Investigating Current Issues with Global Wastewater Management Systems and Associated Health and Environmental Risks

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Background

Global access to clean drinking water is a goal society has yet to attain. Around 25% of the world's population relies on drinking water contaminated with feces, posing a huge risk to human health (WHO, 2023a). Sparsely populated communities in developing countries face the greatest challenge when it comes to managing domestic wastewater, which is waste produced by households (Massoud et al., 2009).

Domestic wastewater is one of five primary types of wastewater; others include agricultural, municipal, commercial, and industrial (Center for Decentralized Wastewater Management, 2012). The differentiating factor between these is the place of origin. For example, agricultural wastewater comes from farms and crop fields (Agricultural wastewater, 2022), whereas industrial wastewater comes from industrial sites, where substances are dissolved into the water (Woodard & Curran, Inc., 2006). The contents and quantity of domestic wastewater change depending on the lifestyles of individual residents. Variables that primarily affect domestic wastewater output include family size, income, food consumption trends, and general hygiene (Zheng & Kamal, 2020). Regardless of these influences, however, the main composition of domestic wastewater is the same: biodegradable organic materials, nutrients, microorganisms, and metals. When treated inadequately, these elements can threaten environmental and public health by inducing the depletion of oxygen in bodies of water, ingestion of pathogenic organisms, bioaccumulation of toxic substances, and climate shifts for wildlife (Mogens & Comeau, 2008).

The solution to this concern, a widely known process called wastewater management, involves the collection, treatment, and reuse of wastewater (Roozbahani, 2021). While installing and maintaining domestic wastewater treatment plants are costly, these systems are vital to preserve human and environmental health (Durán-Sánchez et al., 2020). Unfortunately, only 58% of the world's domestic wastewater is being treated, endangering the health of millions of people globally, particularly those of lower socioeconomic standing (*United Nations*, SDG Target 6.3).

Despite this, countries around the world have adopted new policies wherein families earning larger incomes receive better wastewater treatment services while low-income families continue to lack basic sanitation services (Zheng & Kamal, 2020). From 2000 to 2017, limited sanitation caused by sharing resources in the developing countries Kenya, Bangladesh, and Ghana appeared to increase from 5-8%, meaning that more families were relying on shared resources to meet their basic sanitary needs. This practice is growing more common in other low-income areas; for example, in urban sub-Saharan Africa and South Asia, 31% and 19% of the respective populations utilize shared sanitary resources such as toilets (Meili et al., 2022).

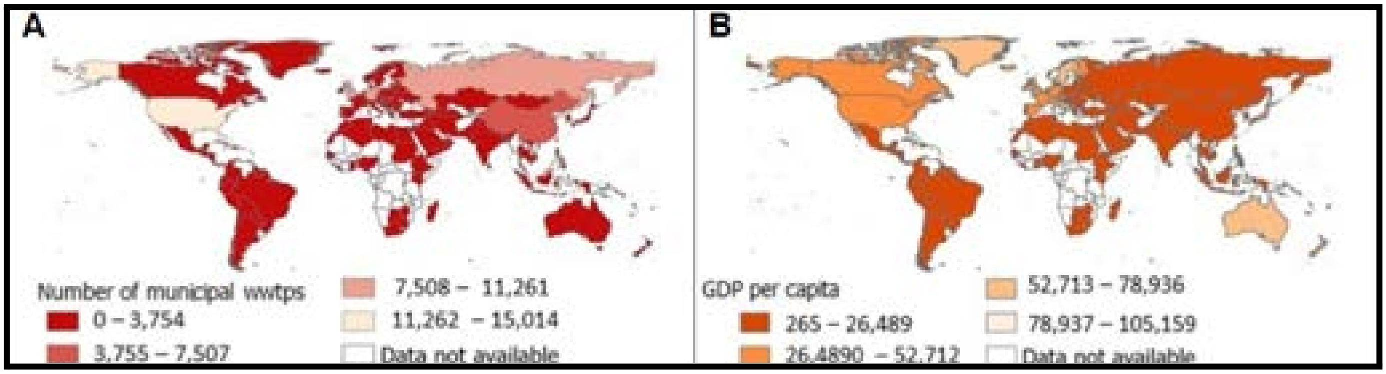
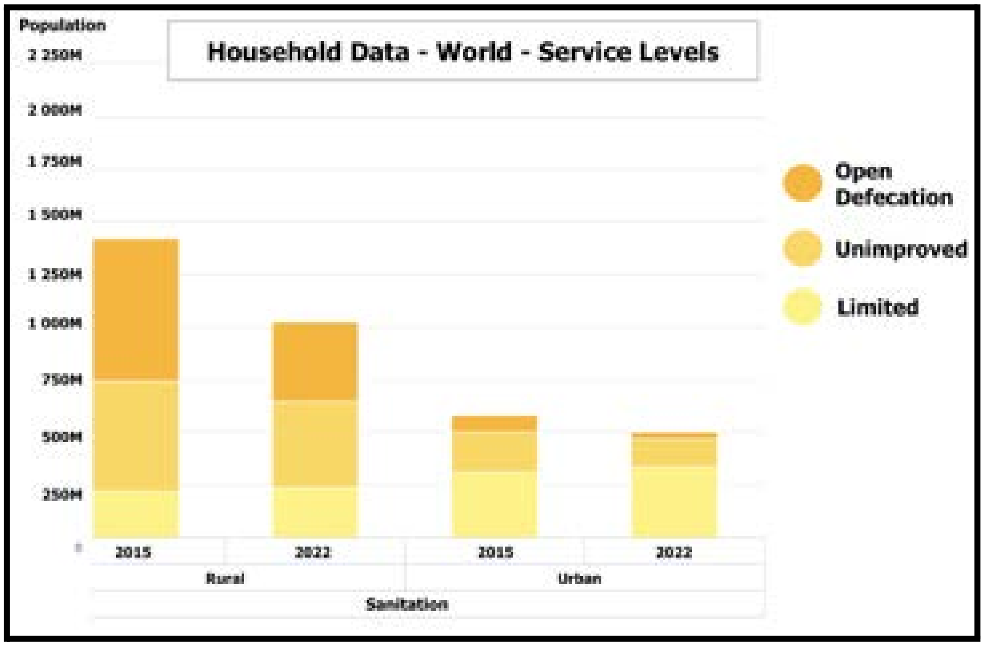


Figure 1. A global spatial distribution of (A) the number of municipal wastewater treatment plants given the country and (B) GDP per capita (US dollar per person) of countries around the world. Countries with lighter coloring indicate the greatest number of municipal wastewater treatment plants (A) and highest GDP per capita (B; Adhikari & Halden, 2022).

