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Urban wastewater management in Nepal: generation, treatment, engineering and policy perspectives

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ABSTRACT

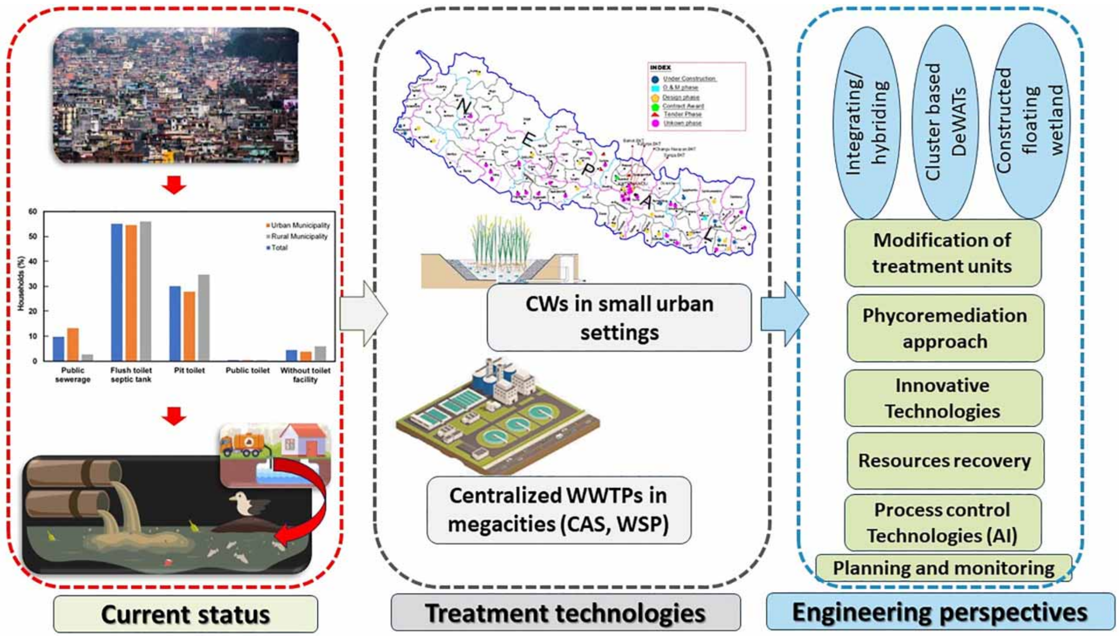
Rapid urbanization has caused a worldwide increase in the discharge of wastewater effluent. Although Nepal has a noteworthy history of wastewater management, progress in this field has been hindered by persistent issues. These problems encompass insufficient sewer coverage, deficient treatment and sludge disposal facilities, inadequate treatment infrastructure, lack of coherent institutional frameworks, and a lack of comprehensive planning. This review provides a glimpse into Nepal's current urban wastewater landscape while also offering a concise historical overview of its wastewater management trends. The study gathered data, information from government organizations, as well as related research, review articles, and reports from 1999 to 2023. Our findings reveal that more than 85% of urban households in Nepal rely on onsite sanitation, with limited access to septage treatment facilities. The ratio of wastewater treatment to generation is disconcertingly low, further emphasized by the concentration of centralized treatment plants in the capital city. This low ratio underscores the inadequacy of the existing wastewater system and the novice approaches of the government, which contribute to the poor sewerage facilities in Nepal. This study unequivocally highlights the imperative need for functional and institutional hierarchy emphasizing local communities, substantial changes in resource allocation, governance practices, and technical infrastructure.

Key words: Nepal, urban wastewater, wastewater management, wastewater treatment

HIGHLIGHTS

- Nepal is struggling with urban wastewater challenges due to a lack of infrastructure.
- Over 85% of urban households are mainly relying on onsite sanitation systems.
- Two of seven provinces provide public sewerage systems covering about 10% of the total households.
- Advanced treatment technologies are suggested in conjunction with conventional ones.
- Proper resource allocation, good governance, and technical skills enhancement are urgent in countries like Nepal, to achieve SDG-6.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The importance of safe water and sanitation for human well-being cannot be overstated. However, unregulated discharge of untreated wastewater and sewage significantly degrades water quality, often making it unsuitable for drinking. The consumption of contaminated water leads to detrimental consequences, such as compromised sanitation and hygiene, which impacts public health. Given the impact of the untreated flow of waste and sewage, there is an urgent need for initiatives focused on controlling and effectively managing solid waste and sewage systems to protect public health and ensure long-term environmental sustainability.

The United Nations' 2030 Sustainable Development Goal 6 (SDG 6) aims to attain equitable sanitation and hygiene, eradicate open defecation, and reduce water pollution by monitoring global indicators, such as sanitation, hygiene, wastewater, water quality, efficiency, water stress, water management, transboundary issues, ecosystems, and cooperation. A recent report from the UN revealed that in 2022, 27% of the global population lacked access to safe drinking water, 43% lacked proper sanitation, and 419 million people practiced open defecation (UN 2023). Simultaneously, approximately 80% of the total wastewater generated is inadequately treated before being released into the environment (UN-WWDR 2017). This percentage increases to over 90% in the least-developed countries, underscoring the alarming global challenge of water pollution.

A significant contributor to this pollution crisis is the widespread use of chemical fertilizers, pesticides, and untreated wastewater in agricultural practices (Rout *et al.* 2021a). These challenges are further exacerbated by the relentless growth of the human population, rapid urbanization, and ongoing economic progress. Despite the potential for wastewater to be sustainably harnessed for water supplies, energy, nutrients, and materials (Kabdaşlı & Tünay 2018), significant disparities persist between global wastewater generation and management.

In the world's least-developed countries, the rapid expansion of urban areas has become a cause for concern, as these regions grapple with a severe shortage of vital infrastructure, particularly in terms of water supply and sanitation facilities. These urban areas find themselves in a state of perpetual change, contending with a multitude of social, political, economic, ecological, and environmental challenges (UNO 2018). To illustrate, the projected influx of an additional 2 billion people into resource-constrained regions of South Asia and Sub-Saharan Africa within the next three decades presents substantial challenges, particularly in the realms of water and food security, as well as waste management (Kookana *et al.* 2020). The absence of well-structured waste management regulations further compounds the problem, contributing to inefficiency and disarray in managing various issues in developing nations. As a result, the unregulated and chaotic discharge of untreated domestic and industrial wastewater, in addition to agricultural runoff, is widespread in developing countries such as Nepal. This unchecked release has led to a concerning transformation of surface water sources into contaminated open sewers and a rise in waterborne diseases (Pantha *et al.* 2021).

Nepal, classified as one of Asia's least-developed nations, is projected to undergo rapid urbanization at a rate of 2.0% per year from 2018 to 2050, second only to Burundi (UNO 2018). These projections are derived from the historical trend in urbanization growth observed since the commencement of the 21st century. Such accelerated and unmanaged expansion of urban infrastructure leads to a surge in population, exacerbating the challenge of managing existing sewage and water facilities. This rapid urban growth, coupled with a disproportionate increase in waste generation, underscores the urgent need for effective waste management strategies to meet the growing demands within the country. The 15th Five-Year Plan (2020–2025) initiated by the Government of Nepal (GoN) aimed to achieve the treatment and proper discharge of a minimum of 20% of wastewater (USAID 2020). However, GoN has only been able to provide effective treatment facilities for approximately 2–3% of the total urban wastewater generated (Fig. S1), with very few treated effluents meeting national standards (JICA 2019). This falls significantly behind the global average of 20% (UN-WWDR 2017). The latest census in 2021 reveals that only around 10% of households in Nepal have access to sewerage networks, with 4.5% of households still lacking access to toilet facilities. Nevertheless, about 65% of households have improved sanitation facilities, surpassing the South Asian average of 50% but falling slightly short of the global average of 68% (WHO-UNICEF 2017; Dorji *et al.* 2019). These statistics emphasize the need for substantial efforts to meet the ambitious targets of SDG 6, which aims to achieve a 95% coverage rate of improved sanitation by 2030 (UN 2023).

