorus, and potassium [9], [10], and mitigate the environmental impacts associated with conventional sanitation systems [5], [11]. Furthermore, the agricultural valorization of recovered nutrients has become one of the cornerstones of the transition toward circular economy models applied to sanitation [12], [13].

Complementing EcoSan systems, constructed wetlands have become one of the most effective Nature-Based Solutions (NBS) and represent an innovative approach to decentralized greywater and domestic wastewater treatment [14], [15]. Their performance relies on physical, chemical, and biological processes that enable the removal of organic matter, suspended solids, nutrients, pathogenic microorganisms, and even emerging contaminants [16], [17], while requiring low energy inputs and reduced operation and maintenance costs [18], [19]. Moreover, the integration of multiple nature-based solutions has been shown to simultaneously improve water quality, enhance water resilience, and increase resource recovery in both urban and rural environments [18], [19].

During the last decade, research on sustainable sanitation has experienced steady growth. Published studies have addressed environmental assessment through life cycle assessment [11], [20], the hydraulic performance and pollutant

removal efficiency of constructed wetlands [16], [17], decentralized sanitation planning [21], nutrient recovery [6], [22], [23], social acceptance of dry toilets [24], [25], [26], [27], [28], and the development of strategies to enhance water resilience through decentralized solutions [29], [30]. However, most of these studies have investigated dry toilets and constructed wetlands separately, while relatively few have evaluated both technologies as an integrated system under real operating conditions, limiting the development and validation of innovative decentralized sanitation solutions [31].

This knowledge gap highlights the need for sustainable technological innovations capable of addressing decentralized sanitation challenges, particularly in Latin America and Peru, where scientific evidence on sustainable sanitation modules integrating source separation, nutrient recovery, and greywater treatment through constructed wetlands remains limited. The bibliometric analysis conducted in this study revealed that scientific production is concentrated mainly in Europe, Asia, and North America, identifying only one study from Brazil and none from Peru. In response to this gap, the present study proposes and experimentally evaluates a Sustainable Sanitation Module integrating a source-separating dry toilet with a constructed wetland for decentralized greywater treatment, implemented at Universidad Nacional Agraria La Molina, Lima, Peru. The proposed innovation was assessed through water quality monitoring during six campaigns, characterization of the system's operational performance, and contextualization of the experimental findings through a bibliometric review of the scientific literature published between 2015 and 2026.

II. Methodology

This study adopted a quantitative approach with an applied research design and an experimental case study. The research involved the technical evaluation of SSM through water quality monitoring and the analysis of its operational performance. Additionally, during the preparation of this article, a bibliometric analysis of the scientific literature was conducted to contextualize the experimental findings within the current state of research on integrated ecological sanitation.

The evaluation of the Sustainable Sanitation Module was conducted between October 6, 2023, and March 13, 2024, comprising a 20-week experimental period. Throughout this interval, the operational performance of the module was continuously monitored. Water quality monitoring of the constructed wetland was performed during the final phase of the study, from the first week of February to the first week of March 2024, through six sampling campaigns carried out at five-day intervals. The overall methodological framework is presented in Fig. 1.

A. Literature Search Strategy

To contextualize the experimental findings obtained from the SSM within the current state of scientific knowledge, a bibliographic search was conducted in the Scopus database during the preparation of this article to support the bibliometric analysis. The search strategy was designed to identify studies related to the integration of dry toilets and constructed wetlands for the decentralized treatment of greywater. The following search query was used:

