A framework for resource recovery from wastewater treatment plants in megacities of developing countries

Short title: Framework for resource recovery from wastewater treatment plants

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A B S T R A C T

In developing countries, there is often a lack of a comprehensive data set that supports the development of coherent policies on resource recovery from wastewater treatment. This paper aims to contribute to the elaboration of resource recovery projects by providing accurate and updated data from wastewater treatment plants such as those located in the region of the Macrometropolis of Sao Paulo. The authors discuss possibilities of improvement of resource recovery for this illustrative example. Comprehensive analyses were performed based on data from 143 municipal wastewater treatment plants to understand the situation regarding resource recovery implementation in this region. The results show that just 26% of the plants perform at least one resource recovery practice. The predominant resource recovery practice is internal water reuse, and recovery is concentrated more in large plants than in medium and small ones. The sludge is disposed in landfills except for three plants, which perform sludge recycling for compost. Some plant managers reported interest in recovering energy from biogas, in expanding water reuse and in recovering sludge for fertilizer production or for building materials. Several aspects that have been regarded as relevant to the implementation of resource recovery processes in previous literature are discussed, such as the size of the plant, related legislation as well as treatment technologies and configurations. Finally, the authors propose a generic framework with several steps that can help to achieve resource recovery implementation. Therefore, the results can provide support for planning of resource recovery projects for large cities in developing countries.

Keywords: Biogas energy recovery; Circular economy; Large cities; Municipal sewage treatment; Survey; Water reuse

1. Introduction

Wastewater contains important resources that should be recovered in wastewater treatment plants to generate value-added products such as renewable energy, biofertilizers and water for different purposes. The recycling of resources through innovative recovery processes is only a recent objective in wastewater treatment systems (Mehta et al., 2015; Rao et al., 2017) and makes the processes of the plants more efficient; it reduces the amount of waste and it provides environmental and economic benefits. Some of the key resources that can be recovered are nutrients and energy.

Regarding nutrient recovery, it provides sustainable use of phosphorus (Sarvajayakesavalu et al., 2018), produces a high-quality effluent with low phosphorus concentration, which mitigates eutrophication risks in water bodies as well as produces an alternative source of fertilizer, alleviating phosphate rock reserves (Chrispim et al., 2019). Regarding eutrophication, Lwin et al. (2017) estimated the amount of phosphorus flowing from agriculture and domestic wastewater and concluded that India, China, Brazil and USA will be the countries with the largest flows of phosphorus by 2100.

A promising solution for wastewater treatment systems is energy recovery, since wastewater contains chemical, thermal and hydraulic energies. In a conventional wastewater treatment plant, it is possible to recover energy in the effluent treatment or in the sludge line to supply at least a substantial part of the wastewater plant's energy demand (Đurđević et al., 2019). The ultimate aim would be for the plant to become energy self-sufficient with zero external energy supply (Svardal and Kroiss, 2011). As there is substantial energy consumption during several stages of the treatment (sewage collection, transportation, effluent treatment, sludge treatment and disposal), energy recovery in a wastewater treatment plant can reduce electricity costs.

In the context of the perspectives described above, there is a need for energy, water and waste systems to be analysed by a nexus approach to move towards more sustainable cities (Wang et al., 2018a) characterised by water conservation and the efficient use of natural resources. According to Mo and Zhang (2013), sustainability in wastewater management needs to consider not only treatment of sewage, but also the potential for resource recovery from the treatment.

However, most of the wastewater treatment installations currently only aim for sewage treatment and final disposal into the environment. Papa et al. (2017) analyzed 600 plants in Italy to understand the situation of resource recovery, and concluded that 60% of the works did not perform any kind of recovery. The most common recovery options in the plants with resource recovery were internal water reuse from treated effluent and sludge reuse for agricultural application. So, these systems did not reach their maximum potential of resource recovery.

Especially in developing countries, there is a lack of reliable, recent and detailed data regarding wastewater flow rates, treatment performance as well as recovery actions from wastewater works (Sato et al., 2013; Malik et al., 2015; Mateo-Sagasta et al., 2015) and solid waste recycling (Harir et al., 2015). Consequently, quantifying the current situation of resource recovery in developing countries is a challenge. According to Guven and Tanik (2018), assessments of applications of water use and energy recovery from wastewater treatment plants in developing countries are generally lacking. The available information does not use uniform terminologies and units to describe current practices, making it difficult to compare data or establish global inventories (Jiménez et al., 2010).

Most of the publications on this topic (Van der Hoek et al., 2016; Kretschmer et al., 2016; Leeuwen et al., 2018) do not cover developing countries. Coats and Wilson (2017) state that real implementation examples of resource recovery remain relatively scarce in the literature. For instance, there is a shortage of research that addresses the implementation of resource recovery actions for different locations in Brazil, where little progress has been made in collecting data to support the development of coherent policies in resource recovery. Few studies have addressed how to integrate resource recovery technologies in municipal wastewater treatment processes. Borges et al. (2015), Santos et al. (2016), Bressani-Ribeiro et al. (2017) and Rosa et al. (2018) analyzed energy recovery in some plants in Brazil. Moreover, only some studies (Chrispim et al., 2017; Paulo et al., 2019) were based on decentralized and source-separation sanitation systems.

Besides analyzing measures and technologies from technical, economic and environmental aspects, it is necessary to implement inventories of the quality and the quantity of the resources in municipal wastewater, the current application status as well as opportunities and challenges for future implementation. Sato et al. (2013) state that this type of information on wastewater generation, treatment and use are crucial for decision-makers, researchers and practitioners for the development of national and local plans aiming at safe wastewater reuse and for assessment of the potential of resource recovery at different scales.

The introduction of resource recovery strategies into existing wastewater treatment systems or into new facilities is particularly interesting for megacities and urban agglomerations. In these areas, there is significant scarcity of natural resources to meet the population demand and a need to improve wastewater treatment services (Wang et al., 2018b). These cities have larger impacts on water resources than smaller urban or rural settlements for several reasons. Because of the large quantities of surface water that may be diverted, the water supplies to downstream users are affected. In addition, as a result of inadequate wastewater management, surface waters can become severely polluted, compromising the quality and availability of future supplies and creating health risks (National Research Council, 1996). Therefore, the main challenges include improvement and expansion of the population's access to water and wastewater services (National Research Council, 1996; WHO, 2018).

Because of their high population, large cities require massive quantities of energy, water and food provision (Khan et al., 2006). So, resource recovery strategies for wastewater treatment plants in megacities could mitigate some of these problems by supplying water, energy or raw materials for products to meet the demand, and simultaneously provide economic benefits from the recovered products. The reduction of operational costs (Catarino et al., 2007) relates to the disposal and treatment of byproducts such as sludge. Environmental benefits include improvement of the effluent quality and reduction of emissions.

In the case study country Brazil, the most populous region is located in the State of Sao Paulo. The term Sao Paulo might refer to four different levels. The State of Sao Paulo (level 1) comprises several regions including the region of the Macrometropolis of Sao Paulo (level 2), which is one of the largest urban settlements in the world, concentrating more than 33 million inhabitants and accounting for 50% of the urbanized area of the State of Sao Paulo and for 75% of its population (São Paulo Metropolitan Planning Company S/A (EMPLASA), 2019). The region of the Macrometropolis of Sao Paulo comprises eight urban agglomerations. One of these agglomerations is the Metropolitan Region of Sao Paulo, also known as Megacity of Sao Paulo (level 3) (The United Nations, 2018). This megacity includes the City of Sao Paulo (level 4). For reasons of simplicity, in this paper, the authors will refer to the above four levels as state, region, megacity and city, respectively, if and when the official meaning is clear from the context. However, this study is mainly concerned with the region (level 2).

The region of Sao Paulo faces several challenges regarding water and sanitation infrastructure. Considering that it is a very populous area, water management is a complex issue. According to projections for the coming years, there is a trend to increase both the water demand and the population in this region (The Department of Water and Electric Power (DAEE), 2013). The qualitative commitment of the water sources used for human supply and the low water availability characterizes a critical scenario in this area. Considering its size, rapid population growth, high population density and economic situation, the region has been chosen as a representative case study for other megacities in developing countries, which face similar conditions such as water scarcity and inadequate wastewater treatment and collection.

In this context, tools that facilitate the process of planning and decision-making are necessary and allow for more cost-effective and sustainable means to recover resources from wastewater. This paper aims to produce organized and reliable data related to resource recovery application in megacities in developing countries to support and facilitate the transition to sustainable wastewater treatment plants through the assessment of the potential of resource recovery implementation at different scales in an effective way. The corresponding objectives are (a) to analyze the current situation of existing plants in the region of Sao Paulo used as a representative case study regarding the implementation of resource recovery solutions; (b) to identify relevant factors that can stimulate and support the implementation of resource recovery from wastewater treatment; (c) to suggest potential areas for improvement in the respective case study such as interventions of resource recovery technologies; (d) to propose a generic framework to facilitate the planning and implementation of resource recovery in plants; and (e) to discuss briefly the results of the case study region and other megacities in developing economies.

2. Methodology

2.1. Region of Sao Paulo (study area)

The region of Sao Paulo is located in the State of Sao Paulo and includes 174 municipalities. The demographic density is 630.5 inhabitants/km². This region has significant socio-economic importance and is well-industrialized, including diversified commerce, complex services and a productive agroindustry (EMPLASA, 2019). It represents 83% of the state gross domestic product (GDP; 1.61 trillion reais, equivalent to 0.4 trillion US dollars) and represents about 27% of the national GDP (referring to the GDP of 2015) (Senese Neto, 2018). The region of Sao Paulo comprises five metropolitan regions and three urban agglomerations (EMPLASA, 2019) (Fig. 1).