Statistics suggest that wastewater management and treatment facilities in the major cities of Nepal are still inadequate. Furthermore, unregulated wastewater disposal into land and water sources, along with ineffective treatment, contributes to environmental pollution, posing significant threats to public health. In fact, the primary disposal locations for wastewater in Nepal are water bodies and landfill, where the limits for disposal are set by Government legislation. However, because of the unregulated disposal practices, pristine water resources are facing detrimental impacts, including the revered Bagmati River in the capital city of Kathmandu, the Sirsiya River, which flows across borders from Nepal to India, and even the popular tourist attraction, Phewa Lake in Pokhara. Consequently, these once-pristine water bodies have become major sources of pollution in Nepal (Rupakheti *et al.* 2017; Ghimire *et al.* 2022). The elevated levels of organic contaminants, fecal coliform, heavy metals, pesticides, and pharmaceutical compounds in surface water have exacerbated the challenges associated with meeting the demand for water for various purposes, such as drinking and agriculture (Thakali *et al.* 2021; Quincey *et al.* 2022; Balkhi *et al.* 2023; Karki *et al.* 2024). These challenges are undeniably linked to the inefficient wastewater disposal system, and so close scrutiny of the quality standards of the wastewater that is being released into the water bodies is urgently required.

To establish an efficient sewage system amidst urbanization, there is value in integrating water supply and sewage network services, drawing from the experiences of other developing nations like Moldova and Romania, which have found cost-effective solutions (Dorji *et al.* 2019). The synergy between these services may result in an economically viable system, potentially reducing overall costs compared to providing them separately. Nevertheless, for a developing country like Nepal, the task of creating comprehensive public sewer collection and treatment infrastructure across all towns presents a formidable financial challenge with respect to the high capital investment required and the ongoing operational and maintenance expenses.

With limited internal financial resources, Nepal often relies on external donor funding. However, as Nepal is expected to transition out of its classification as one of the least-developed countries by November 2026 (UN 2021), access to external aid for infrastructure projects may become more restricted. Consequently, Nepal may increasingly turn to loans from international agencies such as the World Bank (WB) and the Asian Development Bank (ADB), potentially increasing the country's debt burden.

This research represents an effort to gain a thorough understanding of the intricate challenges arising from urbanization, wastewater generation, and water treatment methods in Nepal. Through a critical evaluation of the efficacy of current national effluent standards and the exploration of potential future directions, this study seeks to make a substantial contribution to the comprehension of urban wastewater management within the evolving urban landscape of Nepal. It examines the prospects of urban wastewater management in Nepal, with the overarching goal of safeguarding water resources, preserving the natural environment, and enhancing societal well-being.

2. DEMOGRAPHIC AND URBANIZATION OF NEPAL

Over the past two decades, Nepal has witnessed a significant upsurge in urbanization, as shown in Figure 1. Amidst this swift urbanization, the country has undergone a remarkable increase in its urban population, soaring from 2.9% increase from 1952 to 1954 (Rijal *et al.* 2020) to over 50% increase in the year 2021 (CBS 2021). This rapid urbanization has reshaped the landscape, transforming agricultural and other lands into urbanized areas.

Within the Kathmandu Valley, the built-up areas have expanded notably from 41 km^2 in 1975 to 177 km^2 in 2018. Projections suggest a doubling of this area by 2050, covering approximately half of the valley's land area (Mesta *et al.* 2022). A similar trend is anticipated in the southern part of the country, particularly in Koshi Province, where urban/built-up areas increased from 79.4 km^2 in 1996 to 270 km^2 in 2016 (Rijal *et al.* 2020). Across Tarai districts in associated provinces, substantial growth in urban areas, ranging from 222 to 659.78% from 1989 to 2016, underscores the ongoing rapid urban expansion (Rijal *et al.* 2020; Rimal *et al.* 2020).

Various factors, primarily socioeconomic, such as population growth due to migration and economic opportunities in urban centers, along with political, physical, and planning and policy factors, drive this urbanization (Rijal *et al.* 2020). Additionally, favorable climate and physiographic features, supported by government plans and policies, contribute to the region's appeal for urban development. However, the population surge poses challenges, particularly in terms of increased fecal waste, exacerbating sewage management and sanitation issues (Shrestha *et al.* 2023). This may necessitate the implementation of novel measures to address wastewater management problems in cities.

The urban growth can greatly exacerbate the existing onsite sanitation systems that may lead to fecal sludge management (FSM) issues. However, most fecal matter and wastewater are safely contained at an initial stage in the urban sector, with only a small fraction navigating the entire sanitation chain (Susana 2023) as shown in Figure 2. An excreta flow diagram (commonly known as a 'shit flow diagram,' SFD) for 47 cities in Nepal illustrates that a significant portion of excreta is currently discharged into the environment without undergoing treatment. Newly established urban municipalities show more promising progress in managing fecal matter compared to the megacity of Kathmandu (Fig. S1). This difference may be attributed to the increased population of megacities, which requires a greater allocation of funds for wastewater management infrastructure to accommodate their size. The addition of freshly generated waste to the existing unmanaged waste reduces the efficiency and handling capacity of the current wastewater management system.

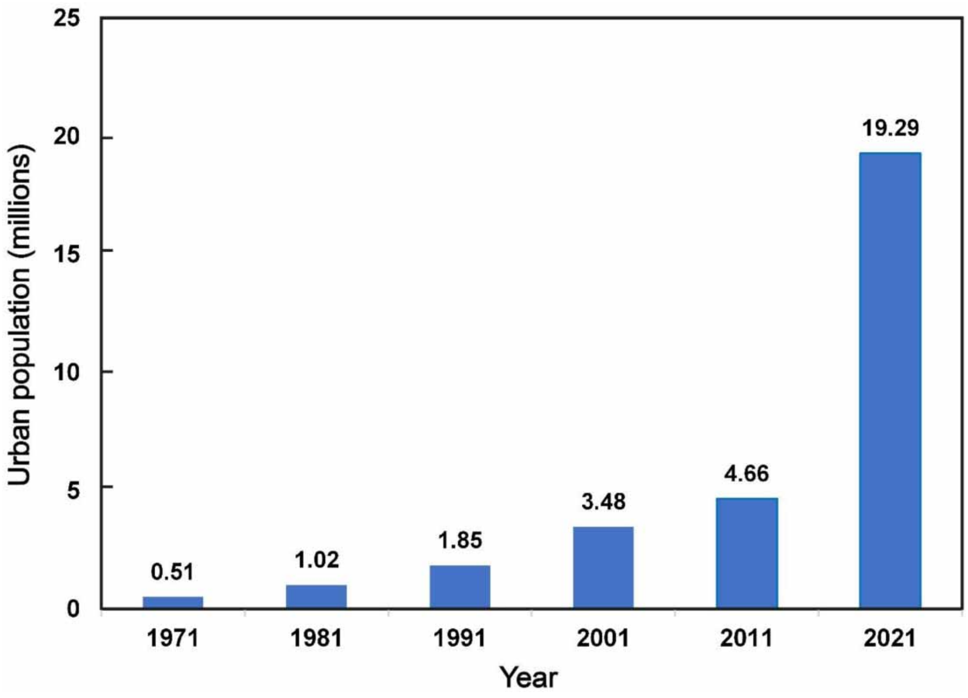


Figure 1 | Trend of the urban population from the year 1971 to 2021 in Nepal (CBS 2021).

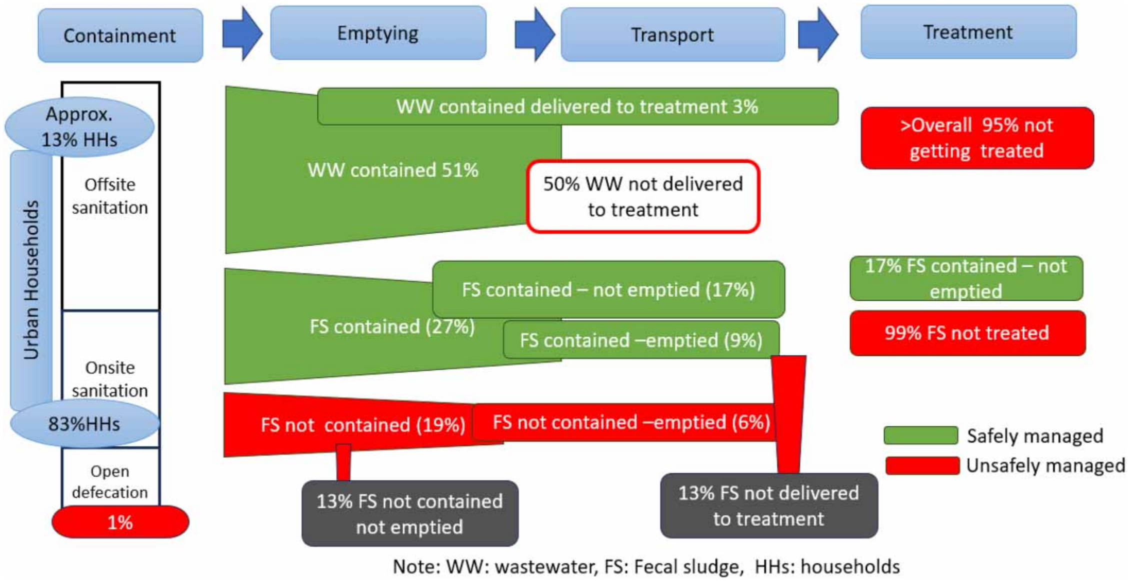


Figure 2 | SFD of urban Nepal illustrating the disparity in generation and treatment schemes (Data source: Susana 2023).