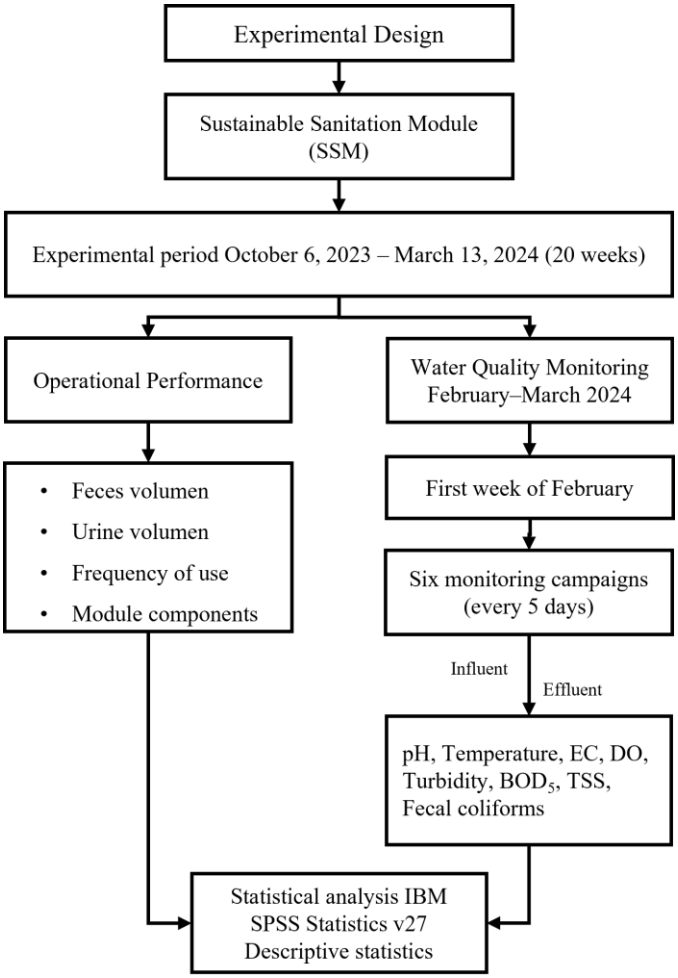


Fig. 1 Methodological framework of the experimental design adopted in this study.

TITLE-ABS-KEY (("dry toilet*" OR "source-separat*" OR "compost* toilet*" OR "ecosan") AND ("constructed wetland*" OR "reed bed*" OR "greywater*"))

The search initially retrieved 41 documents, with no duplicate records identified. Subsequently, the publication period from 2015 to 2026 was established as the inclusion criterion, as a sustained increase in the scientific output related to the integration of dry toilets and constructed wetlands was observed from 2015 onwards. After applying this temporal criterion, the final dataset comprised 16 publications. The document identification, screening, and eligibility process is summarized in Fig. 2.

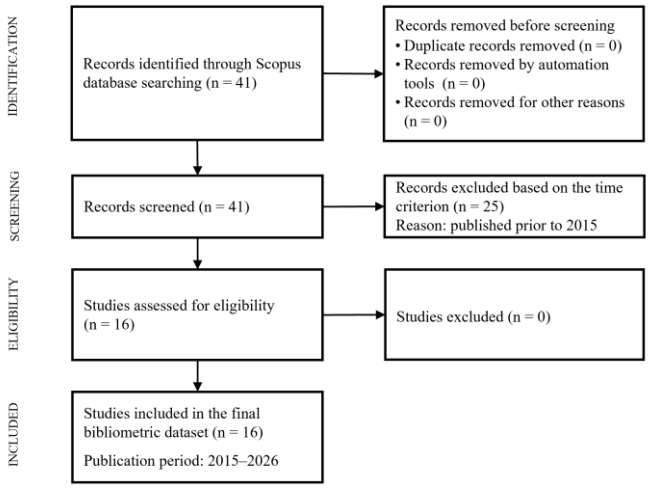


Fig. 2 PRISMA flow diagram of the document selection process for the bibliometric analysis and thematic synthesis of the literature.

B. Bibliometric Analysis

The documents selected through the search strategy were used to construct a keyword co-occurrence map and analyze the thematic structure of the scientific literature in order to identify the major research trends and to contextualize the experimental findings of the present study.

The bibliographic records were exported from Scopus in CSV format and imported into VOSviewer version 1.6.20. A thesaurus file was used to normalize equivalent terms and reduce redundancies among keywords. Subsequently, a co-occurrence analysis based on author keywords was performed, allowing the identification of the main research themes and the thematic structure of the literature on integrated ecological sanitation. The resulting co-occurrence map was used to interpret the relationships among the principal research topics and to complement the discussion of the experimental findings presented in this study.

C. Study Area and Sustainable Sanitation Module

The study was conducted at the campus of Universidad Nacional Agraria La Molina (UNALM), located in the district of La Molina, Lima, Peru. The experimental unit shown in Fig. 3 consisted of the SSM implemented as a pilot ecological sanitation system, whose configuration and operating principles have been previously described [32].