There is a direct correlation between countries with higher GDP per capita and number of wastewater treatment plants (Figure 1). Generally, higher-income countries have more municipal wastewater management systems. Despite recent strides by global governments and communities to improve domestic sanitation conditions, efforts to eliminate the disparity in wastewater management systems must continue.

According to data from WHO and UNICEF, the number of households globally that had to resort to open defecation reduced from 750 million in 2015 to under 500 million in 2022. Additionally, the number of households that stagnated, neither improving nor worsening in sanitation levels, reduced from about 730 million to 170 million (Figure 2). There is an increase in overall sanitation conditions for both rural and urban regions worldwide, and is primarily the result of increasing accessibility to wastewater treatment technology in developing areas.

Figure 2. The sanitation trends of domestic households in rural and urban regions for the years 2015 and 2022. Open defecation (worst sanitation), unimproved (medium sanitation), and limited improvement (decent but not ideal sanitation) are represented by dark orange, dark yellow, and light yellow segments, respectively (WHO, UNICEF, 2022).



There are two main types of wastewater management systems: centralized and decentralized. Of these two, centralized wastewater management systems are more expensive and inaccessible. The cost of these systems is higher because of the pumps, piping materials, and energy required for optimal function. Thus, their uptake in impoverished parts of developing countries is unlikely (Massoud et al., 2009). Additionally, technical expertise is required to effectively operate the machinery in centralized plants. While this provides jobs, it also costs governments more money (U.S. Bureau of Labor Statistics, 2023).

While centralized wastewater management is still uniquely accessible for more wealthy communities, decentralized wastewater management systems are gaining in popularity in developing countries because they are easily accessible, reliable, and consume far less resources–particularly funds (Akpan et al., 2020). Communities with financial limitations benefit from the fact that these treatment plants are only constructed as needed (Massoud et al., 2009). Fundamentally, decentralized systems promote a more sustainable and economically viable approach to wastewater management because they encourage the treated wastewater to reenter the original watershed, all while keeping expenses low. To better understand wastewater management systems in developing countries, this paper will focus on what factors make wastewater management a public health and environmental necessity, the different wastewater management options for regions of varying socioeconomic status, and how society must circumvent the barriers to improving wastewater management processes.

Section 1: Why Is Wastewater Management A Public Health And Environmental Concern?

Untreated domestic wastewater poses severe threats to the health of both humans and the environment. When raw wastewater reaches people and wildlife, a wide array of health and environmental consequences can occur. To minimize these negative effects, a timely identification of the specific type of wastewater contamination should be conducted.

Types Of Wastewater And Associated Human Health Concerns

Domestic wastewater is released as blackwater or greywater. Blackwater consists of wastewater generated by the toilet, and greywater is composed of wastewater from bathing, dish-washing, and laundry. Exposure to blackwater versus greywater can result in starkly different side effects because of their differing contents. The primary components of blackwater are raw excreta and flush water, and therefore this type of wastewater must be handled with extreme caution (Penn et al., 2018).

Fecal matter is a vector for the spread of harmful pathogens, particularly viruses that are resistant to basic disinfection methods. The most common viral strains found in untreated blackwater are norovirus, adenovirus, rotavirus, ebola, and most recently, coronavirus (Elsamadony et al., 2021). The effects of these illnesses are wide-ranging, with some causing respiratory system failure or severe gastrointestinal issues. Viruses are not, however, the only organisms found in blackwater. Bacteria, protozoa, and helminth (parasite) eggs can also present significant health concerns if no treatment is administered. While most bacterial infections can be targeted with antibiotics (Giamarellou, 2010), the cure for helminths is much less simple as each species requires a unique array of medicines (WHO, 2023b). While some of these diseases can be confined to a single host individual, many of them are highly transmissible and can spread easily in more densely populated areas through blackwater ingestion (WHO, 2023a).

Blackwater that is left untreated for long periods is further concerning. When blackwater accumulates and stagnates, it can attract insects such as mosquitoes to breed. Mosquitoes are known to propagate diseases such as malaria and dengue fever, which can be detrimental to small, rural communities with limited access to proper care (Cisneros, 2011). Results from studies conducted in several African countries affirmed this correlation, as countries with unprotected water or no sanitation facilities exhibited higher malaria prevalence than those with protected water or basic sanitation facilities, such as flush toilets (Figure 3).

