Integrated advanced oxidation processes (IAOP) for city water sanitation

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Key Messages

- Insufficient wastewater treatment (WWT) in developing cities has negative impacts on the environment and human health, such as waterbody pollution and the transmission of waterborne illnesses.
- Compared to overhauling existing systems, retrofitting integrated advanced oxidation processes (IAOP) into existing wastewater treatment systems (WWTS) provides an effective solution to improving WWT quality and efficiency, especially in terms of cost and energy.
- Policymakers are recommended to consider formulating policies targeted at the implementation of IAOP into existing WWTS in developing countries.
- Benefits of retrofitting IAOP in WWTS are explored with the help of scenario analysis.

Introduction

In response to the health concerns posed by the COVID-19 pandemic, the need for proper sanitation and wastewater treatment (WWT) has become apparent in cities. An increase in water usage and the demand for safe potable water in cities of middle- to high-income countries has increased wastewater production.[1] **Wastewater** can be defined as domestic effluent consisting of blackwater (excreta, urine and faecal sludge), greywater (used water from washing and bathing), and water from commercial and agricultural establishments and institutions (see Annex 2 for glossary).[2] Ideally, WWT removes biological and chemical contaminants to meet **surface water quality standards** or **discharge standards** (parameters for safe water bodies) before it is discharged back into the environment.[3] This is relevant in the face of COVID-19, as pandemic "hotspots" were largely linked to populations in **cities of developing countries** in which wastewater discharge did not meet these standards.[4] This has environmental and health implications, such as waterbody pollution, the production and discharge of toxic sludge, and an increased risk of infection and transmission of waterborne illnesses.[1,3,5–7]

On average, upper-middle-income countries treat approximately 38% of their generated municipal and industrial wastewater while lower-middle-income countries treat only 28%. Such lack or insufficient treatment of wastewater is categorized by the inability of wastewater treatment systems (WWTS) in developing countries to eliminate the minimum required pollutants and/or pathogens as is required by surface water quality standards.[8] This insufficiency in developing countries is often due to basic WWTS infrastructure, unreliable electricity sources which disrupt WWT processes, and untreated industrial wastewater entering municipal WWTS.[9,10] However, integrated advanced oxidation processes (IAOP) could help to mitigate the environmental and health challenges imposed by such insufficient treatment of wastewater.

IAOP is an emerging technology that can be **retrofitted** into existing WWTS and is comprised of a three-step purification process that produces high-quality water output in a cost-effective and energy-efficient manner.[11] The first step of IAOP, or the primary treatment stage, consists of highly efficient **coagulants** and **flocculants**. The secondary treatment stage uses UV-TiO_2 photocatalysis for the advanced oxidation process while the tertiary treatment stage utilizes reverse osmosis (RO). The UV-TiO_2 photocatalysis and nanomembrane filtration distinguishes IAOP from other WWT technologies [see Annex 3]. These aspects of the technology enhance water quality output and reduce the production of toxic sludge while doing so with relatively less energy input.[11–13] As such, this brief aims to explore how IAOP could address the environmental and health implications of city water sanitation in the context of cities in developing countries.[14]

Environmental and Health Implications of Insufficient WWT

As of 2017, "Two-thirds of the world's population...live in areas that experience water scarcity for at least one month a year. About 500 million people live in areas where water consumption exceeds the locally renewable water resources by a factor of two."[1] By way of flooding and droughts, water scarcity has been exacerbated by climate change and human activities.[1] Thus, water quality output of WWTS is crucial as it optimizes the ability for water reuse and facilitates a circular water system in which WWTS discharge is treated and safe water is put back into natural water resources (i.e., rivers, lakes, etc.). This allows for reduced stress on water resources which increases water availability to regions where water scarcity is prevalent.

Table 1. Features of Conventional WWTS versus IAOP [See Annexes 2 and 3]

KEY FEATURES	CONVENTIONAL WWTS	IAOP
Requirements for System Updates	Total Overhaul	Retrofit
Elimination of Parasites & Pathogens	Low Efficiency	High Efficiency
Energy Efficiency	Low Efficiency	High Efficiency
Implementation & Maintenance Costs	Expensive	Affordable
Amount of Sludge Produced	High Amounts	Low Amounts
Level of Contaminants *(includes heavy metals, toxins, & pathogens)*	High Levels	Low Levels