Compared to urban municipalities, rural municipalities face even greater challenges, with only 2.7% coverage of sewerage networks and a significant reliance on pit latrines (34.70%). This urban–rural disparity in access to safe defecation is unmistakable (Figure 3). Additionally, these figures highlight that a significant portion of the Nepalese population depends on onsite sanitation systems primarily due to lower capital ($70–$360 per person) and operation costs ($4–$12 per person per year) compared to centralized systems (Cairns-Smith *et al.* 2014).

Therefore, the increasing urban growth demands proper sewerage management in the locations experiencing the urban growth, for instance: Kathmandu valley. The institutional framework and policies are required in maintaining the quality standards of the effluents not to further exacerbate the environment caused by the unregulated sewerage disposals, leading to sanitation problems and health hazards.

3. OVERVIEW OF INSTITUTIONAL FRAMEWORK, POLICY, AND REGULATORY STATUS

The Ministry of Water Supply (MoWS) holds the central authority for overseeing water supply and wastewater management at the national level in Nepal. MoWS is responsible for devising development objectives and

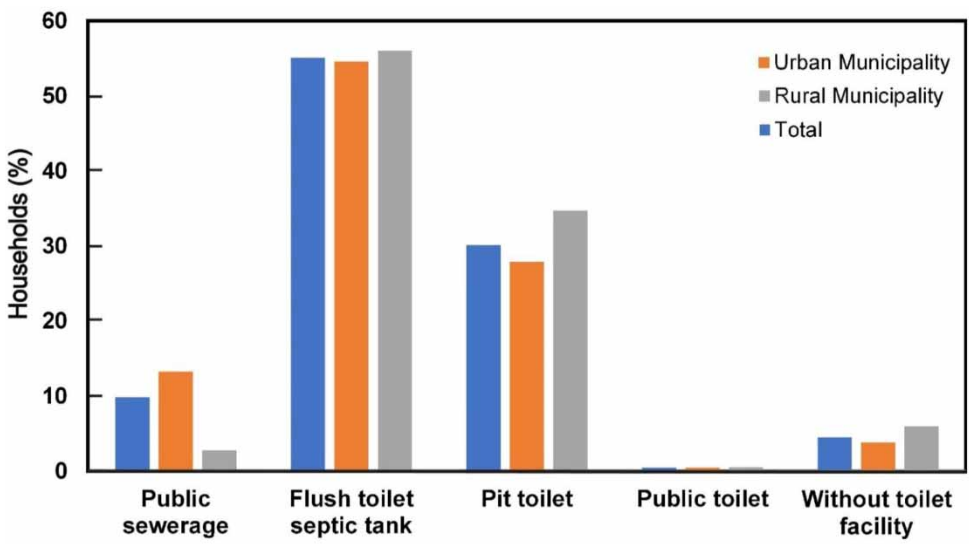


Figure 3 | Sanitation accessed in urban municipality and rural municipality of Nepal (CBS 2021).

policies in these domains across the country, actively implementing measures to enhance water supply and wastewater management within individual municipalities. It facilitates coordination between governmental, non-governmental, and private institutions and bodies in the water and sanitation sector. Particularly, the Environment and Sewerage Management Branch is involved in projects related to sewage and drainage, disaster risk reduction and environmental sanitation projects. Within Bagmati Pradesh, a total of six Water and Sanitation Divisions are currently functioning at different locations: Ramechhap, Sindhupalchowk, Dhading, Bhaktapur, and Makwanpurunder (MoWSEI 2024). Besides, the major agencies working under the ministry include Department of Water Supply and Sewerage (DWSS), Melamchi Water Supply Development Board, National Planning Committee, Kathmandu Valley Water Supply Management Board (KVWSMB), Nepal Water Institute, and Kathmandu Upatyaka Khanepani Supply Limited (KUKL).

DWSS, operating under the purview of MoWS, collaborates with provincial governments and local authorities to provide strategy, design, and execute urban infrastructure projects related to drinking water supply and wastewater management. As a result, various local authorities within each district are actively engaged in endeavors to achieve effective wastewater disposal and uphold the quality of the water supply in Nepal. Under DWSS, Sewerage Management & Environmental Sanitation Section, Sewerage Management & Sanitation Division, and Water Quality Improvement & Service Regulation Section works for the management of sludge waste, wastewater, and sanitation by ensuring the proper water supply. Moreover, Water Quality Improvement and Service Regulation has made policies aligning with SDG (2016–2030) and the national target is set to have 90% of the population using safe drinking water by 2030 (Shrestha *et al.* 2023). This ensures goals for the sanitation, health, and sludge disposal, together with managing the sewerage. All the departments ultimately target the metropolitan, sub-metropolitan, urban, and local municipalities to function according to the policies set by these ministries and departments.

Nepal comprises 7 provinces which are further subdivided into 77 districts including 6 metropolitan areas, 11 sub-metropolitan areas, 241 urban municipalities, and 481 rural municipalities (CBS 2021). These municipalities, in turn, are broken down into wards, representing the lowest tier of local administration. Local municipalities are duty-bound to strategize, develop, and supervise water supply, sewerage systems, and onsite sanitation facilities within their urban jurisdictions. As stipulated by the Constitution of the Federal Democratic Republic of Nepal in 2015, local governments bear the specific mandate for water supply, sanitation management, and business operations. The management of generated wastewater and water supply systems within their respective regions falls under the purview of each local municipality. Consequently, these municipalities establish specific goals and targets for sewerage management based on their individual generation capacities.

The Local Government Operation Act of 2017 in Nepal explicitly designates local governments as responsible for environmental and sanitation management. However, the establishment of systems for local municipalities, particularly with regard to onsite sanitation, has experienced significant delays. Onsite sanitation facilities primarily rely on households, entities, and private companies, and there is a lack of a comprehensive approach to regional water environment conservation and monitoring. The local area communities are still oblivious to the growing need of the sewerage management for the onsite sanitation facilities of the local residents. Urgent action is required to institute onsite sanitation and water environment management systems, inclusive of maintenance, within each local municipality. Even in cities with sewerage systems, enhancing onsite sanitation remains critical, given the challenges associated with implementing sewerage systems citywide.

For instance, one of the most advanced provinces of Nepal, Bagmati, consists of many urban cities, including the Kathmandu valley. Despite this, the province only includes 6 wastewater management divisions covering the whole Bagmati province with 13 districts (JICA 2019). KVWSMB and Kathmandu Upatyaka Khanepani Limited (KUKL) are making strides in improving sewerage facilities, including the construction of new systems and the upgrading of existing treatment plants and sewerage networks in the Kathmandu Valley. On the other hand, other cities often lack clear sewerage plans and have limited existing coverage (JICA 2019). The aforementioned context is supported by Table S1 providing an overview of sewerage and onsite sanitation in key urban centers in Nepal. In the Kathmandu Valley, sewerage coverage stands at approximately 70%, while other economic hubs struggle with almost non-existent sewerage systems, relying heavily on onsite sanitation and often lacking adequate management facilities (JICA 2019). Many urban municipalities face challenges in the realm of onsite sanitation facilities, primarily due to limited institutional and financial support.

Immediate action is needed in cities with sewerage systems to establish operation and management systems for their effective implementation. In cities beyond the Kathmandu Valley, wastewater management master plans and organizational frameworks are essential. The lack of a structured functional hierarchy, extending from the principal governing body to rural community levels, is compounded by the convergence of agendas within entities operating under the purview of sanitation and sewerage divisions, leading to environmental governance inefficiencies. The absence of specific objectives for onsite sanitation improvement, coupled with unregulated sewage treatment practices, underscores the need for comprehensive strategy and action. Furthermore, the unregulated treatment of sewage has raised concerns for governmental bodies striving to ensure quality standards based on various parameters.

National standards for the discharge of wastewater effluents play a pivotal role in the regulation and control of effluent quality from various treatment facilities, industries, and municipalities. The Government of Nepal has recently introduced updated standards (Table 1) governing the discharge of treated effluents into nearby water bodies and public lands, establishing permissible limits for key parameters such as pH (6.0–9.0), total suspended solids (TSS) (60 mg/L), and biochemical oxygen demand (BOD) (50 mg/L) (MoWS 2023). Notably, the BOD limit appears to be more than twice that of Indian standards, as outlined in Table 1. Discharging treated effluents into river systems can potentially lead to pollution in the receiving water bodies, which poses challenges for maintaining water quality in a pristine state, with a BOD level below 5 mg/L (Li & Liu 2019).

