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Research Paper

An overview of wastewater treatment technologies in Minas Gerais, Brazil: predominance of anaerobic reactors

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ABSTRACT

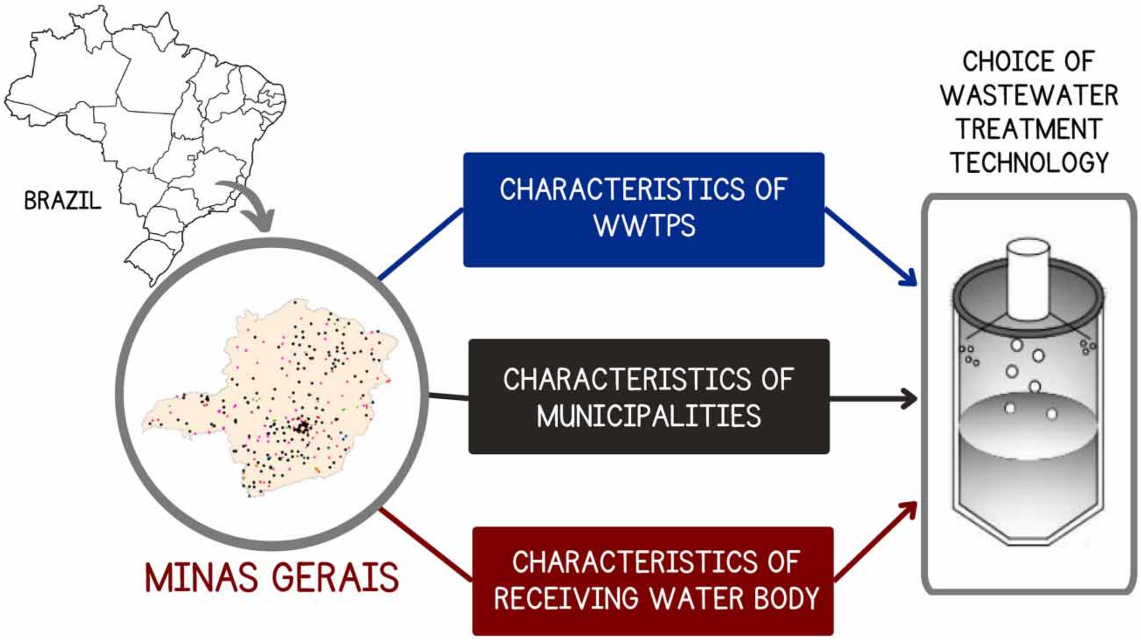
The deficit in sewage collection and treatment is a problem in Brazil, and a large portion of untreated sewage, usually disposed of directly into water bodies, compromises water quality, with implications for public health and environmental balance. This scenario does not differ in the State of Minas Gerais, where only 44% of the urban population has their sewage treated. This study aimed to evaluate the current use of wastewater treatment technologies in active wastewater treatment plants (WWTPs) in Minas Gerais, based on a database from the Sewage Atlas, and analyze how the characteristics of the municipality and the treatment system influence the selection of adopted technologies. Information on 376 active WWTPs and 26 WWTPs designed or under construction was obtained. The most used technologies include upflow anaerobic sludge blanket (UASB) reactors, with or without post-treatment, adopted in more than 70% of WWTPs. A logistic regression model was fitted to explain the presence of post-treatment UASB reactors in the municipality. The model showed that the chance of implementing this technology is 3.3 times greater for municipal autarchies and 7.1 times greater for public companies compared to municipal governments.

Key words: environmental statistics, sewage treatment, UASB reactors, wastewater treatment plants

HIGHLIGHTS

- The characteristics of the municipality and the receiving water bodies are important for defining the treatment technology used in wastewater treatment plants (WWTPs).
- Upflow anaerobic sludge blanket (UASB) reactors are used in more than 70% of WWTPs in Minas Gerais.
- UASB reactors predominate regardless of the characteristics of the municipalities where they are located.
- Post-treatment UASB reactors are prevalent in new projected or under-construction WWTPs in Minas Gerais.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The deficit in sewage collection and treatment is a Brazilian problem, and a large portion of untreated sewage is usually disposed of directly into water bodies, compromising water quality and having implications for public health and the balance of the environment. In Brazil, 45% of the sewage generated by urban populations is untreated. According to the National Water and Basic Sanitation Agency (ANA 2017), biochemical oxygen demand (BOD) in Brazilian waterbodies can reach more than 5,500 tons per day, even with the implementation of wastewater treatment plants (WWTPs) in Brazil.