In the state of São Paulo, tropical climate dominates the central region of São Paulo. This climate is characterized by a rainy season in summer, a dry winter and an average temperature of over 22°C in the warmest month. In some mountainous areas, the average upper temperature is below 22°C in the warmest month. In the higher areas (Serra do Mar and Serra da Mantiqueira), summer is milder and rainier. The coast has a tropical rainy climate without a dry season and average rainfall of the driest month exceeding 60 mm (Sao Paulo State Government, 2018). The Köppen Climate Classification subtype predominant in the study area is "Cfa" (Humid Subtropical Climate) (Weatherbase, 2020).

The region of Sao Paulo presents several challenges related to water management. The megacity of Sao Paulo is an example of this problem, since it concentrates more than 10% of the inhabitants of Brazil in less than 0.1% of its corresponding territory. Moreover, the megacity has low water supply provision. Several municipalities within the region have high industry activity and agricultural production. The coastal area is also subjected to water scarcity, especially because of the intensive water consumption by complex industries, and an increase in water demand during the holiday season (Ribeiro, 2011).

Most surface water bodies within the region are polluted due to urban sprawl (Tagnin et al., 2016). In 2010, there were 3.8 million people living in favelas (Sayuri, 2014), with lack of access to proper wastewater collection and treatment as well as absence of safe water supply. Favelas are known as low and middle-income unregulated neighbourhoods experiencing governmental neglect.

Due to the mentioned characteristics, highlighting the problematic of water vulnerability (National Water Agency (ANA), 2014), the high population concentration, socio-economic urbanization characteristics, the great consumption rate of natural resources and climate zone, the region of Sao Paulo was chosen as a representative case study for other megacities in developing countries.

2.2. Resource recovery implementation survey

The procedure for the survey of wastewater treatment plants in the study region to assess the corresponding resource recovery implementation is outlined in this section. This process was divided into three phases: 1) Definition of the sample in the study area and contact with the organizations responsible for the works; 2) questionnaire for data collection; and 3) data analysis.

2.2.1. Phase 1

This phase comprised the following steps: survey of contacts, communication with the managers and sending of questionnaire. First, the organizations responsible for the plants in each of the 174 municipalities belonging to the region were identified. Regarding the municipalities where the Sao Paulo State Water and Sewage Services Company is the authority responsible for wastewater treatment, the managers of each sub-region were contacted. For the other cities, where other organizations are responsible for wastewater treatment, data were obtained from other sources such as the Water and Sewage Services Diagnostics of the National Sanitation Information System (SNIS, 2018), the websites of the Regulatory Agency of Sanitation and Energy of the State of Sao Paulo (ARSESP, 2019) and websites of the city councils (specifically those linked to the department/secretary managing wastewater treatment; e.g., the municipal secretary of sanitation). For private companies, their respective websites were searched. After this step, the department and the manager responsible for the wastewater treatment services of each municipality received the questionnaire.

2.2.2. Phase 2

In order to collect the data in relation to the resource recovery actions implemented in the wastewater treatment plant, an easy-to-fill-in questionnaire was prepared based on Papa et al. (2017). The questionnaire consisted of two sections: preliminary questions and specific questions about the existence of resource recovery options (Fig. 2). Supplementary Material 1 contains the questionnaire.

The questionnaires were sent by e-mail with an informed consent form to educate the participants about the purpose of the research, following ethical standards. All data collected with the questionnaires are relevant for the period between July 2017 and April 2019. In some cases, managers were contacted with additional questions via e-mail or telephone to clarify the collected information.

2.2.3. Phase 3

After data collection, both qualitative and quantitative data from questionnaires were organised into data spreadsheets for comparison purposes. The results were parameterized according to the size of the plant with three classes being established according to the Brazilian Resolution 377 of the National Environment Council (CONAMA): small WWTP with a wastewater inflow rate ≤50 L/s or a population equivalent of up to 30,000 people; medium-sized plants: the plant with a nominal wastewater inflow rate >50 L/s but ≤400 L/s, or with a capacity to serve 30,000 to 250,000 inhabitants; large plants: the plant with an inflow > 400 L/s and with a capacity of supporting more than 250,000 inhabitants (National Environmental Council, 2006a).

Within the region of Sao Paulo, there are cities without any wastewater treatment. Also, some cities sent their sewage to plants belonging to other municipalities nearby. In order to estimate the number of wastewater treatment plants within the case study region, the authors referred to the questionnaire answers. Concerning non-responsive municipalities, the authors consulted two national databases: Atlas Sewers: Depollution of Water Basins from the National Water

Resources Information System (SNIRH), which contains information about the number of plants for each Brazilian city (SNIRH, 2013); and the Information System on Sanitation for Sao Paulo State (SISAN, 2016) that contains the municipal plan of sanitation for each municipality. Based on this, it was possible to estimate the total amount of plants and to calculate the percentage of the responsive plant managers.

Based on questionnaire findings, existing resource recovery initiatives were mapped and described. Then, the key factors that can affect the implementation of resource recovery were identified and potential areas for improvement were discussed. The authors identified what can be done in the future to develop sustainable works based on successful examples that are already underway in the region. The results were discussed, and key measures of resource recovery were recommended.

2.3. Framework creation

The authors propose a new generic framework for planning and implementation of resource recovery. This framework was initially derived based on the results from the conducted survey. For step 9 of the framework, indicators were selected based on various references. Technical indicators were after Sikosana et al. (2017), Van der Hoek et al. (2016) and Harris-Lovett et al. (2018). Economic indicators were influenced by Sikosana et al. (2017). Environmental indicators were inspired by Hu et al. (2016). Finally, societal indicators as well as institutional and political ones were based on Woltersdorf et al. (2018).

3. Results and discussion

3.1. Overview

The findings are organized in six sections: (1) Findings obtained from the questionnaires and a discussion on how practices vary in the different metropolitan regions; (2) the key factors that affect the implementation of resource recovery; (3) possibilities for resource recovery strategies that could be implemented in the study area, considering the local context; (4) a proposed framework as a tool to stimulate/support planning and decision-making; (5) a comparison between the region of Sao Paulo and other megacities concerning resource recovery from wastewater treatment; and (6) limitations of this study.

3.2. Implementation of resource recovery measures

About 53% of the total number of plants in the region of Sao Paulo were analysed. This equates to 143 facilities located in 75 municipalities across the region. The proportion of plants with responses for each metropolitan region was 100% for MRBS, RUB and UAJ, 85.7% for MRSP, 77.1% for MRS, 67.5% for UAP, 20.3% for MRC and 7.9% for MRPVNC (see Fig. 1 for meanings of abbreviations). From the total (143) analysed, just 37 plants performed at least one resource recovery strategy (not considering the recycling of oil waste). The only other form of recovery mentioned was the separation of equipment-related oil waste, which is collected and conveyed to appropriate facilities for recycling.

Regarding the surveyed plants with some resource recovery action, the situation varies among different metropolitan regions. Considering the plants with surveyed data, the metropolitan area with the highest predominance of resource recovery plants is Baixada Santista (76.9% of the total of plants). Figure 1 displays the distribution of the plants in the study area.

Figure 3 shows the general results for the situation of the implementation of resource recovery strategies from wastewater treatment in the region of Sao Paulo. As can be seen, few plants currently include resource recovery practices. Only 26% of the surveyed plants performed at least one resource recovery action. Among the plants with resource recovery, it can be noted that water reuse for internal purposes was the most common resource recovery action implemented in this region. This finding agrees with the results reported by Papa et al. (2017), where water reuse was the most common resource recovery practice. The prevalence of internal reuse over external reuse was expected since reclaiming water externally involves several other variables such as specific effluent quality requirement compliance, market demand in the surrounding area, higher investments and infrastructure of distribution of the reclaimed water (e.g., pipes or trucks) to the destination. Supplementary Material 2 shows the distribution of all resource recovery practices in the region of Sao Paulo.

Considering the group of plants with internal reuse, the predominant uses for reclaimed water were washing and cleaning of courtyards as well as landscape irrigation (57.1% of the plants), sludge dewatering processes with polymers, cleaning of centrifuges and screens (45.7%), washing of sewage treatment equipment and reactors (40%), cleaning and unblocking of sewage collection networks (20%) and others (sewage lift station, preparation of chemicals and toilet flushing) (20%). The total volume of water reused (considering the plants that perform internal reuse and with response for this question) was about 405,094 m^3/month.

In relation to the plants that practice external water reuse, the applications are mostly (present in 44% of the plants with external reuse) for industrial purposes such as cooling towers, (textile) industry, civil (and ground) construction companies, laundries and urban use. The latter includes irrigation of parks, firefighting, washing streets after fairs, washing of trucks for transportation of recycled waste, transportation (airplanes and trains), urban cleaning, clearing of rain gutters and sewage pipes, washing of courtyards and cleaning of public streets and squares. Considering the responses from the plants, which perform external reuse (n = 9), the total was 1,176,516 m^3/month. In 2018, the plants located in the megacity of Sao Paulo marketed a volume of 1,461,470 m^3 of reclaimed water. This figure does not include the volume provided by the Aquapolo Project (see below). In spite of this, the reclaimed water supplied at nominal plant capacity was 38.3%. In comparison, the reclaimed water sold as treated effluent was only 0.43% (SABESP, 2018a), which indicates that the production and commercialization of reclaimed water is relatively low.