Harmful sludge and effluents, including industrial chemicals, agricultural pesticides, and contaminants of emerging concern (CECs), such as pharmaceuticals and personal care products (PPCP's), cause **eutrophication** (nutrient accumulation), the destruction of aquatic environments, and human exposure to toxic substances.[3,7,8] Sludge is the by-product of each WWT stage. Its components include biosolids, pathogens, microbes, and chemical contaminants.[15] Sludge can be reused as plant fertilizer or to produce energy that can be added to the areas' energy grid. However, sludge has a high microbial content and low heavy metal content, meaning that it cannot be directly reused and must be processed before use. In most developing countries, a large percentage of sludge is not processed, leading to it being disposed into landfills or incinerated.[6]

The accumulation of toxic organic and inorganic chemicals from sludge and municipal, agricultural, and industrial wastewater seeps into groundwater, leading to the leaching of contaminants into drinking, industrial, and agricultural waters. Not only does this affect aquatic environments, but also human health.[8,16] According to the UN,[7] **"safe" drinking water** is defined as water that is free of contaminants. However, safe drinking water is not always achievable as "...711 million people, over 90 percent of whom live in urban areas, have sewer connections that do not receive the minimum level of treatment ...".[17] Drinking water that does not meet water quality standards decreases water reusability and can result in the spread of pathogens and other waterborne illnesses, including diarrhoea, intestinal nematode infections, lymphatic filariasis, schistosomiasis, and more.[6,7]

Proper management of wastewater treatment plants (WWTP) could play a role in containing the spread of such illnesses, including COVID-19.[18] Studies show that COVID-19 can remain present in excreta and faecal sludge. When wastewater is not adequately treated and/or when sewage leaks into freshwater resources, the risk of infection increases.[19] "The sufficient disinfection of [WWTP]...and measures such as the prevention of sewage leakage into freshwater resources are essential to reduce human exposure."[19] Therefore, proper wastewater services and sanitation are important as they enable proper disinfection and hygiene practices. This is especially true when it comes to the prevention of waterborne illnesses and COVID-19.[20]