Minas Gerais is the fourth largest state in Brazil, with an area of 586,513.983 km^2. It has the second-largest population of approximately 19.6 million inhabitants in 853 municipalities and the third-largest gross domestic product (GDP) (IBGE 2010). Despite this, the sanitary situation in Minas Gerais is similar to that of the country: the sewage was collected for 86% of the urban population in Minas Gerais but only 44% was treated, and only 36% of the organic load of domestic effluents was removed in 2013 (ANA 2017). In 2019, 46.8% of the state's urban population had wastewater treatment (ANA 2020). Even in municipalities that have WWTPs in operation, it is common to observe low removal efficiencies, and design, maintenance and operation problems are incurred. The dilution flows of the receiving water body are low, along with an inadequate selection of treatment technologies (IGAM 2018). The installation of a WWTP to serve a municipality depends on technical, financial, and operational factors (Monteiro 2009). It also depends on the level of treatment to be administered, the reliability of the technology, characteristics of the receiving water body, climate, available area, operational complexity, and sludge disposal (von Sperling 2014). Thus, it is important to analyze, in a comprehensive and integrated manner, whether the choice of technology is in accordance with the characteristics of the municipality and receiving water body. It is also important to analyze how these characteristics influence decision-making regarding the technology to be implanted.

The National Water and Sanitation Agency (ANA), the institution responsible for water resource management in Brazil, aims to promote proper and integrated management and the rational and sustainable use of water resources, including those that are used as receiving bodies for domestic effluents (ANA 2017). The ANA and the National Secretariat for Environmental Sanitation proposed expanding knowledge about the sanitation context in Brazil by analyzing the sanitary sewage systems of all municipalities in the country. The Sewage Atlas: Depollution of Hydrographic Basins was prepared as a result of this survey, considering the diagnosis of sanitary sewage in Brazil, highlighting its implications for the quality of receiving water bodies, the necessary investments to universalize sanitary sewage services in the country, and the proposed guidelines and integrated strategy for implementing infrastructure actions (ANA 2017).

Macedo *et al.* (2022) developed a global database of WWTP locations and their characteristics. In the search for information from all countries for the development of the tool, the authors realized that Brazil is one of the few countries that presents data on the number of inhabitants served by WWTPs, the flow treated by each system, the level of treatment and the technology used. These data are available in the Sewage Atlas as reports, sketches of each municipality and spreadsheets that gather all information. However, few studies have evaluated the available data to understand the factors influencing the selection of certain sewage treatment technologies in municipalities. This assessment becomes even more relevant in the current context of the New Legal Framework for Sanitation in Brazil established by Law No. 14,026 of 2020, which defines the goal of universalizing sanitation service attendance rates. According to legislation, by 2033, 90% of the Brazilian population is expected to receive wastewater collection and treatment. Thus, based on new investments, an improvement in the levels of sanitary sewage services in the coming years is expected, which should occur with a technical basis and adequate selection of treatment technology for each context, representing not only the execution of construction but also improving environmental protection and public health (Bicudo *et al.* 2015; ANA 2017).

Several studies have demonstrated the poor performance of WWTPs in Minas Gerais (Dantas *et al.* 2021, 2022a, 2022b). This shows that the criteria for choosing the technologies adopted by WWTPs may not be purely technical and can be influenced by external factors such as prior knowledge of a system by service providers and construction simplicity, failing to consider the characteristics of the municipalities where they are located. Studies have also demonstrated the impact of discharging treated effluents into receiving water bodies (Dantas *et al.* 2021, 2022b), resulting in the hypothesis that the characteristics of receiving water bodies are not always considered when selecting technologies. This situation has caused the indiscriminate growth of certain technologies, such as the upflow anaerobic sludge blanket (UASB) (ANA 2017). UASB reactors are known for their low sludge production, reduced energy expenditure, and the absence of packing media because of the dispersed growth of biomass (Chernicharo *et al.* 2018b). Despite these advantages, UASB reactors have concerning limitations, such as insufficient effluent quality to meet environmental standards, challenges in sludge management and hydraulic overload (Almeida *et al.* 2018; Dantas *et al.* 2022a).

Thus, based on the data available in the Sewage Atlas on the WWTPs in operation in the municipalities of Minas Gerais and data obtained from the Brazilian Institute of Geography and Statistics (IBGE), this study aimed to provide an overview of the WWTPs in Minas Gerais and analyze the factors related to the usage of technologies in each municipality.

2. METHODS

2.1. Structuration and systematization of the database

Data on active WWTPs were obtained from the Sewage Atlas through spreadsheets for 2013 and 2019. This study only considered WWTPs in Minas Gerais. The database contains 437 records of WWTPs in Minas Gerais, including active, under-construction, projected, or inactive plants. Among them, 21 had operational problems, were disabled, or abandoned, and were excluded from the study. After excluding duplicates, the database contained information on 376 active WWTPs, 18 WWTPs under construction, and eight projected WWTPs (Figure 1).