These standards mark significant progress in the regulation and enhancement of wastewater management. However, the new standards do not encompass nutrients and emerging contaminants of concern. Furthermore, the discharge of untreated or inadequately treated wastewater into freshwater bodies can contribute to eutrophication and the excessive growth of aquatic plants like water hyacinth, predominantly driven by excessive nutrient enrichment and harmful algal blooms (Lin *et al.* 2021). Additionally, the presence of emerging contaminants in water systems, such as pharmaceuticals and personal care products, can lead to the proliferation of antimicrobial bacterial genes. This issue is evident in the Bagmati river water, where elevated levels of organic matter, pharmaceuticals, pesticides, and antimicrobial resistance genes (ARGs) have been reported (Thakali *et al.* 2021; Quincey *et al.* 2022). These findings indicate excessive wastewater discharge without proper treatment or insufficient treatment measures in the Kathmandu Valley.

A further challenge arises from the limited availability of resources and expertise for monitoring and complying with prescribed standards, especially in treatment plants operated by smaller industries or situated in rural areas. The existing weak enforcement mechanisms further compound this issue, resulting in instances of non-compliance and violations. Additionally, many operators of treatment facilities, particularly in semi-urban areas, lack the essential technical knowledge and training required to efficiently operate and maintain wastewater treatment systems (Boukalová *et al.* 2021).

Another concern is the oversight of decentralized treatment systems in favor of centralized treatment plants when formulating effluent discharge standards. This oversight neglects the potential of decentralized approaches, such as constructed wetlands (CWs) or bio-digesters, which may be better suited for small-scale industries and rural areas where centralized infrastructure might not be practical or economically viable. Encouraging and incentivizing the adoption of decentralized treatment methods can help address the challenges encountered within these sectors.

To address these challenges comprehensively, it is crucial to implement an approach that includes enhanced monitoring and enforcement, regular updates of standards, capacity-building initiatives, the inclusive coverage of small-scale industries, promotion of decentralized treatment systems, and stricter penalties for non-compliance. Through the adoption of these strategies, Nepal can enhance its wastewater management practices and safeguard its valuable water resources.

4. REVIEW METHODOLOGY

A data collection template was provided to the DWSS and the Project Implementation Directorate of Kathmandu Upatyaka Khanepani Limited (KUKL-PID) to gather essential information for the survey and study. The responses

Table 1 | National effluent standards of treated urban wastewater in India and Nepal

Parameters	pH	Total suspended solids (mg/L)	Biochemical oxygen demand (BOD_5) (mg/L)	Chemical oxygen demand (mg/L)	*E. coli* (colony forming unit (CFU)/100 mL)	Country	Source
Maximum concentration limits	6.0–9.0	60	50	Monitor and report only	1,000	Nepal	MoWS (2023)
	6.5–9.0	<50	20		<1,000	India	CPCB (2017)

obtained were subsequently utilized for analytical purposes (as presented in Table S2 and Table S3). Data from various sources, including government entities such as the Central Bureau of Statistics (CBS, https://www.cbs.gov.np/), DWSS (https://dwssm.gov.np/), and KUKL-PID (https://kuklpid.org.np/), were collected from their respective websites. Additional data were extracted from published literature and reports using the Google Scholar search engine, employing keywords like 'urban wastewater,' 'wastewater,' 'Nepal,' and 'management,' spanning the years from 1999 to 2023. Most of these studies reported the degradation of water quality in the Bagmati River, attributed to the impacts of unregulated urbanization in the Kathmandu Valley, as supported by Ghimire *et al.* (2022), Kannel *et al.* (2007), Regmi *et al.* (2017), and Uprety (2017).

Reports published by funding agencies such as the ADB and the Japan International Cooperation Agency (JICA), along with other pertinent information, were identified, filtered, and documented in Table 2. The gathered data underwent a process of compilation, refinement, and rigorous analysis to yield precise results.

Table 2 | Overview of the literature review on urban wastewater infrastructure with their key findings

S.N.	Pros	Cons	References
1.	Reported the water supply and wastewater status Assessed the water and reported the degradation in the quality of Phewa Lake water due to an increase in anthropogenic activities	Limited within key cities (Kathmandu Valley, Janakpur, Birgunj, Hetauda, Pokhara) Could not cover all seven provinces	JICA (2019)
2.	Report on sanitation plan (sewerage, wastewater treatment) of Biratnagar Metropolitan City	Could not provide the effluent quality of wastewater and its compliance with national effluent discharge standards	GoN (2021)
3.	Progress in the development of a wastewater treatment plant in Birgunj	Financial issues	STIUEIP (2013)
4.	Provides a comprehensive report on improving Bagmati River civilization inside Kathmandu Valley	Could not cover the issues related to fecal matter	BAP (2009)
5.	Provides current progress on wastewater treatment plant in Kathmandu Valley	Slow progress in the design, procurement, and construction phase	ADB (2018), KUKL (2018)
6.	Evaluated water quality management frameworks, examined the urban water quality in Kathmandu Valley, and reported the degradation of water quality of Bagmati River.	Could not include challenges and their engineered alternative solution	Shrestha *et al.* (2015)
7.	Estimated urban wastewater generation rate of 147.37 MLD based on Census data 2011	Covers only major cities (Kathmandu Valley, Pokhara Birgunj, Janakpur, Dhangadi, etc.)	Ashutosh *et al.* (2015)
8.	Reported the poor performance of DeWATs due to negligence in operation and maintenance (O&M)	Covers only Kathmandu Valley with few specific treatment plants	Bartaula (2016)
9.	Reported the performance of the partially operated Guheswori wastewater treatment plant	Poor removal of nutrients	Thapa *et al.* (2019)
10.	Compared the performance of constructed wetlands (CWs) and conventional wastewater treatment plants.	Poor removal of nutrients from both treatment systems	Green *et al.* (2003)
11.	Reported the status of constructed wetlands in Nepal	Poor performance due to lack of upgradation of technologies, negligence in O & M	Gurung *et al.* (2017)
12.	Initiating the implementation of CWs in Nepal dealing with wastewater from different sources (Hospital, domestic)	Poor performance in removing nutrients (phosphorous and nitrogen)	Laber *et al.* (1999), Shrestha *et al.* (2001) and Singh *et al.* (2009)
13.	30% of CWs functional out of 23 CW-units located inside Kathmandu valley	Issues related to public awareness, community participation, and negligence in O&M	Boukalová *et al.* (2021) and Boukalová *et al.* (2019)

Additionally, this study sought to encompass the entire urban area defined by the Constitution of the Federal Democratic Republic of Nepal in 2015. This includes 6 metropolitan areas, 11 sub-metropolitan areas, and 241 urban municipalities to the greatest extent possible.

5. DISCUSSION

5.1. Impacts of urbanization

Urbanization intensifies the demand for expanded and improved urban infrastructure and services, with access to water supply and sanitation services standing as essential requirements for urban areas. However, rapid urbanization over the past few decades has led to a noticeable surge in water consumption and the need for adequate sanitation, as illustrated. Nearly all urban centers in Nepal have access to government-provided drinking water supply infrastructure (GoN 2018), though this is not without issues. Challenges include frequent water supply interruptions, substandard water infrastructures, often arising from low flow rates at water sources during dry seasons, and compromised water quality during heavy rains, particularly in municipalities lacking proper water treatment facilities (Sharma *et al.* 2021). Substantial water loss due to leakage poses a significant concern in urban areas.

Between 2001 and 2011, the urban population expanded by roughly fivefold. One primary factor behind this surge in urban population is the sudden increase in the number of urban municipalities (283) after 2015. Unfortunately, in many metropolitan areas, there is a lack of sewage networks or adequate treatment facilities. Consequently, wastewater is directly discharged without treatment into natural drainage systems, leading to contamination in the surrounding environment. For urban areas, the potential health risks associated with exposure to untreated wastewater effluents are more pronounced (Uprety *et al.* 2020). Therefore, it is imperative not only to ensure a reliable and high-quality water supply but also to establish effective wastewater management systems. Enhanced sanitation is of paramount importance in these urban settings.