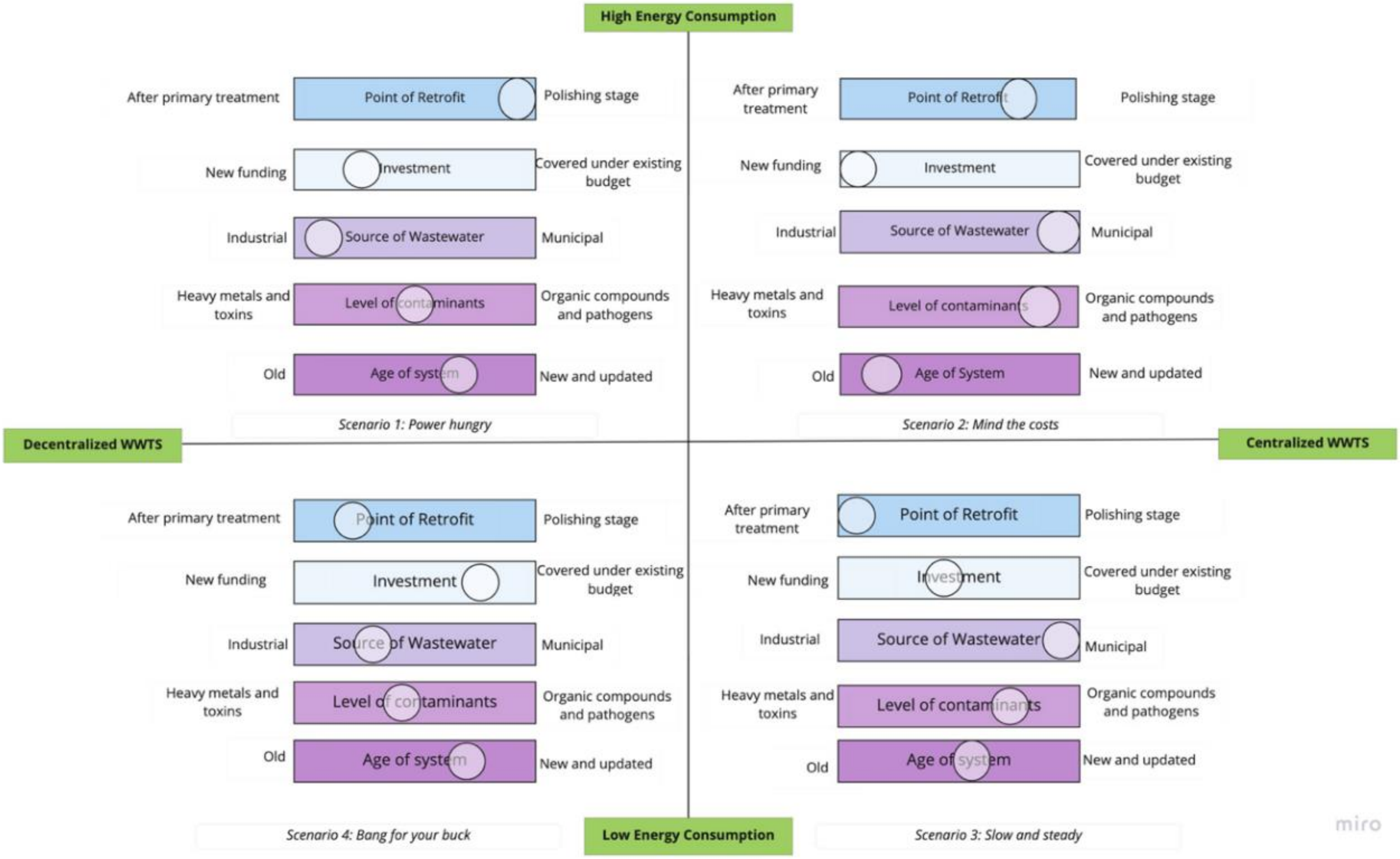
The Future of IAOP

The following thematic scenarios explore future potentials for the implementation of IAOP in cities in developing countries [see Figure 1]. These scenarios highlight drivers (or driving forces) that would play an integral role in these future scenarios [see Annex 6]. The two main drivers of these scenarios include:

End-user Involvement: This defines the level of involvement of individuals/consumers of wastewater and their relationship with treated wastewater. The first, centralized WWTS, are those that have no direct relationship with the treatment of the wastewater or municipal WWTS that only must reach minimal discharge standards for treated wastewater. The second, decentralized WWTS, are those that reuse treated wastewater, such as the industrial and agricultural sectors.

Energy Consumption: The amount of energy that would be utilized to run IAOP depends on whether it is retrofitted into each treatment stage (primary, secondary, and tertiary) or solely after one stage (for instance, the secondary stage).

Figure 1. Scenario Analysis for the Implementation of IAOP in Developing Countries



Scenario 1: "Power hungry", would exert stress on energy supplies and be detrimental to the environment in terms of emissions and energy use. In this scenario, IAOP would only be used as a polishing stage for industrial wastewater treatment. This would not be energy efficient and would also not effectively treat heavy metals and inorganic substances. Therefore, the discharged wastewater, though treated, would still contaminate the environment and impact human health.

Scenario 2: "Mind the costs", deals with municipal wastewater and would more effectively treat wastewater than industrial wastewater. This means that the treatment would be effective in eliminating higher amounts of organic compounds and pathogens. Therefore, discharged water would have less detrimental effects on human health and the environment. However, environmental stress in terms of energy consumption and implementation and operation cost would still be an issue.

Scenario 3: "Slow and steady", would help WWTS meet discharge standards. In the long run, this scenario would improve surface water quality standards of water bodies and would help to restore soil and water nutrients. Likewise, harmful pathogens would be minimized. This scenario would require long term government support in order to be successful.

In Scenario 4: "Bang for your buck", the circular use of water and the environment are at the forefront. Water reuse within industries would reduce heavy metal accumulation caused by discharge and promote the reuse of water in the industrial sector. Since these are newer WWTS they have a good baseline efficiency in terms of eliminating contaminants and would require low levels of investment in terms of maintenance.

Key Policy Recommendations

IAOP have several key features that make it a promising technology. However, this technology has not been retrofitted into many existing WWTS and is still in its pilot phase. As such, several considerations should be taken into account before this technology can be retrofitted into WWTS in cities of developing countries [see Table 2].

Table 2. Considerations for retrofitting IAOP in Developing Countries [See Annex 5]

CONSIDERATIONS FOR RETROFITTING IAOP
The '**Yuck Factor**' People don't want to talk about waste.
Go with What You Know WWTS engineers are hesitant to implement new technologies.
Complex Chemistry High reactivity and non-chemical selectivity of the UV-catalysis stage of IAOP.
Got the Power Sufficient energy supply needed for effectively operating WWTS.