The treatment technology used in the WWTPs was the variable of interest in this study. Several treatment technologies were identified, and for simplification, a classification into six groups was adopted based on Silva *et al.* (2020). WWTPs using UASB reactors followed by some post-treatment (stabilization ponds, filters, land disposal, or activated sludge) were considered as 'UASB + post-treatment'. Those with only the anaerobic reactor were classified as 'UASB'. All configurations of Stabilization Ponds were aggregated into a single category called 'Stabilization Ponds'. The 'Activated Sludge' treatment included the conventional modality and extended aeration. The different types of filters, whether aerobic or anaerobic, were grouped in the category 'Filters' and Septic Tanks followed by filters or disposal in the soil and biodigesters were grouped as 'Septic Tanks'.

In addition to treatment technology, the database contained information on the influent flow, sanitation service provider in the municipality, reference flow of the receiving water body ($Q_{95\%}$), and its class. In Brazil, inland water bodies are categorized into five classes, each with specific target values for water quality parameters that must be achieved to ensure the preservation of water quality and meet the predominant local water use. The special class is designated for the most stringent uses, such as human consumption, with simplified treatment and protection of aquatic ecosystems. 'Class 1' water bodies are suitable for human consumption with simplified treatment and recreational activities, while 'Class 2' requires conventional treatment for human consumption. 'Class 3' water bodies demand more advanced treatment for human consumption, and

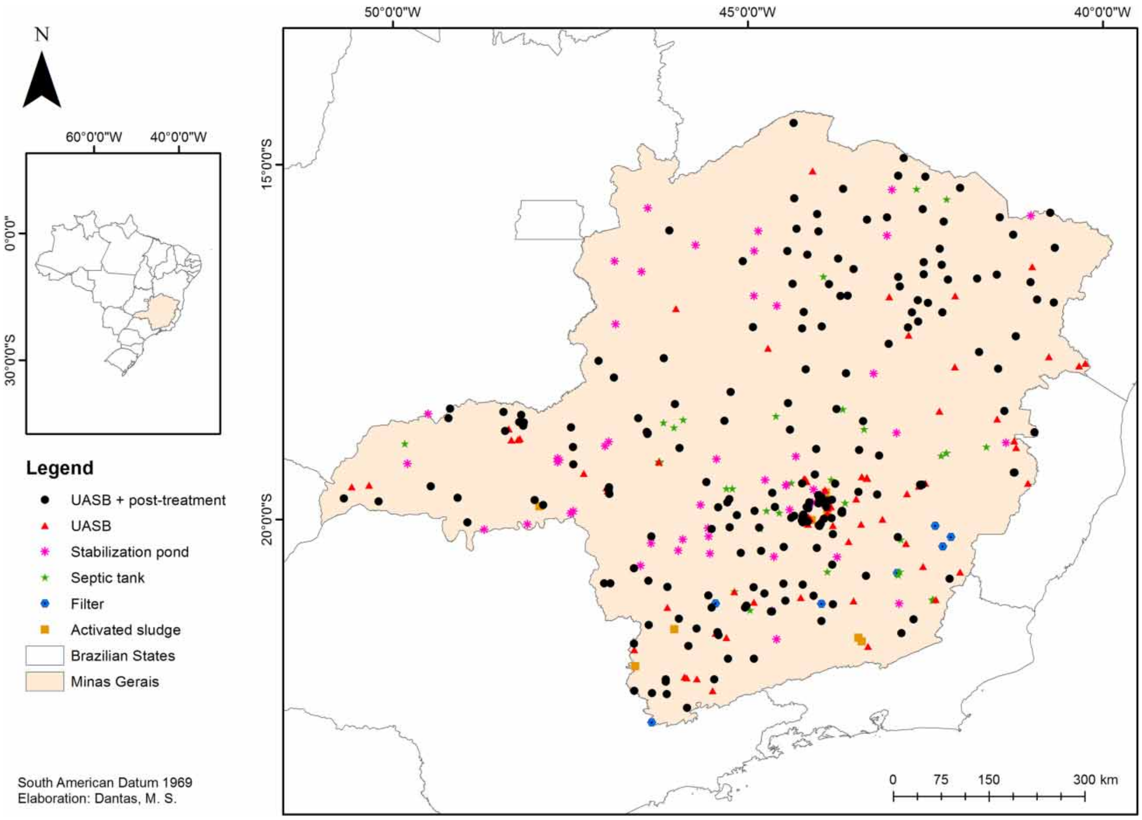


Figure 1 | Location and technology used in WWTPs in Minas Gerais.

finally, 'Class 4' water bodies are primarily used for less-demanding activities, such as navigation. Sewage treatment in Brazil is carried out by different entities depending on the municipality and management system adopted. This can be attributed to state sanitation companies, private companies, municipal autarchies, and municipal governments.

Quantitative variables were categorized (Table 1). The criteria established in the legal framework of the State of Minas Gerais, Normative Deliberation COPAM n. 217/2017, for the treatment capacity of the treatment plant, was used to define the WWTP influent flow categories. A WWTP is classified as small for design flows of up to 50 L/s, medium for flows between 50 and 100 L/s, and large for flows above 100 L/s (Minas Gerais 2017).