At present, the government primarily focuses on developing comprehensive facilities for collecting, conveying, and treating municipal wastewater in limited cities. However, addressing the scarcity of non-potable water requires a proactive acknowledgment of the potential of residential wastewater as a valuable resource once appropriately treated. Embracing a strategic shift toward integrated water supply and sewerage management with a focus on resource recovery (ADB 2022) will address the immediate water demand while playing a pivotal role in preserving essential raw water resources, including groundwater and surface water. By adopting this approach, we can chart a sustainable course that balances the needs of expanding urban centers with the imperative of responsible water management.

5.2. Provincial urban wastewater generation and treatment

Based on the most recent census data (2021), Nepal's total urban wastewater generation capacity is approximately 1,543 MLD (million liters per day), assuming a per capita domestic water supply rate of 100 lpcd (liters per capita per day) as per the Government of Nepal's 2018 data. It is also estimated that approximately 80% of the water supplied for domestic use ultimately becomes wastewater.

However, the existing sewerage network in the country only manages to collect about 30% of the urban sewage generated. A mere 3% of the urban wastewater is directed to municipal wastewater treatment plants (WWTPs) for processing, while the majority is discharged directly into nearby water bodies, as reported by the JICA in 2019.

Figure 4 illustrates the volume of wastewater treated in municipal WWTPs, which employ both conventional and decentralized wastewater treatment systems (DEWATs). It also displays the corresponding treatment ratio over the period from 1971 to 2021. These data reveal a substantial exponential growth in sewage generation, while the available treatment facilities remain inadequate, and in suboptimal condition.

Table 3 shows that there is a discrepancy in provincial-level wastewater generation and the corresponding treatment provisions in Nepal. Bagmati province boasts a substantial wastewater generation capacity, amounting to 376.53 MLD, which is more than five times that of Karnali province at 70.64 MLD. However, the level of wastewater treatment in each province remains inadequate.

It's worth noting that the number of conventional treatment units has increased from 5 to 9, nearly doubling compared to the 1990s. Interestingly, a significant proportion of these new, larger treatment units are concentrated within the capital city, Kathmandu Valley. This distribution is primarily driven by population demographics and government priorities, as highlighted by the KUKL in 2018.

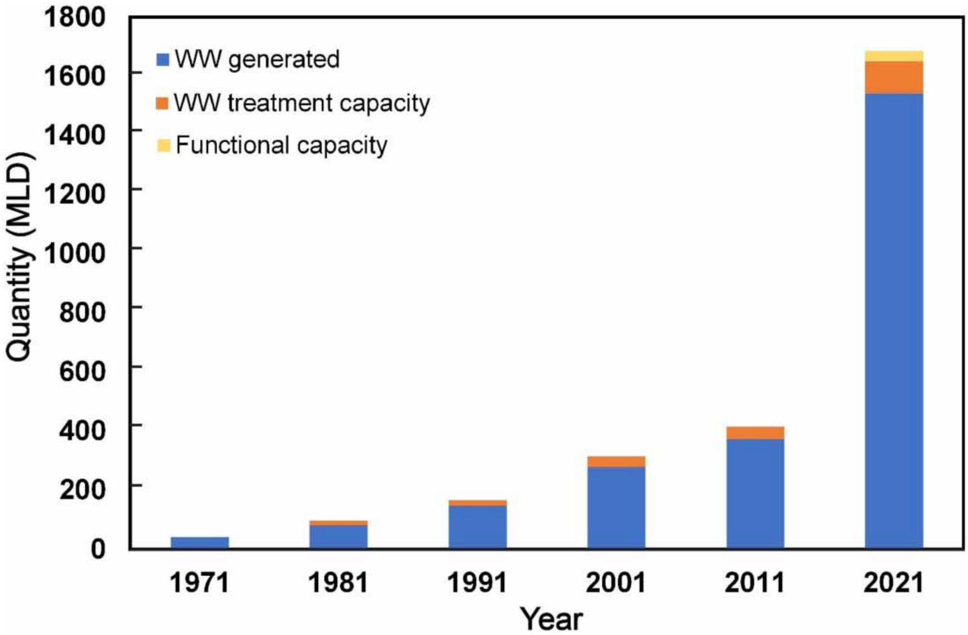


Figure 4 | The quantity of generated urban wastewater, treatment capacity, and functional capacity of plants from 1971 to 2021.

Table 3 | Provincial status of wastewater generation and treatment in Nepal (*Source:* CBS 2021; KUKL 2023; and DWSS 2023)

Province	Estimated WW generated (MLD)	Operational capacity (MLD)	Proposed/construction phase treatment capacity (MLD)
Koshi	247.87	18.50	13.38
Madhesh	357.16	10	8.65
Bagmati	376.53	32.4	124.15
Gandaki	130.36	–	2.31
Lumbini	225.64	–	1.55
Karnali	70.64		0
Far western	135.09		1.26
Total	**1,543.28**	**60.9**	**147.8**

The anticipated wastewater generation rate for the valley is projected to reach 350 MLD, but the treatment capacity is estimated to cover only 44% of this amount by the year 2030, as reported by KUKL. The considerable gap between the wastewater generation rate and the treatment capacity provided is primarily attributed to economic constraints, population distribution patterns, and the rapid pace of urbanization.

5.3. Description of treatment systems

5.3.1. Conventional centralized treatment system

The use of centralized WWTP represents one of the most widely employed approaches for mitigating water pollution on a global scale. Centralized WWTPs are designed to process and treat wastewater from diverse sources through a combination of physical, chemical, and biological processes, all performed in a central facility. These plants mimic natural remediation procedures and subsequently release treated water into the environment, aligning with the principles of natural purification methods (Jamwal *et al.* 2021).

In the history of wastewater treatment in Nepal, a few conventional WWTPs have been established. The total wastewater treatment capacity, encompassing both construction and design phases, is estimated at approximately 170 MLD in Nepal, as detailed in Table 3. However, only 60.9 MLD of this capacity is presently operational. It is noteworthy that centralized WWTP facilities are currently operational in only three provinces: Koshi, Madhesh, and Bagmati, as indicated in Table 4. Approximately 80% of WWTPs (see Figure 5) employ the conventional activated system (CAS), making this the prevailing treatment method.

Over the period 1980–2000, the Kathmandu Valley responded to escalating water pollution and health and sanitation challenges by establishing five wastewater treatment facilities, namely Hanumanghat, Sallaghari, Kodku, Dhobighat, and Guheswori WWTPs (Mishra *et al.* 2017). Regrettably, these facilities have encountered significant challenges stemming from inadequate operational and maintenance procedures, a shortage of qualified personnel, and subpar management. Problems such as sludge accumulation, frequent power outages, and

Table 4 | Conventional wastewater treatment system in Nepal (*Source:* DWSS 2023; KUKL (2023; GoN 2021)

Name of the project	Location	Type of treatment system	Types of treatment plant	Treatment capacity (MLD)	Status	Responsible organization
Guheshwori wastewater treatment plant	Guheshwori, BP	Biological	Activated sludge process	32.4	Functional	KUKL
Sallagahri, Kodku, and Dhobighat wastewater treatment plant	Sallagahri, Kodku and Dhobighat, BP	Biological	Activated sludge process	14.2, 17.5, and 37	Construction phase	KUKL
Dhobighat wastewater treatment plant	Dhobighat, BP	Biological	Activated sludge process	37	Construction phase	KUKL
DEWATS at Gokarna and Hanumanghat	Gokarna and Hanumanghat, Bhaktapur, BP	Biological	Membrane-based biological reactor	1 and 3	Design phase	KUKL
Birgunj wastewater treatment plant	Birgunj, MP	Biological	Waste stabilization pond	10	Functional	STIUEIP (Birgunj Metropolitan)
Biratnagar wastewater treatment plant	Biratnagar, KP	Biological	Waste stabilization pond	18.5	Functional	STIUEIP (Biratnagar sub-metropolitan)

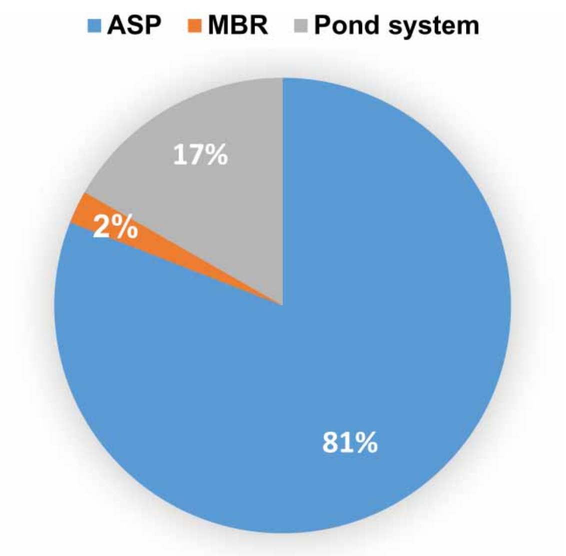


Figure 5 | Proposed proportion of conventional vs modern treatment facilities.

malfunctioning flow control systems have plagued these facilities over the years. These issues have, at times, resulted in system short-circuiting, rendering the plants either non-operational or only partially functional.