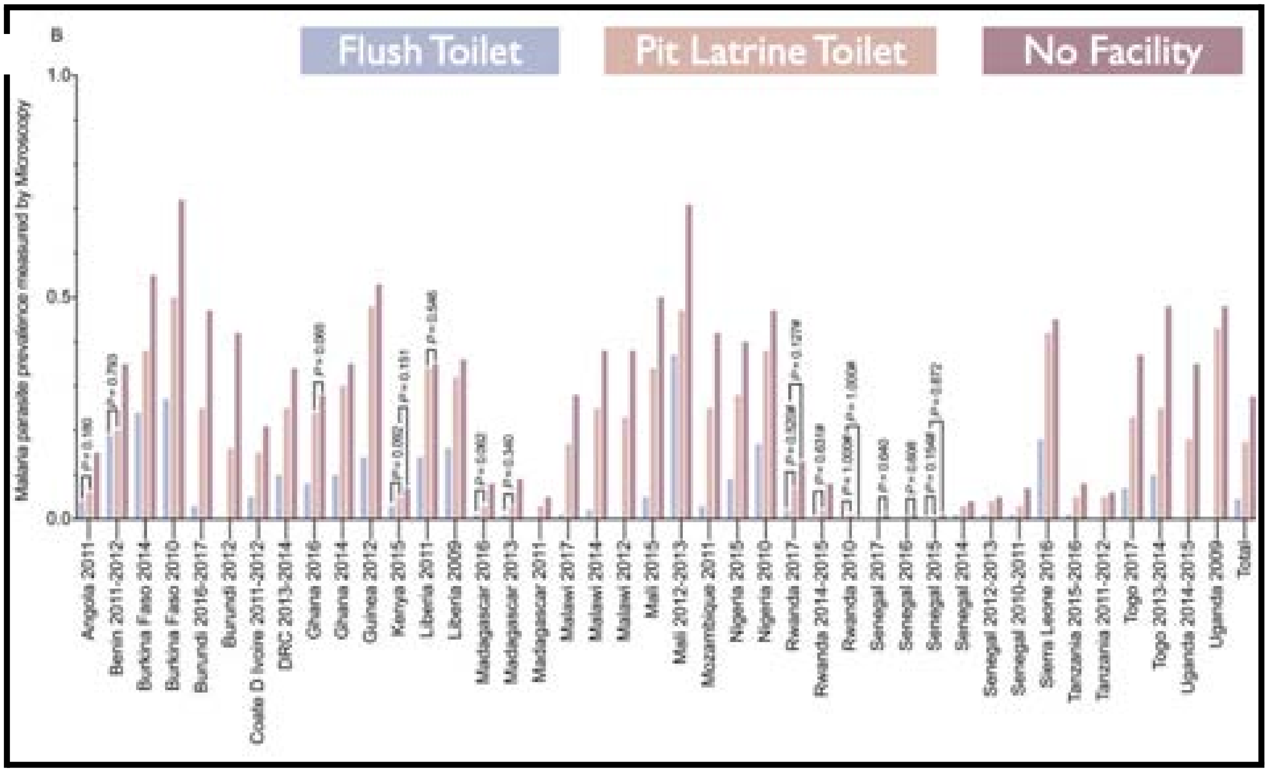


Figure 3. The prevalence of malaria infection in drinking water and sanitation users identified by microscopy for different national surveys. The y-axis represents the fraction of malaria infections for a given country identified by microscopy and the x-axis lists African countries (Yang et al., 2020).

The other component of domestic wastewater, greywater, varies in content depending on the lifestyles of residents. Common contaminants of greywater include acidic and alkaline substances, suspended solids, oil, grease, toxic metals, synthetic chemicals, nitrates, and phosphates, with most of these elements originating from products such as body lotion and hair dye. Emerging pollutants such as endocrine disruptor compounds and personal care and pharmaceutical products (Cisneros, 2011) also pose a serious threat to the goal of recycling greywater and using it as a source of drinking water (Rakesh et al., 2020). Endocrine disruptors are chemicals that essentially trick natural hormones into executing their routine functions incorrectly, and without treatment, these chemicals can cause adverse health effects such as cancer, immune system dysfunction, and impaired thyroid activity (Cisneros, 2011).

While the composition of greywater depends on individual lifestyle choices, greywater from most developed countries generally contains traces of soap, detergent, and cleaning agents (Gross et al., 2015). These substances can be harmful if ingested as they contain a host of strong chemicals that can disrupt the membranes of cells in the body, which can lead to more life-threatening issues such as organ failure (Wang et al., 2019). Heavy metals can also end up in greywater via the breakdown of jewelry, cutlery, arts-and-crafts materials, dental fillings, etc., although in very low concentrations. Because their prevalence in greywater is practically nonexistent, heavy metals only pose a serious concern when the pH of the greywater is low, as it may result in the metals dissolving in the wastewater and turning it into a poisonous mixture (Gross et al., 2015).

Environmental Concerns

Developing adequate wastewater treatment practices is not only crucial to mitigate public health concerns, it also impacts the health of the environment. Untreated wastewater disturbs habitats around the world, but is particularly damaging in coastal regions. In most coastal cities, the final disposal site of wastewater is the ocean. While new technologies have been designed to mitigate water pollution that can result from depositing blackwater and greywater into the sea, recent intensifications in anthropogenic activity have rendered many of these advancements insufficient (Zhang et al., 2020).

Wastewater disposal into the ocean can have strong repercussions on local ecosystems and wildlife. Sludge deposits can cause fatty oils to float on the surface of the water, resulting in sea floor-dwelling plants receiving inadequate amounts of sunlight to perform photosynthesis and grow. Additionally, toxic particles (partially disintegrated from wave movements) can be ingested by aquatic organisms, leading to bioaccumulation of harmful substances and subsequent, detrimental disruptions to food chains (Ramalho, 2012).

Eutrophication, the biological effects on aquatic ecosystems from an increase in nutrient concentrations, is also a cause for concern (*What Is Eutrophication?,* n.d.). Raw sewage is similar to enriched fertilizers, as it has high levels of nitrogen and phosphorus. When vast amounts of those nutrients enter a body of water, plants proliferate, creating a more turbid aquatic environment. Water deoxygenation is another ramification of eutrophication: as plant populations grow rapidly, more oxygen is consumed and less is available in the surrounding water. Additionally, algal blooms originating from an overabundance of nutrients can create dead zones, exacerbating wildlife living conditions (Breitburg et al., 2018).