Some treatment plants implemented more robust technologies such as the combination of physicochemical processes. This is the case for two plants with a high volume of reclaimed water for external reuse. They comprise tertiary treatment. One of these plants is located in Sao Paulo city and has tertiary treatment by granular filters, cartridge filters and chlorine for disinfection. The other plant is part of the Aquapolo Project and comprises disc filters (400 microns), anoxic reactors, aerobic reactors, membrane bioreactors (0.05 micron pores) and reverse osmosis units, producing an effluent of high quality reclaimed water. The Aquapolo Project is an advanced water reuse plant for industrial purposes. In this works, the ABC plant effluent is the supply source to the Aquapolo Project's treatment system, which serves a Petrochemical Complex (SABESP, 2018a). The volume of treated effluent from the ABC WWTP to the Aquapolo project was 1,044,576 m^3/month for the period from January to June 2017.

Regarding sewage sludge, Fig. 3 shows that just three plants recycle nutrients from sludge through composting and subsequent fertilizer production. In all the other plants, the sewage sludge is disposed via landfills. The results of Ribarova et al. (2017) showed that disposal via landfills and temporary storage at wastewater treatment sites were the most common destinations for sewage sludge. Their study indicated that about 26% of the total generated sludge was used in agriculture. In other developing countries such as China, landfilling is also the most common option (about 50%) of treated sludge disposal (Zhang et al., 2016).

In this study, one similarity was observed between the three plants with sludge recycling: the existence of partnerships with private companies and/or with universities. In one of these plants, there was an experimental study collaboration with the Faculty of Agronomical Sciences. At the Jundiai plant, the composting facility was built inside the wastewater treatment area to minimize costs of transport. The operators use dried sludge combined with other organic solid waste (e.g., wood chips, chopped urban pruning, sugarcane bagasse and eucalyptus husk) for composting, resulting in commercial organic fertilizer production for agriculture supported by a spin-off company.

Concerning the surveyed plants, the fertilizer has been accredited by the Brazilian Ministry of Agriculture, Livestock and Food Supply as a safe product, and it is therefore used for cultivation of corn, sugarcane, coffee, apple, orange, soy, citrus, eucalyptus and flowers. However, there is a restriction for crops where the eatable parts have been in contact with soil such as roots, tubers and vegetables. About 28,000 tonnes per annum of fertilizer are being produced from thermophilic composting at the Jundiai plant.

Another important finding of this study is that there is no energy recovery in the surveyed plants. Although several of them produce biogas through anaerobic processes (Table 1), it is not used sustainably but flared. According to the response of some managers, the main reason for not recovering the biogas was that the generated volume is too low and that recycling is therefore not economically feasible. They also mentioned that some previous studies were undertaken to estimate the potential of biogas recovery. However, follow-up statements indicated that some managers do lack knowledge about energy recovery solutions.

According to the Brazilian Association of Biogas (ABIOGAS, 2019), in 2018, there was a potential of 5.8 billion Nm^3 biogas production linked to the sanitation sector in Brazil. Forbes et al. (2018) evaluated the feasibility for biogas recovery for power generation and/or thermal heat production for three plants with anaerobic digestion in Brazil. The results were promising for two of the analysed utilities (wastewater inflow rates of 1,500 L/s and 2,290 L/s). The benefits of installing biogas utilization facilities include the production of electrical and thermal power as well as the reduction of biosolid volume, energy bills, expenses related to sludge transport and disposal, and revenue from sale. For a plant with low capacity (350 L/s), the financial analysis was not favourable, mainly due to the estimated costs of producing electricity, which was higher than the corresponding purchase price. So, as anaerobic digestion and biogas utilization facilities have strong economies of scale, their unit costs tend to decrease and become more attractive as processing capacities increase. Some difficulties related to biogas utilization in Brazil are the high cost of equipment, too few cogeneration (combined heat and power) projects, absence of good data, lack of operator's knowledge of cogeneration systems; potential need for additional staff, lack of area available for new equipment and limited governmental incentives (Forbes et al., 2018). Santos et al. (2016) evaluated the economic viability and the potential of energy generation by biogas in anaerobic plants in Brazil. Their results indicated economic viability only for cities with populations greater than 300,000.

In the study region, some measures that could be applied to stimulate energy recovery are (a) the creation of partnerships with private companies and/or with universities to share knowledge and support on energy recovery technologies and operation; (b) partnership with other wastewater treatment facilities in Brazil, which already have practical experience and perform biogas recovery (e.g. in Paraná State); (c) economic incentives from government, for example, to buying equipment; and (d) co-digestion with organic food waste or combined with biogas from sanitary landfill could be done to increase biogas production. Felca et al. (2018) highlighted the need of public policies to support the generation of energy from renewable sources, lack of research and lack of investment in biogas in Brazil.

Regarding the existence of on-going project and future initiatives of resource recovery, managers of 25 plants answered positively (17.5% of the total of plants). The recovery practices reported were sludge recycling for fertilizer or soil conditioner (16 plants), biogas for energy recovery (6), external water reuse (5) and sludge reuse for civil construction materials (3).

Some plant managers replied that studies were already performed to evaluate the potential of biogas and sludge recovery. One mentioned a study for assessing the potential for biogas recovery. Two other plants already performed studies for evaluating the use of sludge in bricks, tiles or as fuel for ovens. Their results indicated that these solutions could be applied under favourable economic and technical boundary conditions. Three other plant managers expressed an interest in transforming sludge into fertilizer, depending on favourable legislation. One example is Campinas municipality, where there is an intention to compost sludge to produce biofertilizer. There is a current agreement with the city council and a company to recycle urban organic waste (tree pruning waste, fruits and vegetables together combined with sewage sludge) to be treated in a composting process. Also, in the same city, there is a project to expand the reuse of water (from treated effluent) through pipes connecting the reclaimed water to the Airport and Industrial Park of Campinas. In addition, some new plants are being built with the goal of water reuse and another one is being retrofitted for tertiary treatment as well as nitrogen and phosphorus removal for production of water for reuse from the treated effluent.

Some plant managers reported interest in initiatives for recovery of biogas. This is the case for the five largest plants in the megacity of Sao Paulo. It includes the project entitled Waste to Energy Barueri. Barueri is the largest wastewater treatment plant in South America with a wastewater inflow rate of 10.84 m^3/s. This plant receives more than half of the treated wastewater of the megacity. In this plant, the implementation of a pilot plant for sludge thermal treatment using plasma technology is being considered. It aims to reuse sludge either for energy recovery or for civil construction material. In this process, the sludge is subjected to high temperatures of around 1500°C. An inert vitreous residue with a drastic reduction of the initial volume is being created. There is a possibility of application of the material in the construction sector (SABESP, 2017; SABESP, 2018b).

Harris-Lovett et al. (2019) undertook a survey with stakeholders (diverse groups of regulators, wastewater managers, coastal stewards, researchers as well as advocates for environmental or industrial causes) to analyse their preferences concerning nutrient management options and corresponding objectives. Most stakeholders mentioned the option of recycling treated effluent to irrigation to increase resource recovery. In comparison, concerning the region of Sao Paulo, the option of reuse of treated effluent for irrigation in agriculture was not mentioned by the managers, probably because there is not yet local regulation for water reuse in agricultural irrigation, except for the irrigation of landscapes and green areas.

3.3. Factors that affect resource recovery implementation

Some managers reported the following barriers to resource recovery implementation: low amount and quality of biogas; no possibility of energy recovery due to the type of biological treatment through ponds (not true according to the authors' understanding), impracticability of the current legislation for sludge reuse and the low demand for reclaimed water in areas close to the plant. These factors and others reported in the previous literature are discussed below.

According to Bertanza et al. (2018), a key factor that interferes with the ability of plants to incorporate resource recovery strategies is the corresponding scale of operation. For larger wastewater treatment works, the recovery of the corresponding effluent as reclaimed water and the retrieval of major nutrients from sludge can be easier achieved, while potential restrictions are linked to small- and medium-sized works. In relation to this aspect, most of the plants, which perform at least one type of resource recovery, are large- and medium-sized (Table 2). The classification of size is based on Resolution CONAMA 377 (National Environmental Council, 2006a). Supplementary Material 3 shows the distribution of wastewater treatment plant size and inflow rates in the region of Sao Paulo, and Supplementary Material 4 contains the raw data for the surveyed plants. Results indicate that the size of the plant affects its ability to implement resource recovery. Most of the large plants performed resource recovery, while few of the small ones recovered resources. This is likely due to the constraints in investment (economies of scale) for small plants (Papa et al., 2017). Hanna et al. (2018) compared the energy consumption in wastewater treatment facilities and also noticed that larger facilities are usually more energy-efficient in terms of volume of water to be treated. In addition, larger facilities are able to invest more money in their installations and can therefore afford newer and more efficient equipment such as process control systems.

Although in this study we considered a Brazilian regulation to classify the size of plants, the distribution of them in relation to size was similar to another study in the USA (Diaz-Elsayed et al., 2019). Overall, the results in this study showed a higher number of small plants compared to large ones, considering the region of Sao Paulo. Diaz-Elsayed et al. (2019) found that almost 80% of the wastewater treatment plants are of small or medium size (below 10,000 population equivalent), and about 20% plants are classified as large. According to their findings, the strategies of energy recovery from wastewater are more prevalent in large-scale plants in the form of biogas and/or electricity generated from sludge.

Besides the plant size, another important aspect is location. Concerning rural and semi-urban areas, it may not be economically feasible to implement resource recovery technology such as phosphorus recovery, because of the low recovery rate and the elevated cost of innovative technology. Therefore, Sarvajayakesavalu et al. (2018) propose farmland application of sludge as a viable alternative for recovery of phosphorus.