To address these persistent challenges, the Kathmandu Valley Wastewater Management Project (KVWMP), funded by the ADB, is currently underway within the valley. The construction cost of these treatment plants ranges from \$23.77 to \$58.12 per person, excluding sewerage systems, as presented in Table S2. The primary objective of this project is the expansion and renovation of treatment plants, pumping stations, and sewerage networks. In most rehabilitation initiatives, CAS has been employed.

Beyond the valley, pond systems were constructed with the support of the secondary town's integrated urban environment projects (STIUEP). However, these systems have struggled to operate at their designed capacity due to inadequacies in the sewerage networks.

At present, there is no official report available that assesses the compliance of WWTPs with national effluent standards. Thapa *et al.* (2019) reported notable removal efficiencies of 76.12% for COD and 76.13% for BOD in the CAS. Nevertheless, the removal of nutrients exhibited significantly lower rates (phosphate: 47.61–55.60% and ammonia nitrogen: 12.67–29.11%), falling short of the discharge standards prescribed by the Ministry of Forest and Environment. This deficit in nutrient removal is exacerbated by the elevated nutrient concentrations observed in adjacent water bodies, thereby fostering the proliferation of harmful algal blooms.

5.3.2. Decentralized wastewater treatment systems

CWs have proven effective in the treatment of wastewater from a variety of sources, including hospitals, industries, institutions, and domestic settings, by simulating the natural wetland ecosystem (Muduli *et al.* 2022; Timalsina *et al.* 2022). In Nepal, the introduction of CWs took place in the late 1990s where an initial hybrid CW was established to treat hospital wastewater. This system had a design flow rate of 20 m^3/day, employed intermittent feeding, and utilized broken gravel and sand as substrates. *Phragmites karka* was strategically planted within both substrate structures (Laber *et al.* 1999). Impressively, the hybrid CW achieved average reduction efficiencies for a range of pollutants, including TSS, BOD_5, chemical oxygen demand (COD), NH_4-N, NO_3-N, PO_4-P, TP (total phosphorous), total coliform, *E. coli*, and fecal streptococcus, with efficiencies ranging from 92 to 99.95% (Laber *et al.* 1999). However, it is worth noting that phosphorous removal was somewhat less effective, possibly due to the media's limited sorption capacity.

Singh *et al.* (2009) conducted a study examining the performance of anaerobic baffled reactors (ABRs) and hybrid CWs as DeWATs for managing high-strength wastewater. Although the ABR system demonstrated higher pollutant removal efficiencies compared to septic tanks, there was an increase in ammonia concentration in the effluent from the outlet of the ABR, indicating ammonification of organic nitrogen present in the wastewater. The ABR system achieved reductions of 68.3% for TSS, 45.3% for BOD_5, and 47.2% for COD.

DeWATs displayed typical removal efficiencies of 96% for TSS, 90% for BOD_5, 90% for COD, 70% for NH_4-N, 26% for TP, and 98% for fecal coliform. These results suggest that the efficiency of CWs is comparable to contemporary wastewater treatment technologies, such as the conventional activated sludge (CAS) and up-flow anaerobic sludge blanket systems.

Between 2000 and 2010, more than 60 CWs were established across Nepal in various sectors, but only around 20% of them remain operational today (ENPHO 2014). DWSS has recently proposed a modified DeWATs system, incorporating elements of ABR and CWs, and including polishing ponds in select schemes for several small and medium towns nationwide, with a total treatment capacity of around 40 MLD, of which approximately 5 MLD is currently operational. A summary of this infrastructure is shown in Figure 6. The construction cost of CWs in Nepal ranged from \$22.7 to \$172.8 per m^2 (Gurung *et al.* 2017). However, underutilization of CW infrastructure has led to problems such as clogging and blockages in filter media and pipe systems. Additionally, the absence of proper desilting and primary settling ponds complicates the situation, with the potential for wastewater overflow during monsoon periods because of stormwater infiltration. Owing to the significant volume of wastewater generated in densely populated urban areas and high land costs, CW implementation has primarily been limited to peri-urban areas and emerging cities.

5.4. Sludge management and challenges

Sludge management encompasses the collection, treatment, and responsible disposal of sludge, the residual product generated during wastewater treatment processes. Nepal faces distinctive challenges in sludge management, given its unique socioeconomic and geographical characteristics. Nevertheless, the country has been actively

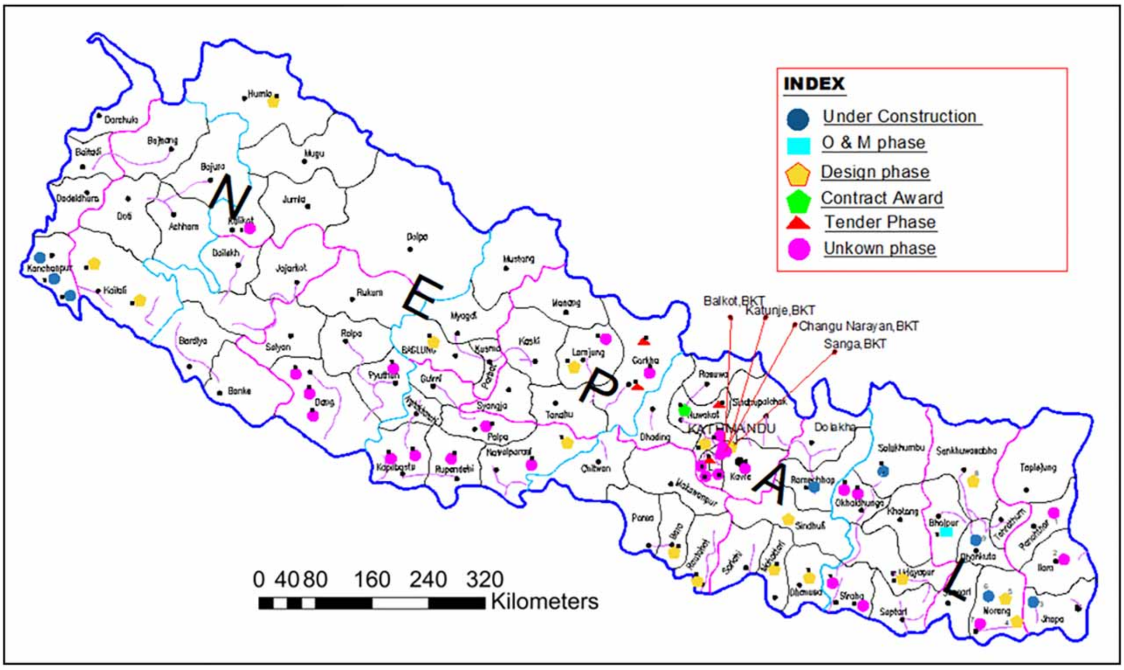


Figure 6 | DeWATs under DWSS in different phases of project: proposed, construction, and operation. (*Source*: DWSS 2023).

striving to enhance its sludge management practices. Particularly, Nepal has been focused on expanding its wastewater treatment infrastructure, primarily in urban areas, where cities like Kathmandu, Pokhara, and Biratnagar host pivotal WWTP (Shrestha *et al.* 2015; Gurung *et al.* 2017). However, the current coverage remains limited, with numerous regions lacking proper treatment facilities. Consequently, new systems are being introduced to enhance the efficiency and adequacy of these treatment facilities.

Innovatively designed WWTPs in the Kathmandu Valley are being equipped to handle both residential septage and the sludge produced during wastewater treatment. This approach employs waste-to-energy technology, whereby waste materials are converted into electricity. Through processes like sludge digestion and/or gasification, approximately 910 kW of energy is anticipated to be generated (KUKL 2018). It is worth noting that digested sludge may contain emerging contaminants (Dubey *et al.* 2023), raising concerns about their persistence in the post-digestion manure, which is intended for sale to farmers. Consequently, assessing potential risks associated with emerging contaminants in digested sludge is of paramount importance to prevent their inadvertent entry into the food chain (Ravichandran *et al.* 2021).

Beyond centralized WWTPs, Nepal heavily relies on septic tanks and onsite sanitation systems, particularly in rural areas. Effective septage management, encompassing the proper collection and treatment of septic tank sludge, constitutes a crucial aspect of the country's overall sludge management strategy. In some locations, FSM strategies incorporate ABR, CWs, and sludge drying beds (ENPHO 2014). Nevertheless, these facilities often grapple with operational and maintenance issues, hindering their efficiency.