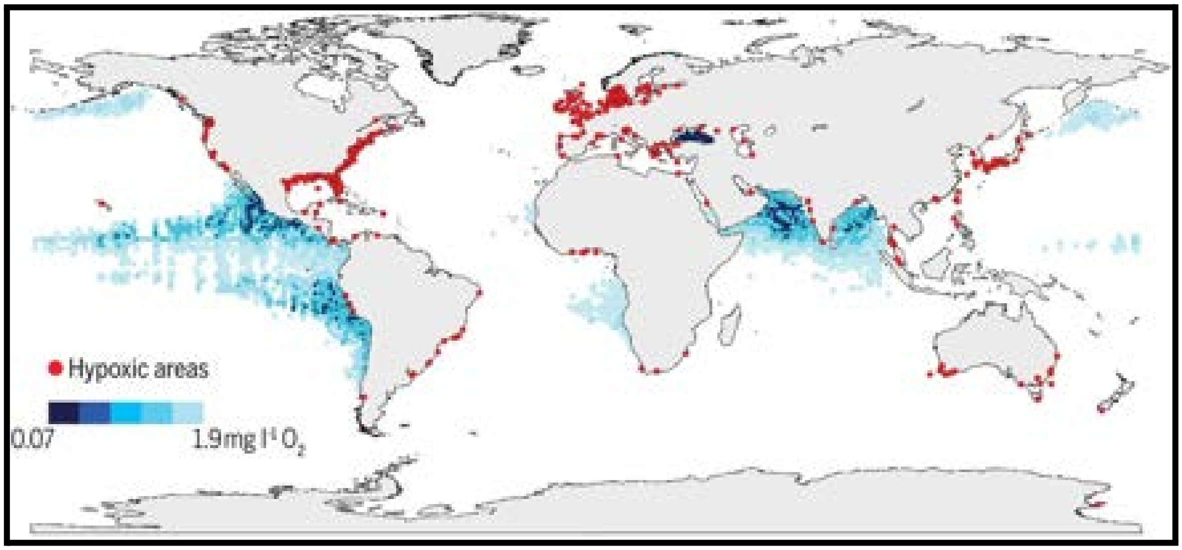


Figure 4. Declining oxygen levels in the open ocean and coastal waters affect environmental and societal processes globally. The map indicates coastal sites where nutrients derived from human activities have worsened oxygen declines to < 2 mg/Liter (< 63 µmol/Liter) (red dots), as well as oxygen-minimum zones at 300 m of depth (blue regions; Breitburg et al., 2018).

When wastewater is released into the sea, people can be indirectly affected. Ocean regions in which wastewater is carelessly deposited can turn hypoxic, meaning they lack oxygen. Surrounding marine wildlife can suffocate due to low oxygen levels, affecting those who rely on those organisms for survival (Figure 4). Around 810 million people globally depend on the ocean as a source of food and employment, 95% of whom live in developing countries. Wastewater disposal into the sea can cause fish populations to decline, and people who rely on them may lose food security and struggle to provide for their families (Taylor et al., 2019).

Section 2: How Do Existing Wastewater Management Options For Regions Of Different Socioeconomic Status Compare?

While domestic wastewater treatment is necessary for people around the world, it is not universally accessible. As the global population climbs, the disparity between wastewater management systems in developed versus developing countries increases. Wealthier countries are rapidly inventing new technologies to treat and recycle increasing levels of wastewater. While developing countries are battling the same issue, the key differentiator is that these countries do not have the required funding and specialized personnel to design collection infrastructure and treatment facilities (Unuinweh, 2021).

Centralized Wastewater Management

Centralized wastewater management systems are at the forefront of wastewater treatment issues for developing countries as they cost an exorbitant amount to design, install, and operate when compared to cheaper decentralized management systems (Massoud et al., 2009). Centralized wastewater systems work by collecting wastewater from households and local commercial areas and transporting the mixture to a wastewater treatment plant, where it is processed and finally redistributed to all types of institutions. A costly part of centralized wastewater management processes takes place in the treatment plant. Plants that receive sufficient funding on a consistent basis will often exhibit more advanced and effective treatment technologies, such as mechanically-accelerated chlorination exposure and strong filters. There may even be a Sixth Water Factory, wherein polyaluminium chloride coagulation-sedimentation processing is completed in order to reuse the wastewater after treatment. Importing and maintaining such equipment is a substantial cost sink for communities (Liang & van Dijk, 2012). Historically, centralized systems constructed in developing countries have only worked in the short-term due to the lack of funds needed to cover operational costs and community resolve to maintain the complex facilities. People with financial limitations have shown reluctance to building centralized wastewater management systems because they are often asked to pay operation and maintenance costs, as well as some of the capital costs (Mac Mahon & Gill, 2018).

A common shortcut taken by policymakers in developing communities is acquiring cheap materials and employing local residents to build the facilities. This often results in system failures, as low-grade material typically yields low-quality products. On another note, inadequate training to construct such facilities can negatively affect equipment function and may present serious health risks in areas lacking preexisting support (Cisneros, 2011).

Beyond unfeasibly high costs and low technical expertise in machinery operation, factors such as topography and climate should also be considered when constructing wastewater management systems. For example, Lima, Peru, is prone to severe hydro-meteorological and geological events such as downpours, burst river banks, mudslides, tsunamis, and earthquakes, which has led to the failure and collapse of centralized wastewater treatment plants throughout the densely populated city (Vázquez-Rowe et al., 2017). To mitigate damage to expensive plant infrastructure, Lima is currently shifting towards a more economically-sustainable decentralized concept, which achieves the same goal while reducing needed equipment and subsequently, cost (Figure 5). Included in this model are aerated lagoons–flexible, suspended growth systems that show high tolerance to sudden loads (Godini et al., 2021).