Legislation is an important aspect to consider when planning resource recovery implementation. For example, water reuse regulations are important to incentivise the wastewater treatment plants to produce water for reuse from their treated effluent. In the State of Sao Paulo, the Joint Regulation SES/SMA/SSRH n.1 (Sao Paulo State Government, 2017) governs the non-potable direct reuse of treated wastewater for urban purposes. This was an important milestone in establishing guidelines and criteria for non-potable direct water reuse. The categories covered by this resolution are landscape irrigation, washing of streets and other public and private spaces, civil construction, clearing of rainwater galleries and sewage networks, car washing, and firefighting. The use of treated effluent for irrigation, agriculture, grazing and forestry are not included. In this regulation (Sao Paulo State Government, 2017), there are quality standards and categories of use such as moderate and severe restrictions.

Regarding sewage sludge reuse, two national regulations (CONAMA 375/2006 and 380/2006) establish the criteria and requirements for agricultural use of sewage sludge and other derived products. Some of the requirements relate to environmental permission, specific treatment processes and criteria for frequent monitoring of the sewage sludge products (biosolids) depending on the specificities of agricultural application. The analysis of several parameters is mandatory including inorganic substances (heavy metals such as mercury, lead, arsenic and copper), pathogens (thermotolerant coliforms, helminth eggs, *Salmonella* spp. and viruses) and organic substances (chlorinated benzenes and non-chlorinated phenols). This regulation also defines the crops that can be cultivated in soil where the sludge will be applied, and restrictions of application for some specific sites such as preservation of natural areas (National Environmental Council, 2006b, 2006c). Currently, there are discussions on proposals to update these regulations, including the flexibilization of some requirements. In the present survey, these regulations were mentioned by some of the managers as a barrier to reuse sewage sludge. For instance, some analyses that are required have high costs and technical limitations.

One factor that could be considered as a barrier to implementation of resource recovery (De Boer et al., 2018) is the mind-set of water boards (plant managers) and the perception of other stakeholders in wastewater management and the general public

(Poortvliet et al., 2018). According to our results, few managers answered positively (17.5% of the total of plants) about their interest in future initiatives of resource recovery. This finding raises the need for awareness about the benefits and importance of resource recovery to increase the interest of stakeholders, and consequently encourage implementation.

Another aspect that varied between the surveyed plants of our case study was the legal nature of the service provider. In the region of Sao Paulo, wastewater treatment management is the responsibility of the municipalities. The legal status of service providers can be divided into the following categories: private company, private right with public administration, public right/autarchy (absolute rule) and public-private partnership. Considering just the management of plant groups that perform resource recovery, the distribution of them according to service providers is as follows: 27 public-private partnerships, 5 private, 2 public right with private administration and 2 public right/autarchy. This indicates that the type of service provider does not seem to be a factor that influences resource recovery implementation since most of the plants (64% of the total of 143) in the Macrometropolis of Sao Paulo are managed by SABESP (public-private partnership).

3.4. Improvement options for resource recovery in the Macrometropolis of Sao Paulo

Our results indicate that most of the evaluated regional plants are not operating at their maximum capacity, and some recently started their operation, which indicates that they can treat a higher volume of wastewater. This represents an opportunity to implement resource recovery actions in parallel to the expansion of wastewater treatment.

In the study area (Macrometropolis of Sao Paulo), the total volume of sewage generated is in the range between 39,885 and 59,238 L/s, considering the data of average water consumption per person per day (SABESP, 2018a), total population data (EMPLASA, 2019) and quantitative information provided by SNIRH (2013). The most populous metropolitan region (MRSP) contributes to 58.4% of the total flow. The other regions provide flow proportions as follows: MRPVNC 12%, MRC 8.9%, MRS 6.3%, MRBS 6%, UAP 5%, UAJ 2.3% and RUB 1.1% (SNIRH, 2013).

Considering the total of 143 surveyed plants, the approximate quantity of wastewater treated per year is 992 million m³. This total volume contains resources that could be recovered, and some options will be presented below. The corresponding real value is certainly even higher, because it does not include all plants in the region, and the volume of sewage, which is not treated or not collected and treated. Based on the data from SNIRH (2013), the average index without collection and treatment was 13%, and the total sewage flow rate without collection and deprived of treatment was 6.8 m³/s for the region.

In addition, based on data from SNIS (2019a), the authors calculated that the total collected sewage was 1.44 billion m³/year and the total treated proportion was 1.06 billion m³/year for the region in 2017. This indicates that about 26% of the collected sewage is not treated and several municipalities still do not have treatment for their collected sewage. Based on the estimate of total sewage generation in comparison with the total collected and treated wastewater (SNIRH 2013), it can be estimated that around 70.3% of generated wastewater is collected and treated. With the future expansion of sanitation services in this area, resource recovery technologies could be integrated in the treatment systems.

In terms of urban and rural population, from the total municipalities (174) in the study region, most of them (162) are predominantly urban (urban population higher than 50%), of which 144 municipalities have an urban population higher than 75%. There are 3 municipalities that have the same proportion (50% rural and 50% urban) and only 9 municipalities have a higher rural population (IBGE, 2010). In developing countries, wastewater management is usually worse in secondary cities than in capital and large cities (Coulibaly et al., 2016). The sanitation issues (lack of proper sewage collection and treatment) are more accentuated in secondary cities, since governments prioritize major cities, which attract most of the economic activity (Coulibaly et al., 2016). The results of this study show that rural municipalities and the group with the same proportion (of rural and urban) have lower collection of wastewater (63.2%) and lower treatment (62.7% of the treated sewage) proportions than the urban municipalities (73.7% of collection and 74.6% of treatment) according to SNIS (2019b). Another finding was that all the surveyed plants with resource recovery are in urban municipalities. So, there is an opportunity to expand wastewater treatment particularly in rural municipalities integrated with resource recovery strategies.

Among the metropolitan regions, the MRSP is the one with the highest flow of untreated and not collected sewage (4,615.8 L/s), followed by MRPVNC (1,218 L/s), MRBS (466.1 L/s) and MRS (347.6 L/s) (SNIRH, 2013). The three first regions (MRSP, MRPVNC and MRBS) have a higher index without collection and treatment; 21.2%, 15% and 15%, respectively (SNIRH, 2013). In terms of access to sewage collection, MRSP is the region with the lowest percentage (58.5%) of which 56% is treated, followed by RUB with 59.7% and 68.5%, respectively. The other metropolitan regions have a sewage collection proportion and treatment percentage higher than 70% (SNIS, 2019b).

Considering the results of this case study, the most adopted treatment technology in the study region is activated sludge, followed by pond systems and anaerobic reactors (Table 1). The treatment process types for the 37 plants in the group with resource recovery solutions are distributed as follows: 25 plants with activated sludge, 7 with anaerobic reactors, 3 with other systems and 2 with pond systems. In general, the authors did not notice that the presence of resource recovery action is dependent on treatment technologies.

Depending on the wastewater treatment works, the recovery technology could be introduced in a way that it fits with the existing configuration of treatment units (Sarvajayakesavalu et al., 2018). Therefore, the existing treatment configuration can be an important aspect to be considered for planning purposes.

Anaerobic treatment processes (e.g., up-flow anaerobic sludge blanket, anaerobic membrane bioreactor and anaerobic digestion of sludge) are some technologies used for energy and valuable biochemical recovery (Akyol et al., 2019). However, in some of the plants with anaerobic processes, the low volume of biogas was reported by some managers as the reason for not performing recovery actions. One alternative would be to include other organic waste such as food waste into the anaerobic treatment process of sewage sludge, which may increase biogas production, and consequently the generation of heat or energy (Tolksdorf and Cornel, 2017). Co-digestion raises the concentration of methane in the biogas, and the biogas production increased by 25% to 50% with the addition of 1%–5% food manufacturing and processing wastes to sewage sludge (Zahan et al., 2016). In some cases, the combined use of biogas from wastewater treatment plants and from sanitary landfills is also an option with great potential, as explored by Santos et al. (2018) within the Brazilian context. Other options for energy recovery such as heat pumps are not commonly applied worldwide (Kretschmer et al., 2016).

Considering that pond treatment was commonly applied in the study area, one possibility that could be evaluated for implementation is microalgae growth technology to make use of the existing infrastructure within these plants. The application of microalgae in open pond systems can offer many advantages such as the reduction of energy consumption (through aeration), improvement of the effluent quality, biomass harvesting for production of biofuel, food supplements and green pharmaceuticals (Craggs et al., 2014). The microalgae harvested can be used as a co-substrate together with primary sludge and waste activated sludge in anaerobic digestion for biogas production (Olsson et al., 2018). The biomass could be transported to larger plants equipped with digesters. Such initiatives are particularly interesting for developing and/or tropical countries, which can reduce their wastewater treatment costs via the recovery of their resources.

Raceway ponds, photobioreactors and hybrid systems of microalgae can be applied as a complement to existing wastewater treatment systems (Christenson and Sims, 2011). This is especially interesting for existing systems with aerated ponds, because of oxygen production by microalgae that reduce energy consumption. This technology is being applied to the side streams such as the reject water from digesters or the excess water from dewatering of digested sludge due to their high nutrient concentrations (Marazzi et al., 2019). As the reject water has a high temperature, it could be diluted to allow for a more optimal temperature supporting microalgae growth. Other sustainable adaptations that could be made to the ponds are floating macrophyte systems with the ability to produce nutrient-enriched plants simultaneously with wastewater treatment.