To address these challenges sludge management in Nepal requires significant further investment, institutional support, technical empowerment, community participation, and improved collaboration and coordination among government agencies, international organizations, and local communities. These measures are essential to advance sludge management practices, safeguard public health, and protect the environment.

6. ENGINEERING PERSPECTIVES

6.1. Advancement in treatment technologies

The global trend of movement toward resource-oriented wastewater treatment emphasizes the reclamation of valuable products from wastewater, with the potential for conversion into marketable goods like fertilizers, bio-plastics, biofuels, and more (Masi *et al.* 2018). The treated wastewater can serve a wide range of purposes. Nepal, too, has the opportunity to adopt similar approaches in pursuit of sustainable water supply, energy self-sufficiency, resource recovery, and environmental equilibrium. In order to realize this vision, the enhancement and objectives in wastewater management can be distinctly channeled toward advancements in wastewater treatment technologies, encompassing four primary avenues of progress.

6.1.1. Modification of treatment processes and units

Wastewater treatment technologies exhibit variations in land area requirements. For instance, technologies like moving bed bioreactors (MBBR) and sequential batch reactors (SBR) are characterized by minimal space needs, approximately 450 m^2 per 1000 m^3/d and 0.05–0.01 m^2 per person, respectively. In contrast, larger land areas are essential for waste stabilization ponds (2–3 m^2 per person) and CWs (1.5–2.5 m^2 per person) (Parde *et al.* 2021). Maintenance costs differ across technologies, with the likes of activated sludge process (ASP), up-flow anaerobic sludge blanket reactor (UASB), trickling filters, and waste stabilization ponds typically accounting for around 10–15% of the capital cost. Facultative ponds, in contrast, incur maintenance costs of approximately 3% of the capital cost, while CWs come in at roughly 1% of the capital cost (Parde *et al.* 2021).

Furthermore, the ecological footprint of conventional ASP is approximately two to five times larger than that of nature-based systems (Garfí *et al.* 2017), depending on the specific impact category under consideration. This discrepancy primarily stems from the significant electricity and chemical consumption inherent in the operational processes of conventional WWTPs. As an economically viable alternative to centralized systems, cluster-type DeWATs with fewer than 16 clusters and simplified sewers can be considered, provided they are meticulously designed to minimize costs (Torre *et al.* 2021). Notably, DeWATs incorporating constructed wetland (CW) systems exhibit enhanced efficiency in removing emerging contaminants compared to conventional WWTPs (Rout *et al.* 2021a). This underscores the suitability of cluster-based DeWATs for developing countries such as Nepal because of their adaptability to transition to centralized systems when funding becomes available.

Of particular note is that the performance of CW and algal pond systems is comparable, aligning closely with the principles of sustainable wastewater management and emphasizing the effectiveness of nature-inspired solutions in mitigating adverse environmental impacts.

In the context of Nepal, enhancements are required for existing treatment systems like ASP, pond systems, and CWs. The aerobic granular process offers advantages such as high-quality effluent, energy efficiency, and a reduced footprint (Qu *et al.* 2019). Extensive research over the past decade has led to the successful implementation in WWTPs across Europe and Africa. To improve the efficiency and reduce the footprint of low-cost technologies like pond systems, integration with constructed floating wetlands (CFWs) or algal ponds has proven effective (Kalubowila *et al.* 2013; Lucke *et al.* 2019). CWs can benefit from improved pollutant removal efficiency by integrating baffled wall horizontal flow CWs and altering substrates with high adsorptive capacity for nutrients and emerging contaminants, such as iron furnace slag, lightweight expanded clay aggregate (LECA), biochar, and brickbats (Manthiram Karthik & Philip 2021; Parde *et al.* 2021). Consequently, there is a compelling need to explore sustainable, highly adsorptive substrate materials and appropriate macrophytes for CWs.

Research should be directed toward the identification of substrates and vegetation that not only efficiently remove organic matter, but also effectively target emerging contaminants, antimicrobial-resistant bacteria, and nutrients while mitigating the risk of clogging within CWs. Given that CWs demonstrate superior performance with pretreated water, it becomes imperative to optimize the processes of pretreatment and post-treatment to align with national effluent discharge or reuse standards (Singh *et al.* 2009). This optimization may involve refining techniques to ensure the effluent consistently complies with stringent regulatory criteria, ultimately contributing to enhanced water quality and environmental sustainability.

There is also an urgent need to evaluate optimal management strategies for the consistent maintenance of CWs, thereby ensuring their prolonged and effective operation. The capital cost of CWs remains relatively low, while the value of urban land is high. This underscores the importance of minimizing the physical footprint of CWs, a critical factor for their viability in urban settings where space is limited. Therefore, the combination of these research directions and considerations is pivotal for advancing the efficiency, applicability, and sustainability of CWs in contemporary wastewater management frameworks. Similarly, the decentralized systems such as the green roof-top water recycling system (GROW) and green wall-CWs offer practical solutions for wastewater treatment without needing permanent land allocation (Boano *et al.* 2020). Striking a commendable balance between effectiveness and efficiency, these innovations are particularly advantageous in urban and developing areas (Ramprasad *et al.* 2017). Implementing such treatment units in small-scale, cost-effective facilities managed by local communities provides a practical approach to address environmental and financial challenges. This establishment not only eases government financial constraints but also empowers communities to actively engage in water resource management, fostering self-sufficiency and contributing to overall societal conditions. Consequently, this approach improves the local environment and instills a sense of responsibility and ownership regarding wastewater management among community members.

On the other hand, addressing the limitations of substrate-based CWs can be achieved through the implementation of CFWs, especially in scenarios involving the treatment of contaminated surface water. CFWs boast a relatively small footprint, making them particularly suitable for densely populated urban areas characterized by limited space (Kalubowila *et al.* 2013; Lucke *et al.* 2019). These innovative systems represent a harmonious blend of ecological engineering and wastewater treatment. CFWs not only enhance water quality by facilitating the removal of contaminants, nutrients, and pollutants, but they also promote biodiversity and provide habitat for aquatic organisms. Their adaptability to various aquatic environments, from urban ponds to wastewater lagoons, underscores their versatility and potential impact.

Moreover, CFWs exhibit the potential to seamlessly integrate wastewater treatment and ecological enhancement. Consequently, the integration of robust research efforts and the development of comprehensive guidelines can significantly aid in fully realizing their potential, enabling them to seamlessly align with contemporary environmental strategies.

6.1.2. Algal-based wastewater treatment (phycoremediation approach)

Phycoremediation represents an innovative approach to the treatment of water and wastewater, capitalizing on the ecological role of microalgae in the removal of pollutants (Danouche *et al.* 2021). Since its inception in the 1960s, phycoremediation has emerged as a promising method for wastewater treatment. This process employs eukaryotic microalgae as bio-remediators for wastewater. Microalgae, being photosynthetic organisms, exhibit a remarkable capacity to thrive in wastewater, even under extreme conditions, by utilizing nutrients and organic substances. The genesis of algal-based wastewater treatment was driven by the desire to reduce the costs associated with algae cultivation while establishing a sustainable wastewater treatment approach. Consequently, this method provides an environmentally friendly means of purging pollutants from wastewater by incorporating algae.

Microalgae efficiently consume carbon and nutrients present in wastewater for their growth, thereby reducing nutrient concentrations in the wastewater. These microorganisms serve as highly effective carbon mitigators and have found integration within the tertiary treatment stages of enhanced wastewater treatment processes (Dayana Priyadharshini *et al.* 2021). In certain regions, oxidation ponds are being harnessed for algal cultivation, enabling the oxidation of wastewater through the release of O_2 and CO_2. As a result, the proliferation of algae can significantly mitigate environmental pollutants. Furthermore, microalgae possess the capacity to remove toxic pollutants, including heavy metals, without engendering secondary contaminations, thanks to various extracellular and intracellular defense mechanisms.

The phycoremediation approach is currently viewed as a sustainable, cost-effective, and energy-efficient method, as it can be powered by energy generated from sunlight or from the wastewater itself, in stark contrast to existing energy-intensive technologies. Additionally, following the removal of nutrients using algal biomass, this process generates energy-rich biomass that can be leveraged for the production of biofuels, value-added bioproducts, and livestock feed supplements, providing an added advantage to this approach (Selvaratnam *et al.* 2022).