The module integrates a urine-diverting composting dry toilet, an independent urinal, and a horizontal subsurface-flow constructed wetland designed to treat greywater generated from the handwashing sink. The system was designed to minimize potable water consumption, facilitate source-separated resource recovery, and promote decentralized wastewater treatment through natural processes.



Fig. 3 Sustainable Sanitation Module implemented at Universidad Nacional Agraria La Molina [32].

D. Water Quality Monitoring

The performance of the constructed wetland was evaluated through six monitoring campaigns, during which influent and effluent samples were collected from the treatment system.

The analyzed parameters included pH, temperature, electrical conductivity, dissolved oxygen, turbidity, five-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), and fecal coliforms. All samples were analyzed by a laboratory accredited by the National Institute for Quality (INACAL) using the standardized methods described in Standard Methods for the Examination of Water and Wastewater [33]. The sampling methodology and experimental design followed the procedures previously described by Clemente [32].

The treatment performance of the system was assessed by comparing the values measured at the influent and effluent during the six monitoring campaigns.

E. Evaluation of Module Performance

Throughout the experimental period, the cumulative volumes of feces stored in the dry chamber and urine collected through the urine-diversion system were systematically recorded. In addition, the frequency of use of the composting dry toilet, urine-diverting urinal, handwashing sink, and the remaining components of the module was monitored. These records enabled the characterization of the operational performance of the system under real operating conditions.

F. Statistical Analysis

Experimental data were organized and analyzed using Microsoft Excel and IBM SPSS Statistics version 27. Descriptive statistics, including mean values and standard

deviations, were calculated for the physicochemical and microbiological parameters measured in the influent and effluent. Removal efficiencies were calculated for each monitoring campaign to characterize the treatment performance of the constructed wetland. Given the pilot-scale nature of the study and the limited number of water quality monitoring campaigns (n = 6), the statistical analysis was restricted to descriptive statistics. Inferential statistical tests were not applied because the available sample size was considered insufficient to support robust inferential conclusions regarding treatment performance. Accordingly, the results are interpreted as descriptive evidence of system performance under the specific operating conditions evaluated.

III. Results

A. Performance of the Greywater Treatment System

To evaluate the performance of the constructed wetland integrated into the SSM, the main physicochemical and microbiological water quality parameters were analyzed at both the influent and effluent during six monitoring campaigns. The comparison between these two sampling points allowed the treatment capacity of the system to be assessed under real operating conditions.

Table I presents the results obtained for five-day biochemical oxygen demand (BOD_5), turbidity, and fecal coliforms during the six monitoring campaigns. Overall, the constructed wetland achieved a substantial reduction in the organic and microbiological pollutant load of the treated greywater. BOD_5 decreased from influent concentrations ranging from 83.3 to 182.0 mg/L to final concentrations between 2.3 and 10.4 mg/L, while turbidity and fecal coliforms also showed marked reductions at the system outlet. These findings demonstrate the ability of the constructed wetland to improve water quality through natural treatment processes.

TABLE I
RESULTS OF THE MONITORING OF THE MAIN WATER QUALITY PARAMETERS AT THE INFLUENT AND EFFLUENT OF THE CONSTRUCTED WETLAND DURING THE SIX MONITORING CAMPAIGNS

Campaign	BOD_5 I	BOD_5 E	Turb. I	Turb. E	Fecal Coliforms I	Fecal Coliforms E
C1	151.0	4.2	195.0	1.28	5.40×10^5	2.20×10^4
C2	91.4	10.4	26.2	21.1	1.10×10^4	68
C3	182.0	6.5	116.0	56.0	5.40×10^5	45
C4	83.3	4.46	84.1	43.3	2.40×10^6	17
C5	101.0	5.25	228.0	38.2	2.40×10^4	17.9
C6	144.0	2.3	43.9	2.74	2.20×10^4	2

Abbreviations: BOD_5 = five-day biochemical oxygen demand; Turb. = turbidity (NTU); Fecal Coliforms = fecal coliforms (MPN/100 mL); I = influent; E = effluent; NTU = nephelometric turbidity unit; MPN = most probable number.

B. Descriptive Analysis of Water Quality Parameters

To summarize the performance of the constructed wetland throughout the evaluation period, the mean and standard deviation of the main water quality parameters measured at the influent and effluent were calculated. In addition, the average removal efficiency was estimated for the parameters where this calculation was applicable.