In addition to the characteristics of the WWTPs, the characteristics of the municipalities were also of interest, thus relating them to the treatment technologies used. IBGE is a public institution responsible for producing and disseminating statistical, geographical, and cartographic information in Brazil. The institution gathers data for each municipality, covering aspects such as population, economy, education, health, and the environment (IBGE 2010). To complement the database, variables related to the municipality's financial capacity and development were selected for this study, as these are typically the features that influence WWTP construction due to the costs of implementation and maintenance of the systems (Pacheco *et al.* 2015; Pessoa 2019). Furthermore, the choice of a specific technology should consider the population to be served. The variables included were the municipal Human Development Index (HDI), the size of the municipality where the WWTP was installed, and GDP per capita.

The structured database contained five variables related to WWTPs and receiving water bodies and three variables related to municipalities (Table 1).

2.2. Statistical analysis

The variable of interest 'Treatment Technology' was evaluated based on the variables in Table 1 to verify the influence of the characteristics of the WWTPs, municipalities and receiving water bodies on the use of each treatment technology in actives

Table 1 | Variables selected for this study

Data Source	Variables	Categories
Sewage Atlas (ANA 2017, 2020)	Sewage treatment technology	UASB/UASB + post-treatment/Stabilization pond/Septic Tank/Activated sludge/Filter
	Sanitation service provider	Public companies/Private companies/Municipal autarchy/Municipal government
	WWTP design flow	<50 L/s/50–100 L/s/ > 100 L/s
	River reference flow rate	<100 L/s/100–500 L/s/500–900 L/s/ > 900 L/s
	Water body class	Special/Class 1/Class 2/Class 3
IBGE (2010)	Size of the municipality (inhabitants)	<20,000/20,000–50,000/50,000–10,000/ > 100,000
	GDP per capita (USD)[a]	< $ 4,000.00/$ 4,000.00–$ 7,000.00/$ 7,000.00–$ 10,000.00/ > $ 10,000.00
	Municipal HDI	Low (0.5–0.599)/Medium (0.6–0.699)/High (0.7–0.799)/Very high (0.8–1.0)

[a]In 2010, R$1.00 was equivalent to approximately $1.70.

plants in Minas Gerais. The results were verified using frequencies and percentages for the characteristics of categorical variables, displayed in tables and graphs. The technologies used in projected or under-construction WWTPs were also analyzed.

As the 'UASB + post-treatment' technology was prevalent, a new dichotomous variable was created from the variable 'Treatment Technology'. This new variable had only two answers: 'yes', when the treatment technology was a UASB reactor with post-treatment and 'no', otherwise. It was possible to fit a multivariate logistic regression model to evaluate the presence of this treatment technology and understand which characteristics of the WWTPs and municipalities were related to it.

In this study, only variables that were significant at the 5% level were included in the model. All models were adjusted using R software. Odds ratios were calculated for analysis of the coefficients. The accuracy of the model was used to verify its classification power.

3. RESULTS AND DISCUSSION

3.1. Active WWTPs

Figure 2 shows the quantity and percentage of each technology used in 376 active WWTPs in Minas Gerais. UASB reactors followed by post-treatment prevailed and were used in 197 WWTPs (52%), followed by UASB reactors without post-treatment in 71 WWTPs (19%), stabilization ponds in 51 WWTPs (13%), and septic tanks in 40 WWTPs (11%). Only 10 WWTPs used activated sludge, and seven used filters. Many plants use UASB reactors, either with or without post-treatment, accounting for more than 70% of the total.

According to Chernicharo *et al.* (2018a), the significant number of UASB reactors in Minas Gerais can be credited, among other factors, to the preference for compact systems in view of the mountainous geography of the State of Minas Gerais, as well as to the influence of research on the post-treatment of anaerobic effluents under the Prosab (Basic Sanitation Research Program), coordinated by the Federal University of Minas Gerais.

Therefore, it is important to understand how the characteristics of municipalities can influence the choice of the treatment process, as the size, water body flow, investment, and available installation area, among other factors, are important in the choice of technology to be implemented.

Figure 3 shows the number of active WWTPs divided into six treatment technologies: sanitation service providers, influent flows, design flows, and water body classes. UASB reactors with or without post-treatment are preferentially adopted by sanitation service providers. Municipal governments and autarchies tend to diversify the technologies used in WWTPs. In contrast, public companies in Minas Gerais use UASB reactors in more than 80% of their systems (Figure 3). According to Chernicharo *et al.* (2018a), despite sufficiently clear technical motivations, the preferential selection of this reactor may be related to the preferences, knowledge, and experience of designers from large state sanitation companies.