The treatment processes grouped under “others” in Table 1 require some further explanations. There are two plants using the Nereda process. This technology can recover valuable biopolymers, because aerobic granular sludge contains alginate-like exopolysaccharides, which can be harvested/extracted for economic applications in the food, paper, medical and construction industries (Van der Roest et al., 2015; Royal Haskoning DHV, 2017; Leeuwen et al., 2018). Thus, combining alginate extraction with existing excess sludge treatment processes has been the focus of some recent research (Van der Roest et al., 2015). In addition, as the Nereda process removes high proportions of phosphorus, consequently it allows for extra phosphorus recovery as struvite (Van der Hoek et al., 2016). Another plant within the “others” group has a bioreactor with ultrafiltration membranes, which produces high-quality effluent that can be reused for several purposes including potable use (Yin and Xagoraraki, 2014). However, for developing countries, economic indicators still have a high weight in decision-making processes (Kalderis et al., 2010; Ngan et al., 2019).

The performances of the WWTP may be very variable and depend on the treatment processes, operational conditions and other factors. For the region of Sao Paulo (Macrometropolis), considering the BOD load of the total sewage volume, which is collected and treated, and the BOD load of the effluent discharged to the receiving surface waters, the estimated BOD removal efficiencies of the plants were around 83% (SNIRH, 2013). For example, a plant with an activated sludge process (the most common treatment process in the study area) unit is located in Sao Paulo city. This plant had mean removal efficiencies of 85.7% for COD, 24.5% for total N and 73.5% for total P (SABESP, 2018b). Oliveira and Sperling (2005) evaluated the performances of plants comprising several different technologies. These plants are located in Sao Paulo State and Minas Gerais State. For the activated sludge process, the removal efficiencies were higher: 85% (BOD), 81% (COD), 76% (TSS), 50% (NTK) and 46% (TP).

Other treatment processes commonly found in the study area are the up-flow anaerobic sludge blanket (UASB) and pond systems. According to Oliveira and Sperling (2005), the removal efficiencies for facultative ponds and anaerobic ponds followed by facultative ponds were 75% and 82% (BOD), 55% and 71% (COD), 48% and 62% (TSS), 38% and 45% (NTK), and 46% and 36% (TP), respectively. Moreover, for UASB systems without and with post treatment, the removal efficiencies were 72 and 88% (BOD), 59 and 77% (COD), 67 and 82% (TSS), -13 and 24% (NTK), -1. and 23% (TP), correspondingly.

Water reuse in cities is an important strategy to address current water shortage and quality challenges (Sun et al., 2016). However, the final water quality has to follow the regulation 01/ 2017 (Sao Paulo State Government, 2017). Therefore, operational plant improvements might be required to uphold the regulation.

The water demand in São Paulo region is about 223 m^3/s distributed in household supply (48.95%), industry (31.32%) and agricultural irrigation (19.73%) (Sao Paulo State et al., 2013). Considering the average water consumption per person (128 L/day based on SABESP (2018a)) and the population of the region of Sao Paulo (Senese Neto, 2018), the total water demand for supplying households is around 4.3 million m^3/day. It is worth highlighting that about 49% of the total water demand is associated with the Alto Tiete river basin, which comprises 87% of the municipalities of MRSP (Sao Paulo State et al., 2013).

The potential of water reuse for industrial purposes was identified in a forecast for 2035 by the Master Plan for Water Resources Use in Sao Paulo Macrometropolis (Sao Paulo State et al., 2013). Mairiporã was the only city classified as having a “very high potential” for water reuse in the future. The other eleven municipalities were classified as “high potential”; all of them belong to the Piracicaba/Capivari/Jundiaí Basin indicating a deficit for industrial water supply. All treated wastewater could be directed to supply part of the industrial demand in these cities, especially Paulínia and Limeira. Based on the results from the survey presented in this paper, there is only one wastewater treatment plant that produces water for external reuse in this basin. Several other municipalities, including some in other metropolitan regions, were classified as having a “medium potential”. There are cities classified as having a “medium potential” in the megacity of Sao Paulo (e.g., Guarulhos, Embu and Mauá), Piracicaba Agglomeration and Sorocaba region (Sao Paulo State et al., 2013).

The agriculture sector also requires a lot of water. The water demand for irrigation in agriculture will increase by 33, 31 and 10% in Tietê and Sorocaba, Piracicaba/Capivari/Jundiaí and Mogi-Guaçu water resources management units, respectively, by the year 2035. Based on this forecast, there are several municipalities, which are likely to face water scarcity challenges. Furthermore, the public water supply demand is also likely to increase according to the projections, especially in the water resources management units of Alto Tietê, Piracicaba Capivari Jundiaí, Baixada Santista and Tietê/Sorocaba (Sao Paulo State et al., 2013).

Nutrient recovery is especially interesting for municipalities that have agriculture as the main economic activity. The predominant economic activity of the municipalities was assessed based on data from The Brazilian Institute of Geography and Statistics (IBGE, 2016). There are five relevant municipalities in the Macrometropolis of Sao Paulo; most of them are located in the Metropolitan Region of Sorocaba. Furthermore, there are 14 other municipalities where agriculture is the second or third main economic activity in terms of importance. If the wastewater treatment facilities in these cities or nearby ones apply nutrient recovery techniques from wastewater treatment, this activity could also benefit them as an alternative fertilizer source.

Some measures of resource recovery compete with each other. Therefore, it is necessary to prioritise. In this context, the value pyramid is a tool that allows for the distinction between the recovered products and can support the decision. According to this tool, the hierarchy from low to high value is as follows: energy (electricity and heat), transportation fuels, materials and chemicals (e.g., fertilizers), food, and health and lifestyle (e.g., pharmaceuticals and fine chemicals) (Van der Hoek et al., 2016; Betaprocess Bioenergy, 2019). Moreover, the framework proposed by the authors in the next section is a tool facilitating further decision-making.

3.5. Framework for resource recovery planning and implementation

In most urban areas within developing countries, there is no effective system for collection and treatment of wastewater, which causes eutrophication and other water pollution issues. The lack of both infrastructure and a legislative framework for the new treatment processes further intensifies this challenge, and poor incentives can be considered as the reason for low resource recovery implementation (Sarvajayakesavalu et al., 2018). Moreover, these areas face the overall challenge of the use of natural and financial resources in a sustainable manner (Woltersdorf et al., 2018).

Informal urban settlements lack infrastructure entirely, and could be the first to adopt new sustainable and cost-effective treatment systems (Mega-cities Project, 2019). In the case of resource recovery implementation, there is an opportunity to implement these solutions in the megacities of developing countries. These areas need to expand the coverage of wastewater treatment through building new wastewater treatment plants or retrofitting the existing ones.

Public acceptance is an important challenge, since low-income communities do not want to have “second class” solutions (Mega-cities Project, 2019). For instance, public perception is commonly an important barrier to implementation of water reuse. For example, low public acceptance for water reuse might be attributed to the lack of information such as evidence demonstrating the technological success and safety for public health (Wilcox et al., 2016).

The selection of an appropriate method is a challenge as it is highly site-dependant. It follows that the regional water quality and influent quantity, size of the treatment plant and other economic considerations play a major part in the selection procedure.

In order to accelerate the process of resource recovery implementation, several complex aspects should be considered. Therefore, the authors created a framework (Fig. 4) to support the planning process and encompass a set of measures to contribute to decision-making.

The proposed framework contains several steps and can work as an action plan to achieve resource recovery implementation. The qualitative and quantitative characteristics of the influent vary in different regions of a country (Sun et al., 2016), and this should be considered for evaluating the effluent for reuse. When mapping the demand, it is useful to analyse regional planning documents. Each city has a different context and a specific demand of what resource is more important to recover from the wastewater treatment plant. According to Günther et al. (2018), plant managers can choose from a wide range of techniques to decide which of them is more appropriate and fits better to local raw material availability, economic and ecological boundary conditions.

For the framework step 9, which is concerned with a comparison between the selected recovery options, some indicators were proposed. This comparison between the recovery methods allows for the discussion of their advantages and disadvantages, considering the option that best adjusts the economic-technical-environmental tripod, facilitating decision-making. This framework could be integrated into the plans of wastewater treatment companies to base strategies of resource recovery at municipal and regional levels. It is expected that the framework is flexible and can be adapted by users, depending on the context (e.g., plant size and specific demand) and available data. Besides supporting retrofitting of resource recovery solutions for existing treatment facilities, the framework can also be applied for new plants at the planning stage.

The expected benefits from a successful implementation of the proposed framework are (a) the reduction in time for decision-making of resource recovery projects; (b) lowering of adverse environmental impacts related to wastewater treatment processes through improvement of effluent quality, reduction of energy consumption and allowance for more efficient natural resources management; (c) contribution to water conservation providing economic benefits by generation of revenues of recovered products; and (d) saving money from operational costs related to, for example, by-product management and disposal as well as energy consumption.

3.6. Comparison of the region of Sao Paulo with other megacities in developing countries

This comparison complements the discussion and contextualizes original results with the literature. Treatment technologies are usually basic in developing economies of the Brazil, Russia, India, China and South Africa (BRICS) group. For example, in Russia, wastewater treatment facilities have a similar configuration compared to the region of Sao Paulo, consisting of preliminary treatment units such as screens and grit chambers.

The wastewater of Moscow City is treated at the Kuryanovskaya and Luberetskaya secondary biological treatment plants, which discharge treated effluents to the Moscow River downstream of the city. In some plants, the wastewater inflow rate is between 10,000 and 100,000 m^3/day. The sludge for these works is only reused for composting after the digestion tank and the mechanical sludge dewatering room. In larger plants with an inflow rate higher than 100,000 m^3/day, digestion gases are also recovered benefitting a mini-thermal power plant (MosvodokanaINIIproject Institute, 2015). After biogas purification, the mini-thermal power plant produces electricity and additional heat to supply a central heat-supply station. This form of energy recovery can improve the energy efficiency of these plants and reduce greenhouse gas emissions (MosvodokanaINIIproject Institute, 2015).