The results presented in Table II indicate that the constructed wetland maintained stable pH and temperature conditions between the influent and effluent, demonstrating consistent system performance throughout the evaluation period.

Likewise, dissolved oxygen increased from an average concentration of 0.11 ± 0.12 mg/L in the influent to 2.14 ± 1.62 mg/L in the effluent, indicating a transition toward more favorable conditions for the development of aerobic biological processes during the final treatment stages within the constructed wetland. In contrast, electrical conductivity increased from 787.50 ± 137.27 µS/cm to 3080.00 ± 489.69 µS/cm, a behavior attributed to the concentration of dissolved salts resulting from evapotranspiration effects and the mineralization of organic matter during the treatment process.

Regarding treatment performance indicators, BOD_5 exhibited an average influent concentration of 125.45 ± 39.32 mg/L, which decreased markedly to 5.52 ± 2.76 mg/L in the effluent, corresponding to an average removal efficiency of 95.0 ± 3.4%. Similarly, fecal coliforms decreased from (5.89 ± 9.24) × 10^5 MPN/100 mL to (3.69 ± 8.97) × 103 MPN/100 mL, achieving an average removal efficiency of 99.2 ± 1.6%. Turbidity also exhibited a substantial reduction, with an average removal efficiency of 66.0 ± 31.2%, confirming the capacity of the constructed wetland to reduce the suspended solids load and improve the quality of the treated water.

For total suspended solids (TSS), an average removal efficiency was not reported because of the variability observed among monitoring campaigns, including occasional increases in some measurements. Nevertheless, the overall mean concentration decreased from 24.62 ± 34.75 mg/L in the influent to 15.52 ± 12.17 mg/L in the effluent, indicating an overall reduction trend throughout the monitoring period.

C. Performance of the Sustainable Sanitation Module

Throughout the 20-week monitoring period, the SSM operated continuously, with a total of 401 recorded uses of its main components. As shown in Table III, the urine-diverting urinal exhibited the highest frequency of use (256 records), corresponding to an average of 12.8 uses per week, whereas the dry chamber of the composting toilet recorded 145 uses, with a weekly average of 7.25 uses.

TABLE II
DESCRIPTIVE STATISTICS OF THE WATER QUALITY PARAMETERS RECORDED DURING THE SIX MONITORING CAMPAIGNS

Parameter	Unit	Influent (Mean ± SD)	Effluent (Mean ± SD)	Removal (%) (Mean ± SD)
pH	–	7.42 ± 0.78	7.38 ± 0.56	—
Temperature	°C	28.12 ± 1.96	27.75 ± 1.99	—
Electrical conductivity	µS/cm	787.50 ± 137.27	3080.00 ± 489.69	—
Dissolved oxygen	mg/L	0.11 ± 0.12	2.14 ± 1.62	—
Turbidity	NTU	115.53 ± 81.32	27.10 ± 22.44	66.0 ± 31.2
Total suspended solids (TSS)	mg/L	24.62 ± 34.75	15.52 ± 12.17	*
Five-day biochemical oxygen demand (BOD_5)	mg/L	125.45 ± 39.32	5.52 ± 2.76	95.0 ± 3.4
Fecal coliforms	MPN/100 mL	$(5.89 \pm 9.24) \times 10^5$	$(3.69 \pm 8.97) \times 10^3$	99.2 ± 1.6

* TSS exhibited increases during some monitoring campaigns; therefore, an average removal efficiency was not reported because of the high variability observed.

TABLE III
FREQUENCY OF USE OF THE MAIN COMPONENTS OF THE SUSTAINABLE SANITATION MODULE DURING THE 20-WEEK EVALUATION PERIOD.

Component	Total Uses (n)	Weekly Average
Dry chamber (composting dry toilet)	145	7.25
Urine-diverting urinal	256	12.8
Total recorded uses	**401**	**20.05**

Source: Prepared by the authors based on the operational records of the Sustainable Sanitation Module [32].

The continuous use of both components confirms that the module operated under real operating conditions throughout the entire monitoring period, ensuring the continuous generation of greywater and source-separated waste streams. These conditions provide a reliable basis for interpreting the results obtained from the evaluation of the treated water quality in the constructed wetland.