The receiving water body flow did not seem to influence the choice of technology, maintaining the same standard for both low and very high flows. This result is concerning because treatment systems that discharge effluents into water bodies with reduced dilution capacities must adopt more robust technologies and encourage and achieve better effluent quality. However, this did not prove to be relevant to the choice of treatment technologies for WWTPs in Minas Gerais (Figure 3).

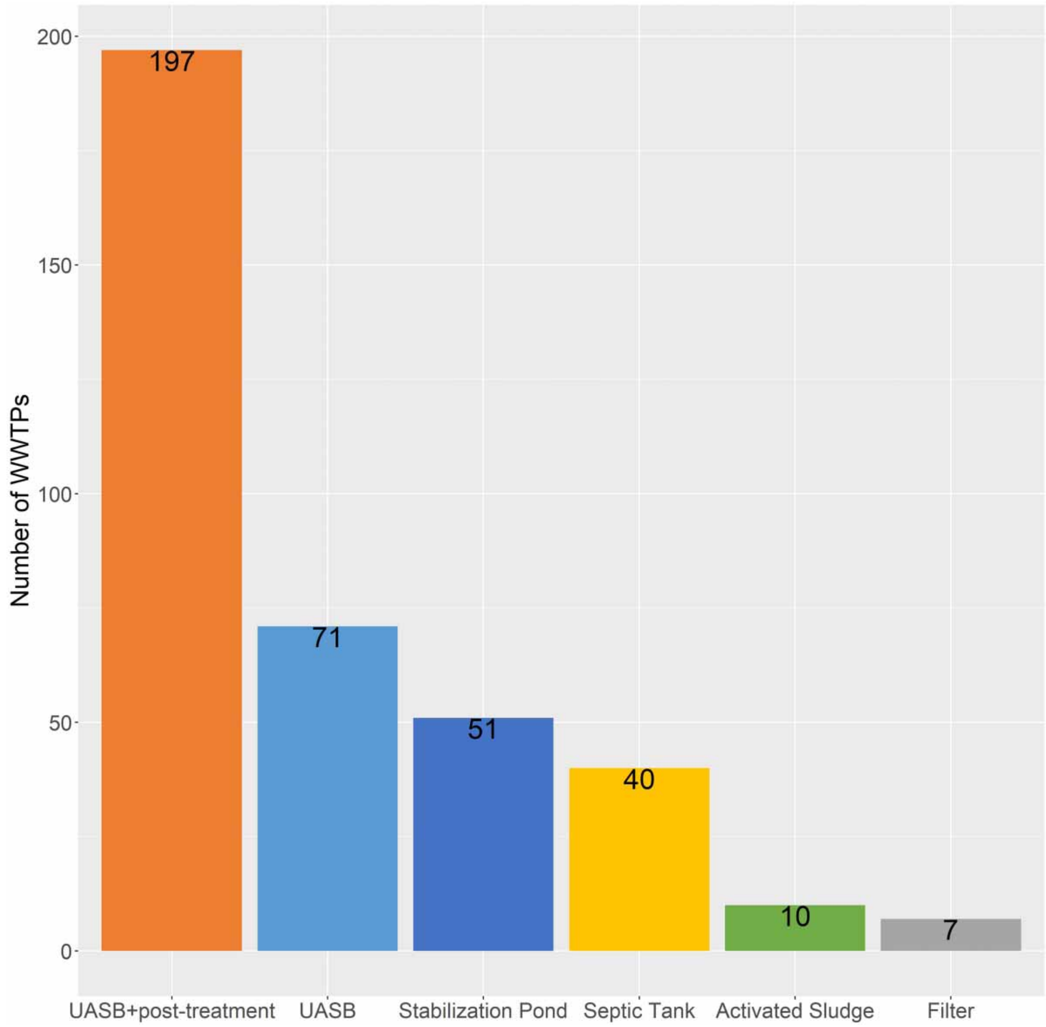


Figure 2 | Number of WWTPs by treatment technology.

Regarding the classes of receiving water bodies, there appears to be an increase in the use of UASB reactors without post-treatment in higher classes. This may be associated with the current deteriorating state of the water body in classes 2 or 3, leading to less concern in obtaining a better effluent quality, which could be achieved by adding post-treatment (Figure 3).

Smaller WWTPs utilize a wider variety of technologies. They diversified by adopting septic tanks with post-treatment and stabilization ponds, in addition to a significant portion of UASB reactors. WWTPs that use activated sludge are mostly medium- and large-sized, which can be explained by the complexity of the system and operating costs (Figure 3).

Figure 4 shows the results of the technologies adopted according to the characteristics of the municipalities in which they were installed.

There were no major differences in the treatment technology choices within the per capita GDP range. When analyzing the sizes of the municipalities, UASB reactors followed by post-treatment were the majority of all sizes, demonstrating the wide use of anaerobic technology as the first stage of the treatment process. Stabilization ponds are especially used in small- and medium-sized municipalities with populations below 100,000. A possible explanation for this is the lower operational demand and greater availability of areas for installing WWTPs in the countryside. In contrast, the highest occurrence of activated sludge was observed in large municipalities with very high HDI-M (Figure 4).