6.1.3. Implementation of innovative technologies

The landscape of municipal wastewater treatment has undergone a profound transformation, driven by the emergence of a range of innovative technologies. These advancements are reshaping the operational aspects of wastewater treatment and impacting its ecological, economic, and sustainable dimensions. A prime example is the MBRs, which seamlessly integrate biological processes with state-of-the-art membrane filtration. This fusion leads to a substantial improvement in the removal of solids and microorganisms while reducing the physical footprint of treatment plants (Garfí *et al.* 2017).

Anammox offers an alternative to the traditional nitrification/denitrification route, significantly reducing energy consumption (Rout *et al.* 2021b). It also paves the way for the efficient implementation of energy-producing carbon bioconversion processes, such as anaerobic membrane bioreactors. Nutrient recovery technologies, such as struvite precipitation and biological nutrient removal (BNR), play a crucial role in reclaiming valuable resources from wastewater and mitigating nutrient pollution (Batstone *et al.* 2015).

Advanced oxidation processes (AOPs), including ozone treatment, ultraviolet (UV) photolysis, and plasma membrane techniques, prove effective in breaking down persistent organic pollutants (Choudhary *et al.* 2021). These pollutants often present a significant challenge in conventional wastewater treatment methods due to their resistance to degradation (Pesqueira *et al.* 2020). AOPs facilitate the *in situ* formation of highly oxidizing compounds, such as hydroxyl radicals, which can oxidize complex wastewater streams containing recalcitrant contaminants. This contributes to more efficient and environmentally friendly wastewater management practices. However, it is important to note that various AOP methods involve the utilization of iron ions, ozone, and UV radiation, which must be exposed to specific pH and temperature conditions to expedite the oxidation process. These systems can be costly and may potentially generate toxic byproducts.

Various products can be recovered from sludge, potentially transforming the waste into a valuable repository of energy, metals, and chemicals through resource recovery initiatives (Tyagi & Lo 2013; Ramtel *et al.* 2021). Compounds found in sludge can also be repurposed for industrial and agricultural applications, such as polyhydroxyalkanoates (PHA) production and the use of sludge-derived biochar to amend soil (Ahmad *et al.* 2022; Goh *et al.* 2022). Beyond economic incentives, resource recovery aligns with sustainability goals by reducing waste volumes, lessening the environmental impact of sludge disposal, and promoting a circular economy. This shift underscores the innovative and adaptive nature of wastewater management, where waste is no longer a problem to eliminate but rather emerges as a source of opportunities and potential solutions.

6.1.4. Development of efficient facilities, materials, and process control techniques

The synergistic advancement of efficient facilities, innovative materials, and precise process control techniques marks a significant stride in the field of wastewater treatment. This progress is instrumental in enhancing treatment effectiveness, resource recovery, and environmental sustainability. It encompasses the development of cutting-edge treatment plants, novel materials designed to enhance pollutant removal capabilities, and the implementation of sophisticated control strategies aimed at optimizing treatment processes. Furthermore, there is a pressing need for advancements in wastewater treatment and sludge management to fine-tune the operation of WWTPs by harnessing improved facilities, materials, and process control techniques. This includes the development of efficient carrier materials to promote biofilm growth, the introduction of enhanced aeration devices for more effective oxygen supply, the adoption of advanced membrane technologies to achieve higher effluent quality, and the implementation of online monitoring and artificial intelligence (AI) control techniques to bolster process stability (Qu *et al.* 2019).

The integration of AI models, such as artificial neural networks (ANN) and neural fuzzy (NF), within WWTPs plays a pivotal role in simplifying the intricate challenges posed by natural conditions, influent variations, and the inherent uncertainties associated with wastewater treatment technologies (Zhao *et al.* 2020). These uncertainties often lead to fluctuations in effluent water quality, operational costs, and environmental risks to receiving waters. AI has emerged as a potent tool for addressing these complexities and effectively streamlining wastewater treatment processes.

6.2. Future challenges and ways forward

Urban wastewater management in developing countries like Nepal confronts a multitude of challenges, including inadequate infrastructure, limited financial resources, lack of public awareness, outdated standards and policies governing wastewater effluents, emerging contaminations, and the need for sustainable wastewater management practices. In summary, the absence of proper sewerage systems and WWTP results in the discharge of untreated wastewater into water bodies, leading to pollution and health risks. To address the evolving demands of wastewater management, developing countries must invest in developing sewage networks and treatment facilities, expand sewerage coverage, and upgrade existing infrastructure. Additionally, exploring alternative financing mechanisms and prioritizing wastewater management in budget allocations are imperative steps to address these challenges.

The successful implementation of plans and policies depends significantly upon robust public support. Therefore, it is essential to prioritize proactive awareness campaigns and educational initiatives aimed at encouraging the public to embrace safe sanitation practices, particularly through the adoption of hygienic defection systems. Plans and policies should avoid overemphasizing a binary choice between centralization and DeWATs. Instead, a comprehensive approach should be adopted, integrating both methods rationally, considering their suitability for specific regions based on appropriateness and local conditions. The incorporation of both systems is conducive to establishing resilient site-specific solutions for urban environments, especially beneficial for developing nations (Torre *et al.* 2021). Quantitative management tools such as life-cycle cost analysis and other optimization models can enhance policy support (Garfí *et al.* 2017). Integrating water resource management, adopting sustainable technologies, and strengthening the policy and regulatory framework are essential for effective urban wastewater management in developing countries like Nepal.

It is encouraging to see that Nepal is progressing toward implementing more stringent and comprehensive measures for water pollution control. Nepal's efforts to implement rigorous water pollution controls, especially in cities like Kathmandu, are commendable. Effluent standards are formulated based on the impurity levels of wastewater and are adapted to specific urban settings. Uniform standards prove impractical given the diversity from megacities to small municipalities. Therefore, it becomes essential to implement standards that are respective to each urban setting. The flexibility of this approach facilitates aligning regulations with specific city needs, thereby introducing more efficient and sustainable wastewater solutions. Besides, considering the international development trend, the next logical progression would be controlling emerging pollutants and promoting water reclamation. These areas are still in the very early developing stages in Nepal but are expected to become increasingly important in the coming future.

The shift in the target of wastewater management from pollutant abatement to water reuse, resource recovery, and water ecology restoration is a significant change. This change has made it possible to consider the avenues for sustainable water resource management beyond mere pollution mitigation strategies. This approach is in line with global efforts to alleviate water scarcity, promote environmental sustainability, and foster the principles of a circular economy. Nepal must continue updating, implementing, and enforcing these new standards and policies, contributing to achieving cleaner water resources and advancing into a more sustainable and resilient wastewater sector in the country.

7. CONCLUSIONS

Wastewater management has emerged as a significant concern in Nepal, particularly with the rapid urbanization witnessed in major cities. The urban population, comprising approximately 85% of the total, heavily relies on onsite sanitation facilities to meet their sanitation needs. However, these onsite sanitation systems come with inherent challenges related to maintenance, contamination risks, and limited capacity. The urban growth has led to a substantial increase in wastewater generation due to population growth, further exacerbating Nepal's wastewater treatment issues and hindering access to safe sanitation facilities. Of the country's seven provinces, only two have established public sewage systems, which serve a mere 10% of households in Nepal. Consequently, Nepal is grappling with a significant crisis in establishing an effective wastewater management system.

Nepal currently faces various wastewater treatment challenges, including the discharge of untreated wastewater into water bodies, poorly managed sewage systems, and the lack of proficient treatment systems. The addition of newly generated sewage to the existing unmanaged systems compounds the challenges of uncontrolled waste disposal, leading to significant environmental degradation and deterioration of public health. While the government is making efforts to address these issues by investing in treatment plants, enforcing regulations, and promoting treated wastewater reuse, it is impractical for the government to provide centralized treatment systems to all municipalities. Therefore, it is essential to explore and advocate for upgraded onsite treatment systems to align with long-term environmental goals.

However, several challenges persist, such as funding constraints, limited expertise, and low awareness. Overcoming these hurdles requires collaboration among the government, stakeholders, and international partners, with a focus on infrastructure development, capacity building, and awareness campaigns. The experiences of Nepal in urban wastewater management hold global relevance, offering valuable insights to nations facing similar challenges. Sharing knowledge and fostering international cooperation can drive sustainable and resilient wastewater management practices, benefiting communities and the environment worldwide.

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AUTHORS' CONTRIBUTION

B.K.K. wrote the original draft, visualized the data, prepared the literature review, and rendered support in data collection and analysis; S. B. wrote the original draft and prepared the literature review, and visualized the data: H. L. K. wrote the original draft and literature review; M. J. A. wrote the review and rendered support in critical editing; S. R. P. supervised the article, wrote the review, and rendered support in critical editing.

COMPETING INTERESTS

The authors declare that they have no any competing interests.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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