D. Bibliometric Overview of Research on Integrated Ecological Sanitation

To contextualize the experimental findings obtained from the SSM, a bibliometric analysis of the scientific literature related to the integration of dry toilets, ecological sanitation, and constructed wetlands for the decentralized treatment of greywater was conducted. Based on the selected document corpus, the keyword co-occurrence analysis identified two major thematic clusters, which are visualized in the scientific mapping network shown in Fig. 4. The first cluster groups studies focused on constructed wetlands and water quality, whereas the second cluster is centered on ecological sanitation and nutrient recovery. The interaction between these clusters reveals an increasing convergence of both research areas; however, their physical integration into a single sanitation module remains limited.

The detailed literature search resulted in the selection of 16 publications covering the 2015–2026 period, comprising nine research articles, three book chapters, three conference papers, and one review article. The methodological approaches, the evaluated characteristics (such as life cycle assessment, performance evaluation, nutrient recovery, and social acceptance), and the main contributions of each study are summarized chronologically in Table IV.

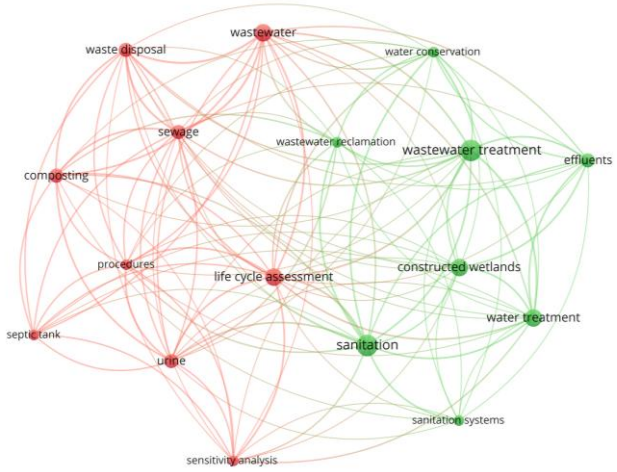


Fig. 4 Keyword co-occurrence network generated using VOSviewer for research on integrated ecological sanitation.

The literature review indicates that studies published between 2015 and 2026 have primarily focused on the performance of constructed wetlands, life cycle assessment, the social acceptance of EcoSan systems, nutrient recovery, and the implementation of decentralized sanitation solutions. However, most of these studies have examined these components independently, addressing greywater treatment, excreta management, or the environmental and social aspects of sanitation systems separately. In contrast, the present study integrates the evaluation of greywater treatment through a constructed wetland with the operational performance of a source-separating dry toilet, providing experimental evidence on the performance of a sustainable sanitation system under real operating conditions. This integrated approach contributes to narrowing the knowledge gap identified in the literature and expands the current understanding of the combined application of these two technologies in decentralized sanitation contexts.

TABLE IV
CHARACTERISTICS AND MAIN CONTRIBUTIONS OF THE STUDIES INCLUDED IN THE LITERATURE REVIEW (2015–2026)

N.°	Reference	Year	Document Type	Main Contribution
1	[8]	2015	Research article	Evaluates the integration of dry toilets with decentralized greywater treatment systems from a cost-effectiveness and nitrogen mitigation perspective.
2	[5]	2015	Review article	Analyzes the factors influencing the performance, maintenance, and acceptance of decentralized ecological sanitation systems.
3	[21]	2015	Research article	Presents tools for the planning and evaluation of ecological sanitation alternatives through sensitivity analysis.
4	[31]	2015	Conference paper	Presents an integrated system combining dry toilets and constructed wetlands for wastewater treatment and reuse.
5	[34]	2016	Research article	Compares the energy consumption and environmental performance of source-separating decentralized systems with those of conventional sanitation systems.
6	[9]	2017	Research article	Demonstrates the agricultural use of human urine as a nutrient source within a circular economy framework.
7	[22]	2018	Book chapter	Describes an agro-sanitation system based on the reuse of greywater, urine, and compost for resource recovery in rural communities.
8	[16]	2018	Research article	Examines the integration of constructed wetlands into sustainable buildings and its influence on environmental and energy performance.
9	[17]	2020	Research article	Evaluates the efficiency of constructed wetlands for the removal of BOD_5, TSS, and nitrogen in decentralized greywater treatment systems.
10	[6]	2021	Book chapter	Describes the principles of ecological sanitation, source separation, and nutrient recovery for the sustainable reuse of resources.
11	[28]	2021	Conference paper	Evaluates the social acceptance of ecological sanitation and the performance of constructed wetlands for domestic wastewater treatment.
12	[23]	2022	Book chapter	Supports the application of Nature-Based Solutions and environmental education to promote integrated ecological sanitation.
13	[11]	2023	Research article	Evaluates the environmental performance of EcoSan systems through Life Cycle Assessment and the recovery of water, nutrients, and organic matter.
14	[20]	2023	Research article	Compares the environmental performance of different decentralized treatment systems using Life Cycle Assessment.
15	[30]	2025	Conference paper	Proposes decentralized water resilience strategies through the reuse of greywater and dry toilets in compact housing.
16	[29]	2026	Research article	Analyzes technological models for rural sanitation systems adapted to different climatic and environmental conditions.