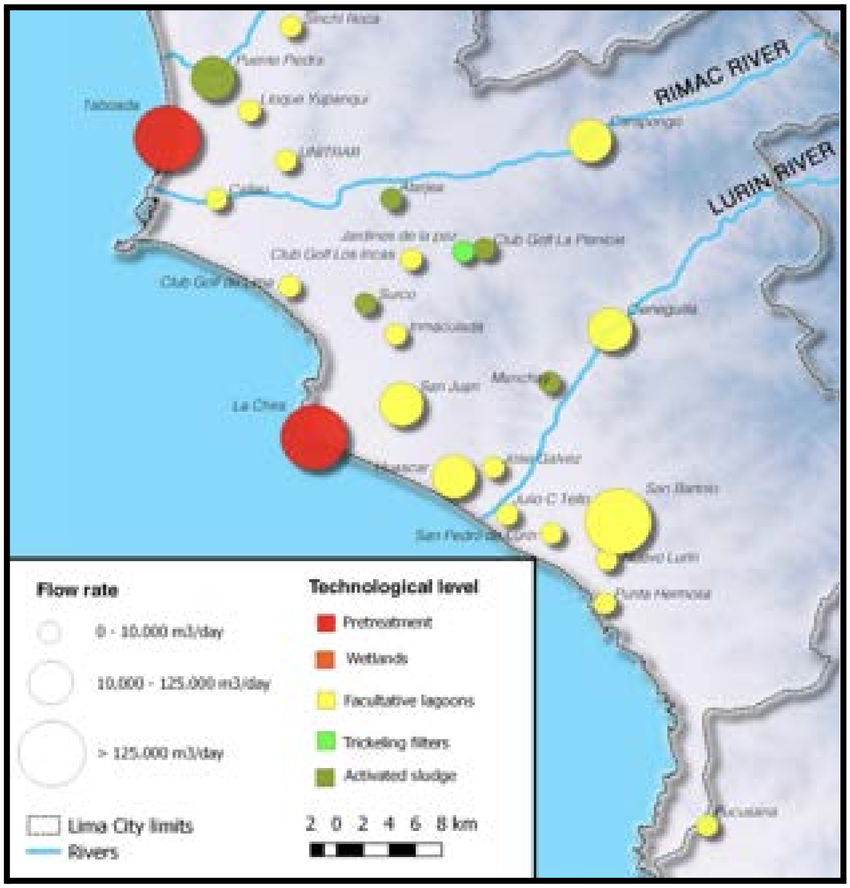


Figure 5. Wastewater treatment plants in Lima by type of technology and relative size. Facultative lagoons, aerated lagoons, and combined aerobic/anaerobic lagoons represent roughly 10% of wastewater treated (Vázquez-Rowe et al., 2017).

Decentralized Wastewater Management

There are three integral steps in any wastewater management system: collection, treatment, and disposal. The collection phase typically covers around 60% of the total cost for wastewater management in centralized systems, especially for more dispersed communities (NC State Extension, 2015). In decentralized wastewater management processes, however, the collection step is minimized and central focus is placed on treatment and disposal. For this reason, decentralized wastewater management systems are beneficial for communities that are rural, small in both population and area, and need to conserve funds.

Septic tanks are the most common form of decentralized wastewater management because they are relatively inexpensive and simple to control (Massoud et al., 2009; Figure 6A). These storage units, positioned underground, act as reserves for raw wastewater. High-density solids sink to the bottom of the tanks and become sludge while lighter solids and grease float to the surface as scum. The remaining water, effluent, is then discharged to a local drain field or wastewater treatment plant (EPA, 2023).

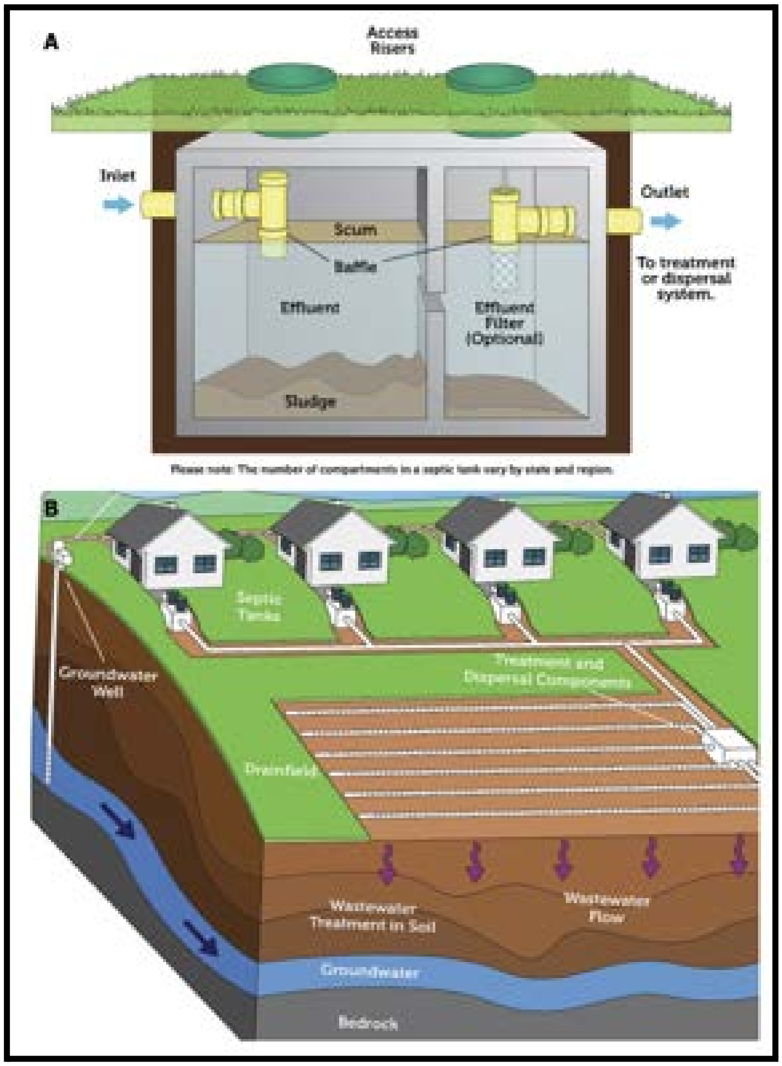


Figure 6. (A) A cross section of a traditional septic tank that shows the separation of raw wastewater into scum, effluent, and sludge, and the motion of effluent discharge from the septic tank to a treatment plant. (B) View of a cluster septic system. Individual septic tanks separate out the effluent, which is redirected through a series of pipes to a communal treatment plant. Some of the effluent is guided to a drainfield or to soil for nutrient absorption (EPA, 2023).