In Johannesburg, South Africa, there is a need for policy change and implementation to promote the reduction, reuse and recycling of phosphate as well as to control pollution. The wastewater treatment capacity is insufficient in South Africa for the treatment of all wastewater types. This causes pollution both from untreated wastewater and from treated effluents, which do not meet standards and might cause microbial contamination, particularly due to the rapid urbanization of informal settlements located near cities (Food and Agriculture Organization of the United Nations (FAO), 2016). Policies could be updated to promote the reduction, reuse and recycling of phosphate. Consequently, this would mitigate the pollution challenge. Regarding phosphorus recovery, struvite processes were shown to be unprofitable, partly due to low struvite prices, which are subject to relatively low regional South African phosphate fertilizer market prices (Sikosana et al., 2017). As such, fertilizer policy and price regulations would help to improve the placement of struvite in the fertilizer market and to increase fertilizer prices to values more comparable to the global market (Sikosana et al., 2017).

In China, the mostly adopted treatment technologies in municipal plants are oxidation ditches (30.5%), anaerobic-anoxic-oxic processes (16.2%), conventional activated sludge systems (10.0%), anaerobic-oxic processes (8.2%) and sequencing batch reactors (6.8%) (Sun et al., 2016). Thus, the analysis of each context is important to assess the potential for resource recovery strategies. There is some resource recovery from municipal wastewater in some regions, but the proportion of resources utilization after treatment is low. According to Zhang et al. (2016), who studied 656 WWTP in 70 cities of 7 Chinese regions, the proportion of resource recycling (recycled building materials and compost) is only 25%. Approximately 15% of wastewater is inefficiently treated, and the water reuse from treated effluent is low. Another concern is that up to 40% of sewage sludge is still improperly disposed of (Lu et al., 2019). In addition, the operation ratio of the treatment plants is below the design capacity due to insufficient sewer networks (Lu et al., 2019).

Sun et al. (2016) estimated the recovered resources from wastewater in China: water reuse of 3.76×10^9 m^3/year, NH_3-N recycling of 2.05×10^5 tons/year and total phosphorus recovery of 2.92×10^4 tons/year (Sun et al., 2016). The water reuse rate in some megacities in China has reached 35–60%, and provinces with low available water resources and high gross domestic product (GDP) levels showed larger proportions of reclaimed water construction and utilization (Chen et al., 2017). Thus, the calculated potential for recovery of water, nutrients and organics from wastewater at national scale is much higher (Sun et al., 2016).

Regarding energy recovery, there is a large wastewater treatment plant with a population equivalent of 3.5 million in Shanghai recovering energy from biogas to meet the heat demand of both digesters and sludge thermal drying processes. The remaining biogas is burned (Zhao et al., 2019).

Resource recovery measures are not commonly implemented in wastewater treatment plants in developing countries, so studies supporting the planning of more recovery practices are important. Potential multiple societal benefits linked to resource recovery should be highlighted to attract more investment from new sectors such as agriculture (Andersson et al., 2018). For example, in countries with strong agricultural activity, there is an opportunity to develop a biofertilizer market model resulting from anaerobic digestion (Felca et al., 2018; Battista et al., 2019) or other nutrient recovery solutions from their wastewater treatment plants, benefitting both rural and urban communities.

3.7. Study limitations

Some wastewater treatment organisations did not answer the questionnaire, which limits the interpretation of findings. Also, in some municipalities with a high number of wastewater treatment plants and/or insufficient staffing resources, it was not possible to collect data from all plants. Another limitation was that few responses concerning less important data were incomplete. Furthermore, some plant managers were temporarily unavailable, which led to a pre-longed period (July 2017 to April 2019) of data return.

4. Conclusions and recommendations

This study was undertaken to increase the evidence base of resource recovery options by providing accurate and relevant data from wastewater treatment plants and their resource recovery levels in the most populous area in South America; the region of Sao Paulo. These data should support the planning of various resource recovery projects in the region: water reuse, biofertilizer production and energy recovery initiatives based on local socio-economic activities and regional demand, contributing to long-term sustainable water management in urban areas.

The results show that there is currently low implementation of resource recovery in the region, but there is a great potential to expand the strategies of resource recovery, either for new plants or for retrofitting existing ones. The predominant recovery action is internal water reuse while other options have not been much explored. Another finding is that recovery is concentrated mainly in large- and medium-sized plants. However, there are more small plants in the studied region, so it is important to evaluate how to expand the recovery solutions to these small plants as well.

For most of the studied works, the sludge generated is disposed in landfills. In dense large cities, there is no space available for this, which involves additional costs for wastewater treatment facilities. So, other options such as sludge reuse are very promising. One factor that can help to support the implementation of such options is partnership with universities for new developments and with private companies for implementation as shown for sludge reuse cases. In addition, results can facilitate the identification and evaluation of the regional demands for which resources can be recovered; e.g., fertilizer or water for reuse, and the identification of priority areas in each metropolitan area that comprises the region of Sao Paulo.

Most of the addressed megacities in developing countries have low implementation of resource recovery and poor management and operational conditions for their wastewater treatment facilities. Incentive-based policies are important to stimulate the interest of water utilities on implementation of resource recovery technologies and to support the introduction of recovered products in the market. According to some of the managers, some barriers for sludge reuse implementation are the lack of government incentives and legislation. These are thus interesting aspects for future studies.

This study also offers several further research possibilities. Specifically, the detailed data obtained for the region of Sao Paulo could be compared with data from other urban agglomerations to establish a global inventory. Further studies involving life-cycle assessments are recommended, particularly for the evaluation of environmental impacts related to resource recovery options. Moreover, they could be combined with the framework application. Our contribution can be useful for decision-makers applying the same procedures as proposed in this study to other cities and regions with similar conditions. Also, countries with different conditions from the ones described in this study might benefit from the proposed assessments. The proposed framework has been designed for application in similar case studies. However, further studies are encouraged to validate its potential.

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Supplementary material

This article includes Supplementary Materials 1 to 4, which can be found in the online version of this paper.

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Figure captions

Fig. 1. (a) Map of geographical location of Brazil, highlighting the State of Sao Paulo in bold; (b) Macrometropolis of Sao Paulo location in the State of Sao Paulo; and (c) locations of the 143 wastewater treatment plants in the metropolitan regions and urban agglomerations. RUB, Regional Unit Bragantina; UAJ , Urban Agglomeration of Jundiaí; UAP, Urban Agglomeration of Piracicaba; MRBS, Metropolitan Region of Baixada Santista; MRC, Metropolitan Region of Campinas; MRS, Metropolitan Region of Sorocaba; MRSP, Metropolitan Region of Sao Paulo; MRPVNC, Metropolitan Region of the Paraíba Valley and the North Coast.

Fig. 2. Summary of the content of the questionnaire provided to the managers of wastewater treatment plants located in the Macrometropolis of Sao Paulo.

Fig. 3. Implementation of resource recovery options in the surveyed wastewater treatment plants in the Macrometropolis of Sao Paulo. Data from 143 wastewater treatment plants collected between 2017 and 2019. Note that there were plants that performed more than one action.

Fig. 4. Framework to guide decision-making on resource recovery for water and sanitation service providers. Notes: [1] It is also a technical indicator; and [2] The environmental load includes pollutants (nutrients and organic matter) measured through the removal efficiencies of biological oxygen demand (BOD), chemical oxygen demand (COD), ammonia (NH_3), nitrate (NO_3) and phosphorus (P).

Table 1

Table 1.
Different municipal wastewater treatment plant (143 plants) processes in the region of the Macrometropolis of Sao Paulo, and corresponding possibilities of resource recovery.

Type of data	Treatment process configuration						
	Secondary treatment line				Sludge line[4]		
	Activated sludge[1]	Pond systems[2]	Anaerobic reactors[3]	Others	Thickening	Anaerobic digestion	Dewatering
Proportion of plants (%)	38.5	30.8	21.7	9.0	21.7	2.8	46.9
Potential of resource recovery	Water reuse[5] and phosphorus recovery	Water reuse[5] and energy recovery	Water reuse[5] and energy recovery	Not applicable	Phosphorus recovery from supernatant and sludge for reuse	Phosphorus from digester supernatant and biogas for energy recovery	Phosphorus from dewatering effluent, biosolids for fertilizer, sludge for composting (or to manufacture building materials) and biosolids as source for valuable metals
Usage possibilities	Internal purposes or external reuse	Power supply (on-site and external)	Power supply (on-site and external)	Not applicable	Application in agriculture	Application in agriculture and power supply (on-site and externally)	Application in agriculture and insertion of the recovered products into the market

[1] Includes batch, continuous and extended aeration as well as the activated sludge process followed by a moving bed biofilm reactor.

[2] Includes the following: aerated pond and settling pond (with or without disinfection); aerated pond, settling pond and maturation pond; anaerobic pond and facultative pond maturation; anaerobic pond, aerated biological filter and settling tank; anaerobic pond, aerobic pond and maturation pond; anaerobic pond and facultative pond; facultative and settling pond; facultative pond (with or without disinfection); facultative pond and maturation pond; aerated pond, anaerobic filter, secondary clarifier and disinfection; and stabilization pond with aeration and mixing as well as settling pond; anaerobic pond, facultative pond, flotation with diffuse air and disinfection.

[3] Includes anaerobic reactor followed by aerobic reactor; upflow anaerobic sludge blanket (UASB); UASB and submerged aerated filter; combined systems of UASB and aeration tanks; UASB and ponds.