Owing to the large percentage of post-treatment UASB reactors among all the active WWTPs in Minas Gerais, a logistic regression model was fitted. The dependent variable was the presence or absence of this treatment technology in the WWTPs. Thus, we attempted to understand the factors related to the adoption of this treatment technology using coefficients.

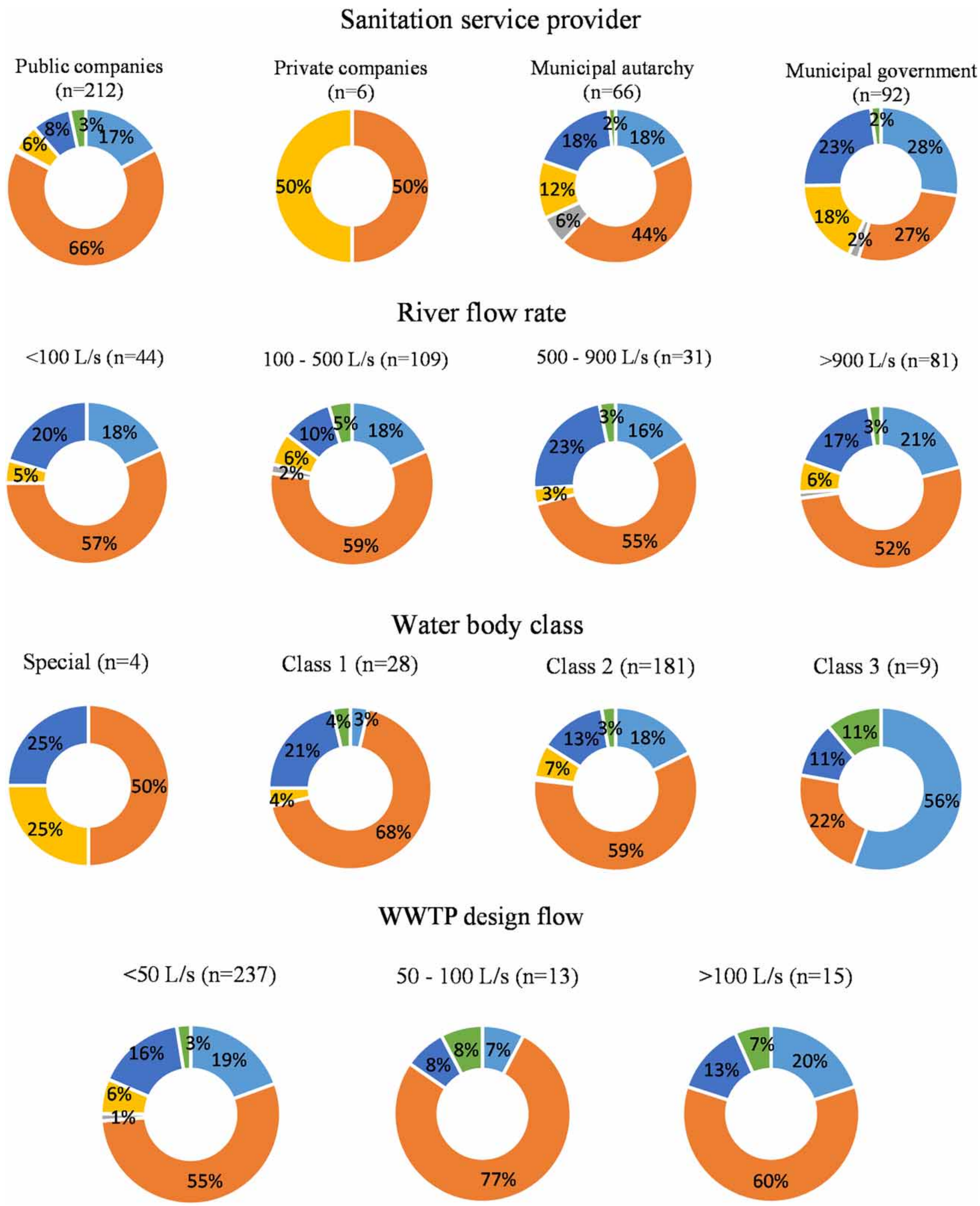


Figure 3 | Treatment technologies by characteristics of active WWTPs.

The logistic regression model with only significant variables for the response variable 'UASB + post-treatment' is presented in Table 2. The significant explanatory variables were sanitation service providers and municipality population size. The other variables were not significant at the 5% level; therefore, they were not included in the model.