Another form of decentralized wastewater management is the cluster community system (Figure 6B). This process essentially matches the septic tank system, but is scalable to serve an entire community. Here, wastewater from multiple households is collected and redirected to a treatment plant through a series of underground pipes (EPA, 2023).

The importance of constructing these foundational wastewater management facilities cannot be overstated, especially for low-income communities with low access to quality healthcare and the impending threat of water scarcity, worsened by climate change (Cisneros, 2011). That said, while this new process is revolutionary for many developing countries and rural regions, it comes with its fair share of concerns. Septic tank systems, typically used as onsite wastewater treatment, are notoriously known for inadequate containment. Despite their brick-and-mortar construction and efforts to water seal their bases, septic tanks often leak sludge into their surrounding environment. A septic tank operating underground with a sludge leak can contaminate clean groundwater, introducing harmful pathogens and substances into the groundwater which routes directly into drinking water sources (Cisneros, 2011). This can be detrimental for communities that already lack proper health services.

Section 3: What Are Some Barriers For Wastewater Management Implementation In Developing Countries And How Can We Circumvent Them?

In order for developing countries around the world to receive adequate wastewater treatment, social, technological, political, and economic barriers must be broken. The social rejection of proposed systems, problematic legislation, and lack of funding to build functional and durable facilities have all contributed to the inaction shown by communities and governments in developing countries around the world in designing wastewater treatment plans. In order to circumvent these challenges, information transparency, policy adjustments, and increasing funding must be prioritized.

Social Acceptance

The acceptability of reclaimed water usage for non-potable purposes is a hurdle society has failed to overcome. The “yuck factor,” the instinctive revulsion people have for reclaimed wastewater, has hindered the implementation of wastewater reclamation systems in countries all over the world (Garcia-Cuerva et al., 2016). Wastewater reuse has historically been associated with disgust from the public in part due to labeling with inadvertently negative connotations. For example, “recycled water” has elicited greater approval from the public than “treated wastewater,” and “purified water” is preferred to “recycled water” (Wester et al., 2015). In the United States, case studies regarding public acceptance of reclaimed wastewater for residential application such as food crop irrigation were conducted in areas of low socioeconomic status, and it was determined that financial incentives influenced more families to get involved in water reuse programs, as long as the water was not used for crop irrigation or within the residences. This is indicative of the underlying reluctance to ingest reclaimed wastewater (Garcia-Cuerva et al., 2016).

For communities dealing with problems of water scarcity, public acceptance of reclaimed wastewater is a huge relief because these regions may not have a choice in the future but to incorporate reclaimed water into their lives. Numerous case studies conducted in rural, low-income regions around the globe have demonstrated that a large percentage of residents, especially farmers, have expressed a willingness to reuse treated wastewater for agricultural purposes. In a small town in Italy, farmers were eager to use previously discarded wastewater as a means of fertilizing their crops (Saliba et al., 2018). Countries with lower socioeconomic standing in the Middle East have also shown a high acceptability of recycled wastewater for crop irrigation, likely due to the higher-than-average awareness of limited water resources (Akpan et al., 2020). Likewise in South Africa, which has decreasing freshwater availability and correspondingly high water demands, wastewater is being reused for non-potable services such as landscape irrigation and other industrial processes (Adewumi et al., 2010).

In the last 15 years, funding for elite wastewater reclamation research programs has been streamlined, although despite technological advancements that have ensued, such as the recovery of biogas from treated wastewater, communities worldwide have shown little interest in such endeavors. Intent on securing funding, some corrupt institutions have falsified their lab findings to ensure the alignment of research results from different experiments (Soares, 2020). Any leakage of this to the public can cause communities to have little trust in wastewater management authorities.

While widespread social acceptance of reclaiming wastewater for applicability in developing countries remains a work in progress, a crucial method to circumvent this barrier is to simply inform the public about wastewater management systems: an overarching view of how they function, why they are important to the overall health of communities, and why their expense is worthwhile (Figure 7).