Source: Prepared by the authors based on the documents retrieved from the Scopus database for the 2015–2026 period.

IV. DISCUSSION

The results demonstrate that integrating a source-separating dry toilet with a constructed wetland represents a technically viable sustainable innovation for decentralized greywater treatment within an ecological sanitation framework. The average BOD_5 removal efficiency reached 95.0%, while turbidity was reduced by 66.0%, demonstrating the efficient performance of the constructed wetland throughout the six monitoring campaigns. These findings confirm the capacity of Nature-Based Solutions (NBS) to improve water quality through physical, chemical, and biological treatment processes [16], [17]. The BOD5 removal efficiency obtained in this study is comparable to the 96% reported by Shillington et al. [17] for a decentralized greywater treatment system integrated with dry sanitation facilities. Similarly, Collivignarelli et al. [35] reported BOD_5 removal efficiencies above 88% in a pilot-scale horizontal-flow constructed wetland treating real greywater, together with removal efficiencies above 92% for turbidity and 85% for total suspended solids. These comparisons indicate that the organic matter removal performance observed in the present SSM is within the range reported for comparable decentralized greywater treatment systems. Likewise, previous studies have highlighted that constructed wetlands require low energy inputs, are easy to operate, and involve relatively low maintenance costs [14], [15]. They also represent an effective alternative for expanding access to sustainable sanitation services in regions with limited water resources [18], [19].

From the perspective of ecological sanitation, the continuous operation of the SSM throughout the 20-week evaluation period demonstrates that the integration of a dry toilet with a constructed wetland is operationally feasible under real operating conditions. The high frequency of use recorded for both the urine-diverting urinal and the dry chamber ensured a continuous greywater flow to the constructed wetland while facilitating the separate recovery of source-separated waste streams. These findings are consistent with the principles of ecological sanitation, according to which source separation provides the foundation for efficient resource recovery and reduced potable water consumption [6]. Moreover, several studies have reported that the successful implementation of decentralized sanitation systems depends not only on their technical performance but also on user acceptance and sustained use over time [5], [8]. Recent research has likewise emphasized that social acceptance and community engagement are key determinants for the sustainable implementation of these technologies in rural and peri-urban settings [24], [25], [26], [27]. In the present study, the recorded frequency of use demonstrates that the module remained in continuous operation throughout the monitoring period, thereby providing representative conditions for the experimental evaluation of the system.

The separate recovery of urine and material accumulated in the dry chamber constitutes another relevant contribution of the present study, as source separation represents an enabling step toward resource recovery within a circular sanitation framework. During the evaluation period, approximately 242.65 L of urine and 170.60 L of material from the dry chamber were separately recovered, demonstrating the system's capacity to generate source-separated streams with potential for subsequent nutrient valorization. However, the present study did not evaluate nutrient recovery efficiency or the agronomic application of these recovered streams; therefore, their effective nutrient valorization requires further assessment. Previous studies have identified nutrient recovery from human excreta as one of the principal environmental benefits of ecological sanitation [9], [23]. Likewise, nutrient recovery has been recognized as an essential component for promoting circular approaches to water and sanitation management [12], [13]. Furthermore, studies based on Life Cycle Assessment (LCA) have demonstrated that resource recovery can reduce the environmental impacts associated with conventional sanitation systems, further supporting the potential of EcoSan systems as sustainable innovations within circular economy models [11], [20].