[4] The data do not include the following cases: plants without sludge line, where the sludge is stored and subsequently transferred to other large plants; mainly pond treatment where the removal of sludge does not occur at a fixed frequency or the sludge is removed after 10 or 20 years; and replies with no specifications for the sludge line.

[5] Depending on water quality and regulatory requirements.

Table 2

Table 2.
Size distribution of the wastewater treatment plants (see also Supplementary Material 3) and corresponding indication of resource recovery implementation.

Size of plant	Number of plants	Number of plants with resource recovery	Proportion (%)
Small	86	4	4.7
Medium	47	25	53.2
Large	10	8	80.0

Note: The classification of size was based on Resolution CONAMA 377 (National Environmental Council, 2006a).

Figure 1

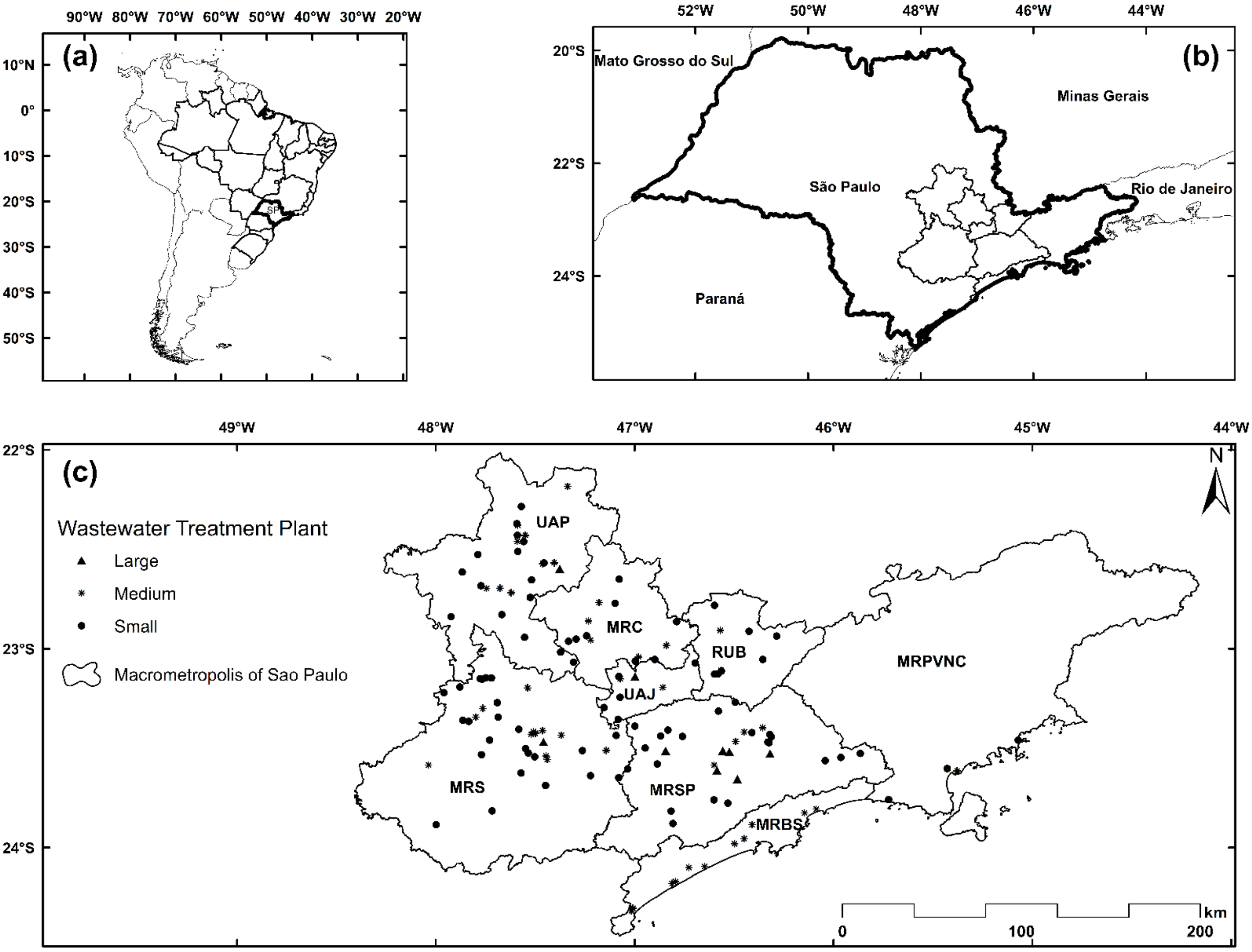
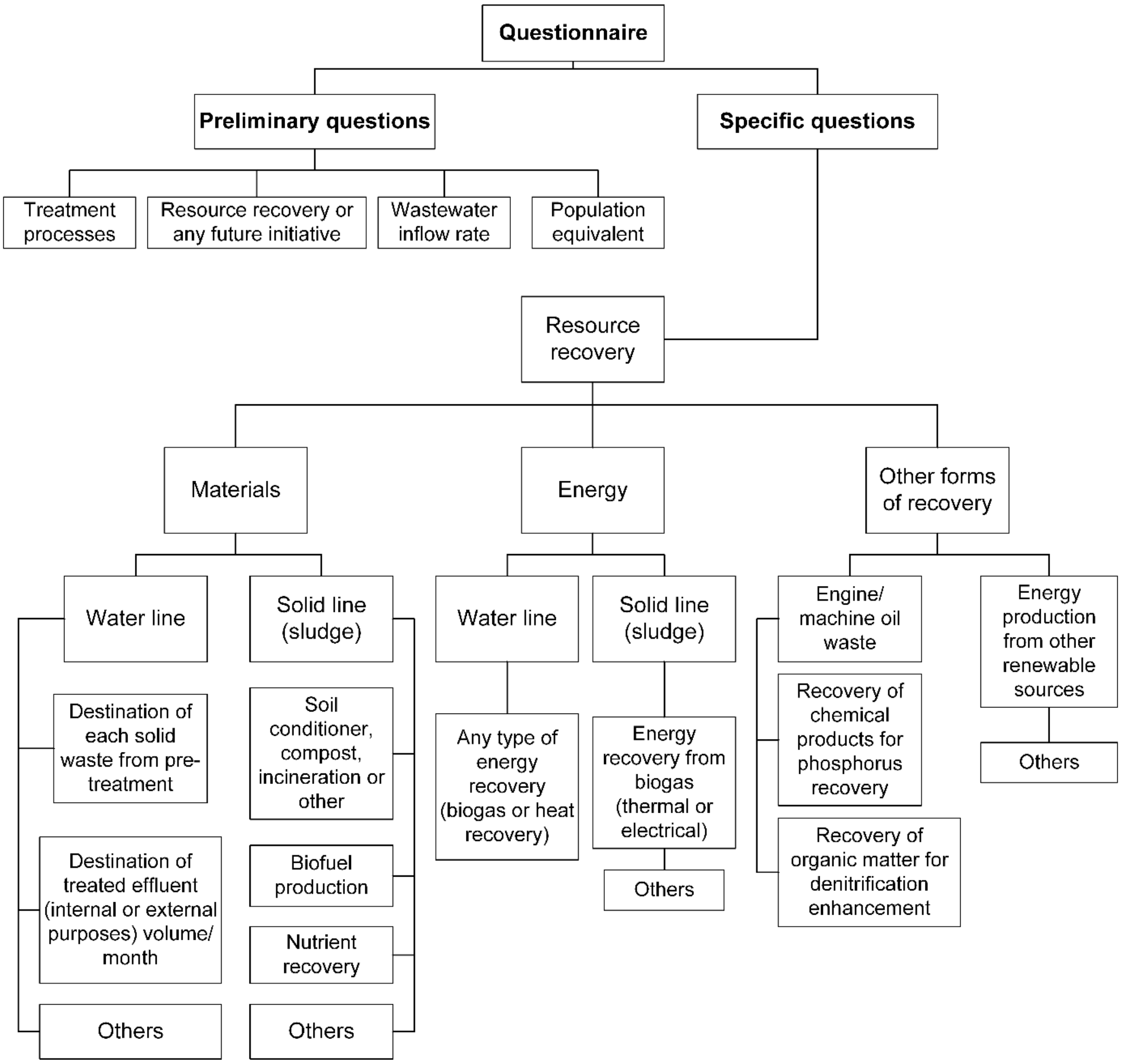
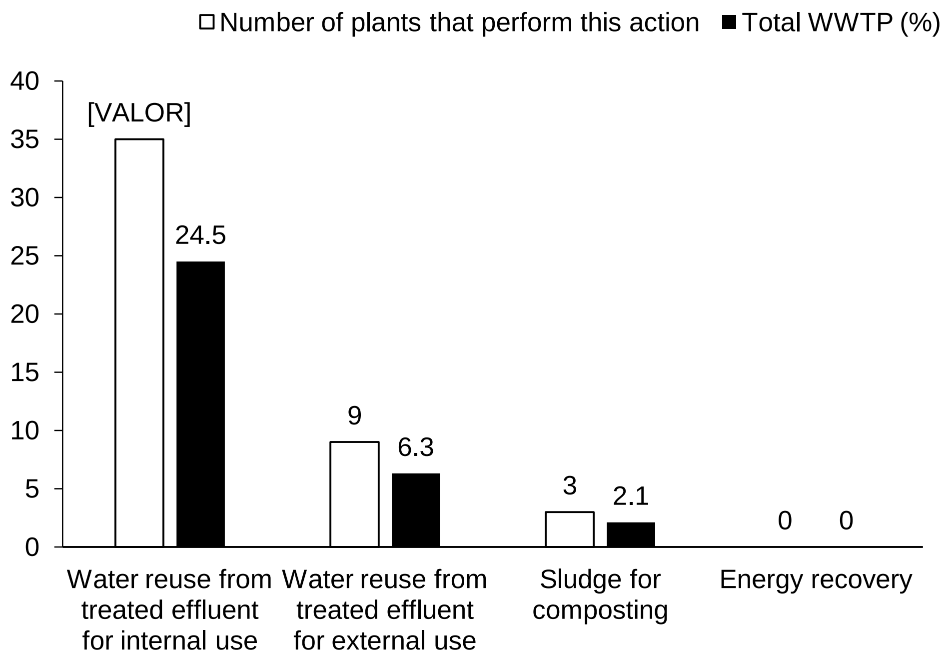