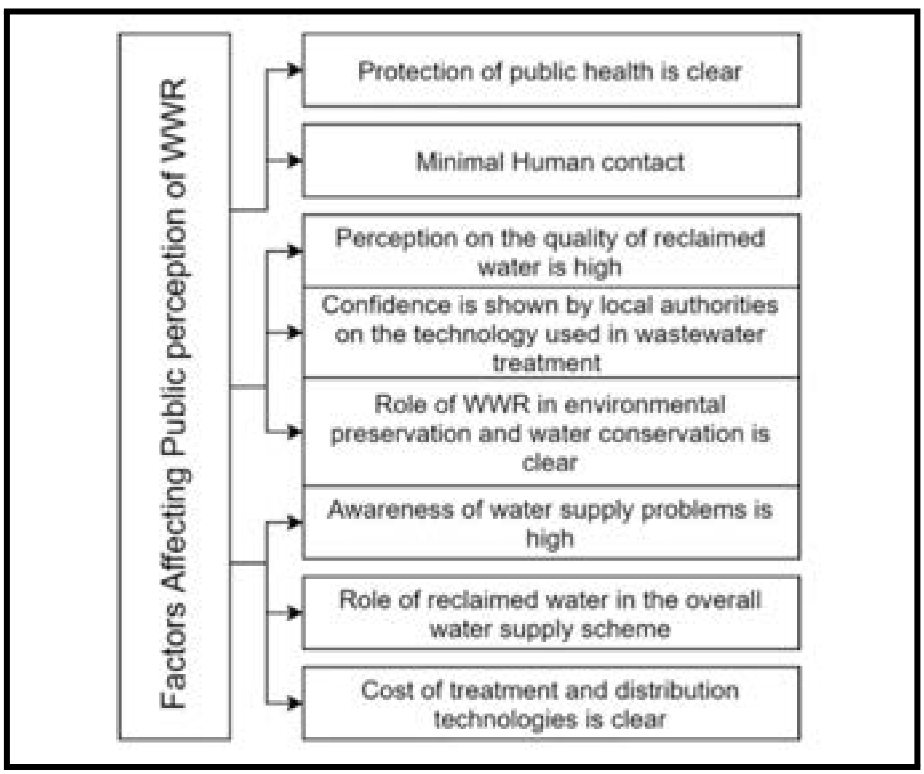


Figure 7. Social, technological, environmental, and economic factors that affect the public perception of recycling treated wastewater (Akpan et al., 2020).

Another way to forge trust between skeptical community members and wastewater authorities is to engage in fair procedures such as routine consultations with the community and to provide accurate information about current and upcoming projects. When plans are transparent, the shared goal of safe reclaimed wastewater integration is made more attainable and water authorities boost their credibility (Ross et al., 2014).

Altering Policies And Removing Legislative Barriers

Public resistance to wastewater reclamation projects has rendered past ventures ineffective (Adewumi et al., 2014). In regions where wastewater management is not encouraged by the community, policymakers must take into account factors that made previous efforts to construct wastewater treatment systems unsuccessful, such as the lack of social acceptance and treatment plant cost. The responsibility to design perception appraisals before establishing policies that do not align with the public's ideals and subsequently fail lies with government officials (Akpan et al., 2020).

A novel concept gaining in popularity worldwide is the circular economy and its applicability to improving wastewater management systems in developing countries. Circular economies align with the present focus on water sustainability. They are closed loops, meaning that energy, system resources, and materials are used multiple times with minimized processing (Sgroi et al., 2018). With the ideals of sustainable water reuse and resource recovery, it takes on a holistic approach to the problem of wastewater recycling and addresses it by looking at political-decisional, social-economic, environmental, and technological factors (Figure 8).

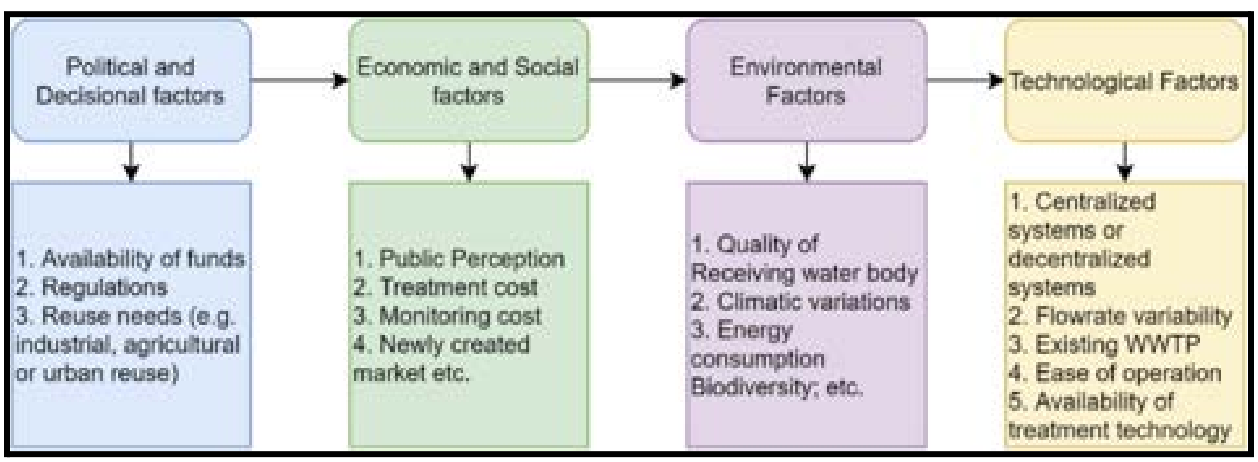


Figure 8. The holistic approach to making wastewater reclamation more appealing to the public. Political and decisional factors (blue), economic and social factors (green), environmental factors (purple), and technological factors (yellow) are all considered as part of this strategy (Sgroi et al., 2018).

With more countries following the circular economy paradigm model, legislative policies regarding inadequate wastewater management practices in developing countries are adapting, but not quite to the extent that these regions need. For small decentralized systems, there are noticeable gaps in clear legislation regarding regulatory framework, institutional support, and financing plans. While water tariff structures cater to urban environments with larger utilities, smaller communities must find their own solutions using local services (Cipolletta et al., 2021).

Regulation of wastewater treatment plans appears to be one of the most commonly cited shortcomings by developing countries. Poorly devised frameworks and excessive bureaucratic policies have driven many potential wastewater treatment projects set up in low-income areas into the ground (Morris et al., 2021). In Colombia, regulation of wastewater practices was downscaled at technical offices and water quality standards were not met, leading to the failure of the treatment plan (Jiménez Contento et al., 2018). There is also the concern of lacking the resolve to uphold regulations (Morris et al., 2021). In Kuwait, regulations regarding wastewater reuse were neither emphasized nor followed, and as a result, the wastewater recycling project was unsuccessful. For areas like Kuwait which are arid, water scarcity is a significantly more severe issue. Thus, the plan to conserve water by simply authorizing a regulatory structure should not be trivialized (Aliewi et al., 2017).