The adjustment of the model provides additional information on the data presented in Figures 3 and 4. Regarding the sanitation service provider, the chance of implementing a UASB reactor with post-treatment by municipal autarchies was 3.3 times greater than that by municipal governments, the category reference in this model. This chance was 7.1 times greater

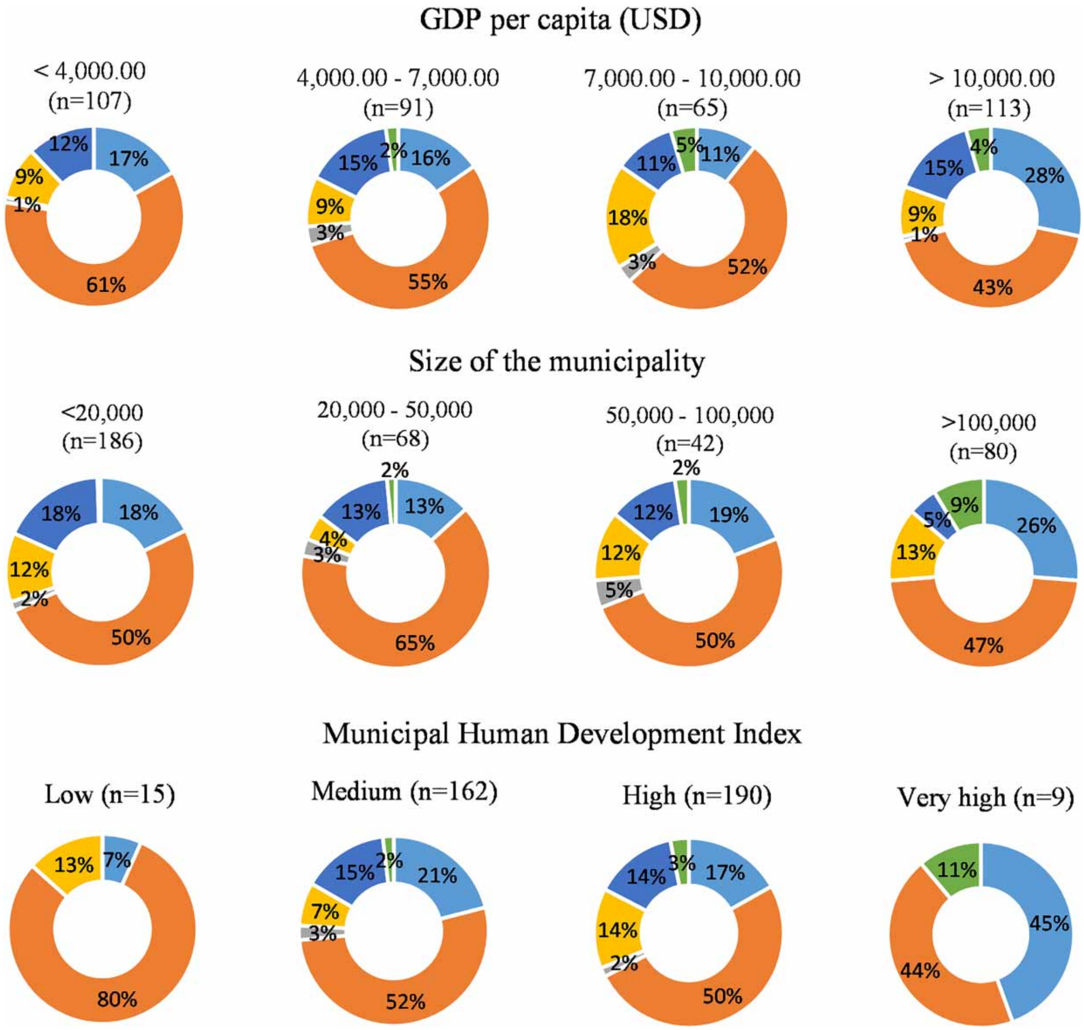


Figure 4 | Treatment technologies by characteristics of the municipalities where the active WWTPs are installed.

Table 2 | Logistic regression model for the presence of the UASB reactor with post-treatment

Characteristics	Odds Ratio	CI (95%)	*p*-value
Sanitation service provider			
Municipal government	Reference	–	–
Private companies	3.9	(0.7; 24.3)	0.119[a]
Municipal autarchy	3.3	(1.5; 7.4)	0.003
Public companies	7.1	(3.8; 13.7)	<0.001
Size of municipality			
< 20,000 inhabitants	2.3	(1.2; 4.4)	0.009
20,000–50,000 inhabitants	2.0	(1.0; 4.0)	0.044
50,000–10,000 inhabitants	1.0	(0.5; 2.1)	0.951[a]
> 100,000 inhabitants	Reference	–	–

[a]Category does not show statistical significance at the 5% level; CI = confidence interval.

for public companies. The private company category was not significant, indicating that there was no difference between them and the municipal governments.