(a)
90°W 80°W 70°W 60°W 50°W 40°W 30°W 20°W
10°N
0°
10°S
20°S
30°S
40°S
50°S
SP
(b)
52°W 50°W 48°W 46°W 44°W
20°S
22°S
24°S
Mato Grosso do Sul
Minas Gerais
São Paulo
Rio de Janeiro
Paraná
(c)
49°W 48°W 47°W 46°W 45°W 44°W
22°S
23°S
24°S
Wastewater Treatment Plant
Large
Medium
Small
Macrometropolis of Sao Paulo
UAP
MRC
RUB
UAJ
MRPVNC
MRS
MRSP
MRBS
N
0 100 200
km

Figure 2



Questionnaire
Preliminary questions
Specific questions
Treatment processes
Resource recovery or any future initiative
Wastewater inflow rate
Population equivalent
Resource recovery
Materials
Energy
Other forms of recovery
Water line
Solid line (sludge)
Water line
Solid line (sludge)
Engine/ machine oil waste
Energy production from other renewable sources
Destination of each solid waste from pre-treatment
Soil conditioner, compost, incineration or other
Any type of energy recovery (biogas or heat recovery)
Energy recovery from biogas (thermal or electrical)
Recovery of chemical products for phosphorus recovery
Others
Destination of treated effluent (internal or external purposes) volume/ month
Biofuel production
Others
Recovery of organic matter for denitrification enhancement
Nutrient recovery
Others
Others

Figure 3



Number of plants that perform this action
Total WWTP (%)
40
35
30
25
20
15
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[VALOR]
24.5
9
6.3
3
2.1
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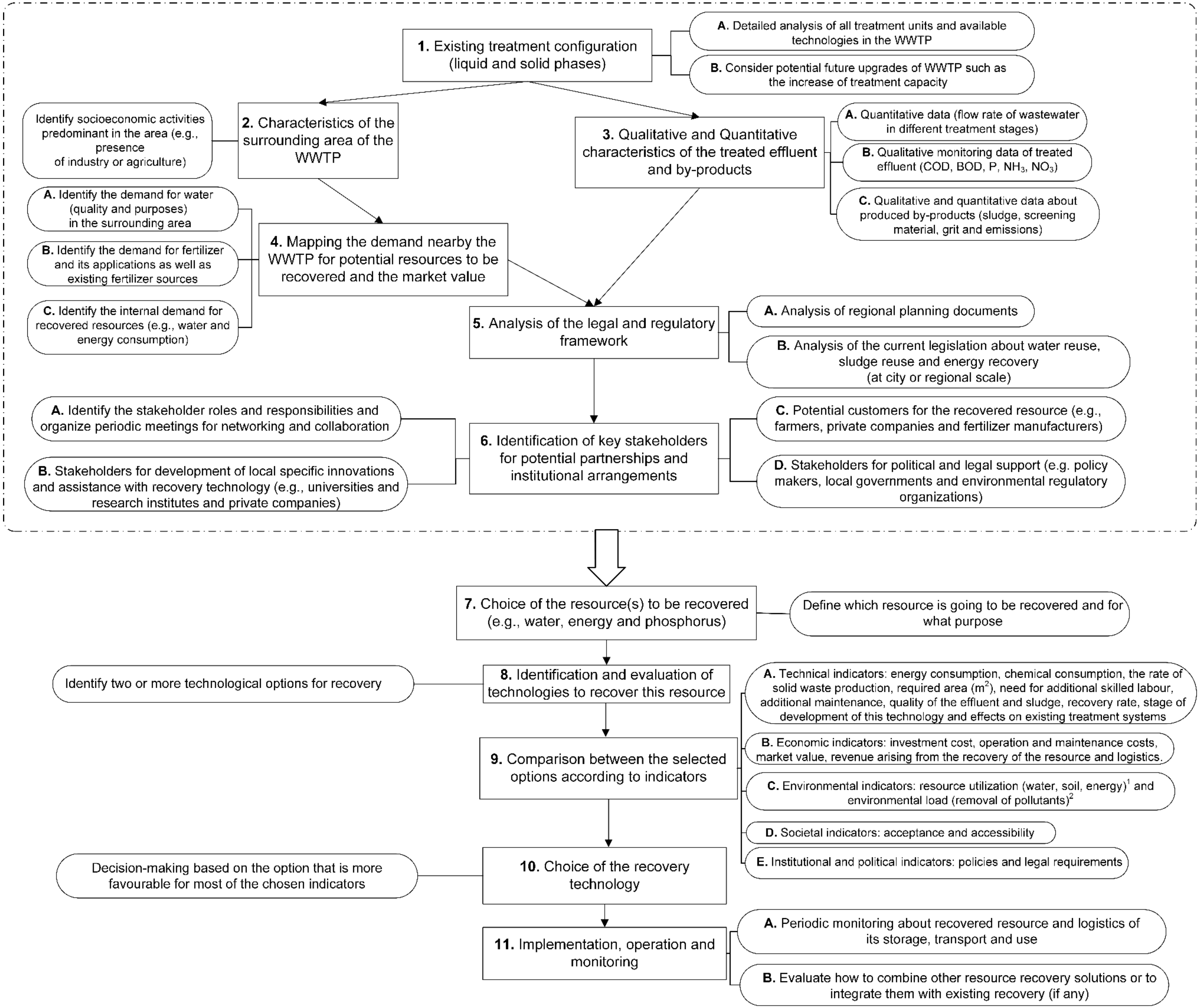
0
Water reuse from treated effluent for internal use
Water reuse from treated effluent for external use
Sludge for composting
Energy recovery

Figure 4


1. Existing treatment configuration (liquid and solid phases)
A. Detailed analysis of all treatment units and available technologies in the WWTP
B. Consider potential future upgrades of WWTP such as the increase of treatment capacity
Identify socioeconomic activities predominant in the area (e.g., presence of industry or agriculture)
2. Characteristics of the surrounding area of the WWTP
3. Qualitative and Quantitative characteristics of the treated effluent and by-products
A. Quantitative data (flow rate of wastewater in different treatment stages)
B. Qualitative monitoring data of treated effluent (COD, BOD, P, NH_3, NO_3)
C. Qualitative and quantitative data about produced by-products (sludge, screening material, grit and emissions)
A. Identify the demand for water (quality and purposes) in the surrounding area
B. Identify the demand for fertilizer and its applications as well as existing fertilizer sources
C. Identify the internal demand for recovered resources (e.g., water and energy consumption)
4. Mapping the demand nearby the WWTP for potential resources to be recovered and the market value
5. Analysis of the legal and regulatory framework
A. Analysis of regional planning documents
B. Analysis of the current legislation about water reuse, sludge reuse and energy recovery (at city or regional scale)
A. Identify the stakeholder roles and responsibilities and organize periodic meetings for networking and collaboration
B. Stakeholders for development of local specific innovations and assistance with recovery technology (e.g., universities and research institutes and private companies)
6. Identification of key stakeholders for potential partnerships and institutional arrangements
C. Potential customers for the recovered resource (e.g., farmers, private companies and fertilizer manufacturers)
D. Stakeholders for political and legal support (e.g. policy makers, local governments and environmental regulatory organizations)
7. Choice of the resource(s) to be recovered (e.g., water, energy and phosphorus)
Define which resource is going to be recovered and for what purpose
Identify two or more technological options for recovery
8. Identification and evaluation of technologies to recover this resource
A. Technical indicators: energy consumption, chemical consumption, the rate of solid waste production, required area (m^2), need for additional skilled labour, additional maintenance, quality of the effluent and sludge, recovery rate, stage of development of this technology and effects on existing treatment systems
B. Economic indicators: investment cost, operation and maintenance costs, market value, revenue arising from the recovery of the resource and logistics.
9. Comparison between the selected options according to indicators
C. Environmental indicators: resource utilization (water, soil, energy)[1] and environmental load (removal of pollutants)[2]
D. Societal indicators: acceptance and accessibility
E. Institutional and political indicators: policies and legal requirements
Decision-making based on the option that is more favourable for most of the chosen indicators
10. Choice of the recovery technology
11. Implementation, operation and monitoring
A. Periodic monitoring about recovered resource and logistics of its storage, transport and use
B. Evaluate how to combine other resource recovery solutions or to integrate them with existing recovery (if any)

Supplementary Material 2
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Supplementary Material 4

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Graphical abstract

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Credit Author Statement

Mariana Cardoso Chrispim – conceptualization, methodology, investigation, formal analysis, framework creation, visualization, writing-original draft, writing-review & editing. **Miklas Scholz** – conceptualization, writing-review & editing, and supervision. **Marcelo Antunes Nolasco** – project administration, writing-review & editing, and supervision.

Competing interest statement

There are no competing interests.