The bibliometric analysis revealed that although scientific production related to ecological sanitation has shown sustained growth since 2015, most studies continue to address dry toilets, nutrient recovery, and constructed wetlands as separate research topics. The two thematic clusters identified through VOSviewer clearly reflect this distinction between studies focused on greywater treatment and those emphasizing resource recovery through source separation. Recent investigations have addressed the design of decentralized sanitation systems and nutrient recovery [6], [21], [22], whereas others have focused on water resilience and the implementation of sustainable solutions for decentralized wastewater treatment [29], [30]. In addition, the acceptance and adaptation of these technologies remain topics of growing research interest [25], [28]. Nevertheless, only a limited number of studies have evaluated the integration of dry sanitation and constructed wetlands within a single experimental system. For instance, Afifi et al. [31] proposed an integrated sustainable sanitation system combining dry toilets and constructed wetlands, whereas other studies have primarily examined specific dimensions such as constructed wetland performance [17], [20], nutrient recovery [9], [23], or decentralized sanitation planning [21]. In contrast, the present study simultaneously evaluates greywater treatment performance, the operational use of a source-separating dry toilet, and the separate recovery of urine and dry material within the same pilot system under real operating conditions. Therefore, the contribution of the present study lies not in the novelty of the individual technologies, but in their integrated evaluation within a Sustainable Sanitation Module and in the experimental evidence generated in the Peruvian context.

Finally, the findings demonstrate that the SSM represents a technically viable sustainable innovation for decentralized greywater treatment, source-separated resource recovery, and reduced potable water consumption under the pilot-scale conditions evaluated. These characteristics indicate its potential applicability in rural and peri-urban areas with limited access to conventional sanitation infrastructure, where decentralized solutions may contribute to achieving Sustainable Development Goal 6 (SDG 6) [1] while promoting water resource protection and circular approaches to sanitation. However, the scalability, economic feasibility, and community-level applicability of the SSM were not evaluated in the present study and therefore require further assessment before broader implementation.

Although the results demonstrate the technical feasibility of the SSM, this study was conducted using a single pilot unit implemented at Universidad Nacional Agraria La Molina and covered a 20-week monitoring period, with water quality assessed through six monitoring campaigns. Consequently, the findings should be interpreted as pilot-scale evidence under the specific operating conditions evaluated, and the limited number of monitoring campaigns restricts the generalization of the observed treatment performance. In addition, the study does not account for seasonal variability or performance under different geographical and community contexts. Future research should extend the monitoring period, increase the number of water quality monitoring campaigns, evaluate multiple sanitation modules under different climatic and operational conditions, and incorporate complementary assessments, including Life Cycle Assessment (LCA), techno-economic analysis, and community-level evaluation, to determine the scalability, economic feasibility, user acceptance, and broader implementation potential of the proposed system.

V. CONCLUSIONS

This study demonstrated that the proposed SSM, integrating a source-separating dry toilet with a constructed wetland, represents a technically viable sustainable innovation for decentralized greywater treatment. The system achieved an average BOD_5 removal efficiency of 95.0%, while also significantly reducing turbidity and fecal coliforms, thereby confirming the effectiveness of constructed wetlands in improving water quality through natural treatment processes.

Monitoring the module over a 20-week period confirmed its continuous operation under real operating conditions. The sustained use of its main components, together with the separate recovery of approximately 242.65 L of urine and 170.60 L of material from the dry chamber, demonstrates the operational feasibility of the system and its capacity to generate separately recovered streams with potential for subsequent nutrient valorization within a circular economy framework.

The bibliometric analysis of the scientific literature published between 2015 and 2026 revealed sustained growth in research on ecological sanitation and constructed wetlands. However, it also showed that most studies continue to investigate these technologies independently, highlighting the limited evidence available on systems that simultaneously integrate source separation, greywater treatment, and resource recovery. In this context, the present study provides experimental evidence obtained under real operating conditions in the Peruvian context, thereby contributing to narrowing the knowledge gap identified in the literature and supporting the development of integrated sustainable sanitation innovations.

Finally, the SSM represents a promising sustainable innovation with potential applicability in rural and peri-urban areas with limited access to conventional sanitation infrastructure. By integrating decentralized greywater treatment, source-separated resource recovery, and efficient water use, the proposed system contributes to the development of more sustainable sanitation solutions aligned with circular economy principles and Sustainable Development Goal 6 (SDG 6).

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