Regarding population size, there were no differences between the chances of medium-sized municipalities (between 50 and 100,000 inhabitants) and large municipalities (over 100,000 inhabitants) deploying post-treatment UASB reactors. However, compared to large municipalities, small municipalities (with fewer than 50,000 inhabitants) are approximately twice as likely to use this treatment technology.

The overall accuracy of the model was 66% (Table 3), which is within a satisfactory range, indicating that the model can be used to understand the relationship between the selected variables and the use of post-treatment UASB reactors.

3.2. WWTPs projected or under construction

In addition to the active plants, 18 WWTPs under construction and eight projected WWTPs were analyzed to evaluate the expected scenario of treatment technologies. The prevalence of post-treatment use of UASB reactors was verified. Of the 26 WWTPs evaluated in Minas Gerais, 22 will use post-treatment UASB reactors.

These numbers show that there is a concern about adding post-treatment to the UASB reactors, which improves the quality of the effluent that reaches the water bodies when compared to the UASB reactors without post-treatment. However, according to Miki (2010), the final effluent of UASB reactors barely reaches the BOD load removal parameter of the secondary treatment. Over the years, owing to the recognition of the need for post-treatment after UASB reactors, many WWTP projects have incorporated UASB as a process step, replacing the primary decanter, primary sludge thickener, and digester. However, obtaining high-quality effluent remains a challenge, even in systems that use some type of post-treatment (Dantas *et al.* 2021, 2022a, 2022b).

The use of UASB reactors in Brazil still presents challenges that prevent maximum operational performance, despite their recognized advantages. An important portion of the problems associated with these anaerobic reactors originates from deficiencies in the initial design phases. Inadequate construction processes and operational problems have been reported by sanitation service providers in various regions of Brazil (Almeida *et al.* 2018; Lobato *et al.* 2018; Marques & Nunes 2018). Operational issues such as system management issues can prevent the proper execution of procedures. Thus, it is important to consider a fast solution to these problems, as they could jeopardize the important advances achieved thus far and have an unprecedented impact on the national sanitary sewage sector, with enormous risks of stagnation of sewage treatment coverage rates in the country.

Effluent discharge standards in Minas Gerais have recently changed. Normative Deliberation COPAM/CERH n. 08/2022 established a limit of 20 mg/L of ammonia nitrogen for sanitary system discharge, which was not required by previous legislation (Minas Gerais 2022). UASB reactors are inefficient for ammonia nitrogen removal. Even when post-treatment is applied, many WWTPs in Minas Gerais have limitations in preventing the contamination of receiving water bodies with ammonia nitrogen (Dantas *et al.* 2022b). For this reason, in the coming years, treatment technologies in the state must adapt and be modified to achieve compliance with environmental standards.

Interestingly, as stated by Chernicharo *et al.* (2018a), although energy use was not responsible for the great expansion of technology in the past, recent advances have demonstrated this potential. Despite the tendency to adopt UASB reactors with post-treatment in Minas Gerais owing to regional preferences, biogas can be a new attraction for the continued expansion of technology in a scenario that increasingly seeks sustainability. However, it is important to note that the main objective of WWTPs in the country is to generate high-quality effluent to minimize the impact of discharge into water bodies. In Brazil, the basic objective of removing only organic matter and solids still prevails, and they are often not properly removed.

Table 3 | Confusion matrix for the consolidated logistic regression model

		Classified	
		UASB + pt	**Others**
Actual	UASB + pt	157	87
	Others	40	92

4. CONCLUSIONS

There are a large number of WWTPs in municipalities of Minas Gerais adopting UASB reactors, either with or without post-treatment, reaching more than 70% of the total. Thus, there is a growing concern regarding the choice of technology. UASB reactors with or without post-treatment are preferentially adopted by sanitation service providers. Smaller WWTPs employ a wider variety of technologies.

The results also show that receiving water body flow, per capita GDP, and WWTP design flow did not seem to influence the choice of technology. Concerning the classes of receiving water bodies, there seems to be a rise in the utilization of UASB reactors without post-treatment in the higher classes.

The logistic regression model indicates that the chances of implementing a UASB reactor with post-treatment by municipal autarchies is 3.3 times greater than that of municipal governments. For public companies, this chance was 7.1 times greater. Regarding the size of the municipalities, small municipalities are approximately two times more likely to use this treatment technology than large ones.

In addition, the prevalence of the use of UASB reactors with post-treatment was verified, and of the 26 new WWTPs projected or under construction in Minas Gerais, only four will use another treatment technology.

The importance of preliminary studies for the construction of WWTPs is highlighted here, so that the design of a WWTP meets the technical, financial, and operational factors of the municipalities, leading to decision-making that is in accordance with the local reality. Thus, investments in WWTPs have both short- and long-term returns. The outcomes of this study may guide the decisions of public managers in formulating new public policies with the goal of not only ensuring access to this sanitation service but also promoting the adoption of technologies that meet environmental standards and minimize the impact of discharging treated effluents into receiving water bodies.

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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