Increasing Funding To Support Wastewater Management Systems

One of the most common reasons for low-income regions having insufficient wastewater management practices is the unavailability of funds (Massoud et al. 2009). A possible solution to this issue is for governments and community leaders to focus on less expensive technologies in order to achieve the same goal of treating wastewater. Instead of the modern decentralized systems, low-income regions should consider implementing constructed wetlands. This nature-centered invention is beneficial to developing communities because they are simple to build, operate, and manage, and are cost effective. A variety of plant species and soil types specific to a given region are used to treat wastewater at various stages in the management process. For example, while some constructed wetlands serve to absorb effluent discharge (tertiary), others exist to separate sludge and effluent (primary and secondary; Haberl, 1999).

Another method to circumvent a lack of funding to design, operate, and maintain wastewater treatment plants in developing communities is to invest in research. Although it seems futile given the preexisting absence of money to develop these systems in the first place, putting funds into research programs can be beneficial for low-income communities in the long run because it can assist in finding alternative solutions to their wastewater treatment problems (Morris et al., 2021). A prime example of how the benefits of investing in research can outweigh the initial con is the creation of constructed wetlands, which are both easy for locals without technical expertise to operate and regulate as well as inexpensive to implement (Kivaisi, 2001).

Conclusion

The differences in domestic wastewater treatment between high and low-income countries is stark. Wealthier countries possess technology, such as intricate and expansive centralized wastewater management systems, resources to train the public and create jobs, and sufficient funds to build, operate, and maintain facilities. In general, developing countries struggle to obtain all of these things, forcing dependence on decentralized wastewater management systems (Figure 9).

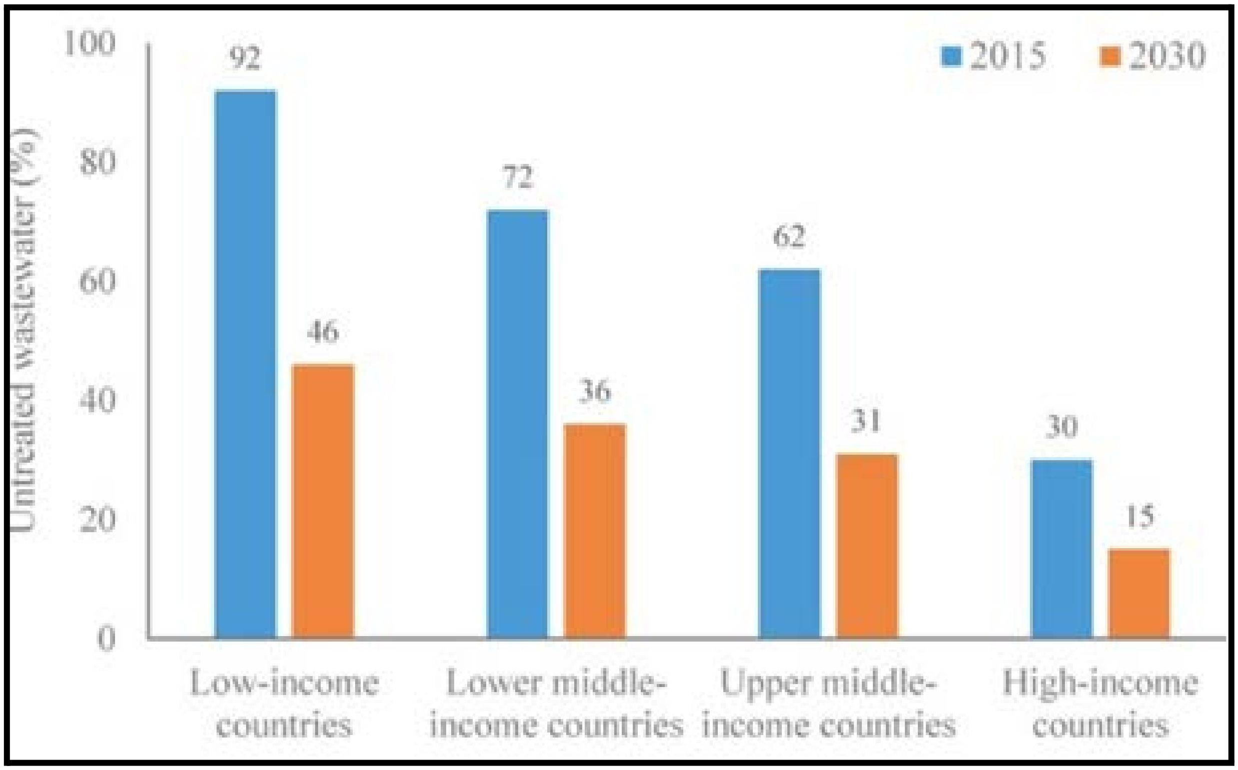


Figure 9. Percent of untreated wastewater for countries of varying socioeconomic status in 2015 (blue) and the predicted percentages for 2030 (orange). The percent of untreated wastewater for low-income countries is consistently higher than that for countries with increasing income, in 2015 and predicted as well in 2030. However, the percentage of untreated wastewater for both high-income and low-income communities appears to decline from 2015 to 2030 (Khalid et al., 2018).

Many decentralized wastewater management processes have worked for low-income regions due to their cost-effectiveness and reliability. The most important factor to ensure this trend of acceptance continues is to maintain channels of project transparency between wastewater management authorities and the public. Equipped with the knowledge of what can ensue in areas with inadequate sanitation conditions, such as the contraction of serious diseases, people are more willing to accept proposed wastewater treatment systems, even if they cost time, effort, and funds. Treating domestic wastewater in low-income regions is not an easy or quick goal, but it is a tangible one. It is one that will require the collaboration of communities and their governments and an open mind to technological alternatives to ensure water safety for all.

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