Based on the goal of improving environmental and health conditions of city water sanitation in developing countries, the following is recommended:

- Local and state governments of developing countries should encourage municipalities to implement IAOP as a retrofit into existing WWTS for as a cost-effective way to improve city sanitation.
- Policymakers are encouraged to form mandates for decentralized systems to reuse water as this encourages pre-treatment before the water re-enters the main WWTS.
- Governments should introduce fiscal mechanisms, such as grants, subsidies, and tax incentives, to mitigate the costs of retrofitting and maintenance. Such intervention(s) should be tailored to each individual country and cost, energy and the sophistication of the existing system should be taken into consideration.
- Wastewater engineers and research units should conduct carrying-capacity assessments of discharge-receiving water bodies to aid policymakers in setting more accurate surface water quality standards.
- Scenario analysis shows important considerations for carrying-capacity.
    - Setting and enforcing standards specific to the quantity and toxicity levels of sludge and effluent discharge from municipal, industrial, and agricultural sources.
    - Monitoring and enforcing standards by public bodies, such as local water and environmental agencies and/or authorities.
    - Universal parameters for measuring wastewater, with specific levels of said parameters varying across urban contexts depending on local need.

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ANNEX 1. Consulted Experts

Expert	Institution	Position	Interview Date	Country	Topic
Alabaster, Graham	UN-Habitat	Chief of Sanitation and Waste Management; Urban Basic Services	31-11-2021	Switzerland	Advanced Oxidation Processes
Bahadur, Napur	TERI	Research Fellow & Area Convenor	22-11-2021	India	TERI Advanced Oxidation System (TADOX)
Garcia Tapia, Jose	Constructora RODSA, S.A.	Mechanical Engineer	17-11-2021	Panama	Wastewater Treatment Process
Kujawa, Katarzyna	Wageningen University & Research	Lecturer; Department of Agrotechnology & Food Sciences (Environmental Technology)	23-11-2021	The Netherlands	Wastewater Treatment Process
Saha, Pradip	Wageningen University & Research	Researcher; PhD	19-11-2021	The Netherlands	Advanced Oxidation Processes
Schroder, Fritz	City of Dayton Water Reclamation	Laboratory Supervisor	30-11-2021	United States	Wastewater Treatment Process
Sondhi, Akash	IHFC; Technology Innovation Hub of IIT Delhi	Lead Researcher	23-11-2021	India	Wastewater Treatment Process
Steemers-Rijkse, Irma	Wageningen University & Research	Program Manager; Water Treatment & Technology	29-11-2021	The Netherlands	Advanced Oxidation Processes

ANNEX 2. Glossary

Cities of Developing Countries/Developing Countries: Tier 1 cities in Middle-Income Countries (MIC's) (countries where the Gross National Income ranges from $1,036 to $12,535) with established WWT infrastructure, overlaid with sufficient income to invest in WWTS.[14,21] The application of IAOP's shall be targeted towards these cities in developing countries.

Coagulants: Chemicals that are used to neutralize the charge of particles present in wastewater to encourage the bonding and creation of aggregates.

Conventional Wastewater Treatment Systems (WWTS): Basic wastewater treatment facilities that use traditional primary, secondary, and tertiary stages of treatment. The aim of these systems is to meet the basic minimum standards for wastewater discharge into water bodies.

Discharge Standards: Parameters for safe water bodies.

End-of-Pipe Users: Individuals who use, pay for, or interact with treated wastewater from conventional WWTS.

Eutrophication: Nutrient accumulation in water bodies.

Flocculants: Chemicals that bring together the coagulated aggregate to form larger aggregate which settle at the bottom and can be removed.

Retrofit(ed): The addition of a new technology or feature to an older existing system

Surface Water Quality Standards: Parameters for safe water bodies.

Safe Drinking Water: Water that is free of contaminants.[7]

Wastewater: Domestic effluent consisting of blackwater (excreta, urine and faecal sludge) and greywater (used water from washing and bathing), water from commercial and agricultural establishments and institutions.[2]

Yuck Factor: A phenomenon in the subject of wastewater treatment in which individuals do not like to discuss this topic as it is considered repugnant.[10]

ANNEX 3. Key Features of IAOP

Compared to current conventional WWTS in developing countries, IAOP more efficiently removes higher amounts of toxic and organic chemicals, turbidity (muddiness), PPCP residue, and pathogens. This technology decreases the energy and load input as it "...process[es]...oxidative degradation and mineralization of targeted pollutants..." before the biological/microbial treatment phase of the WWT process.22 Likewise, IAOP decreases sludge output and improves the quality of water output which enables the ability for water reuse.[22]

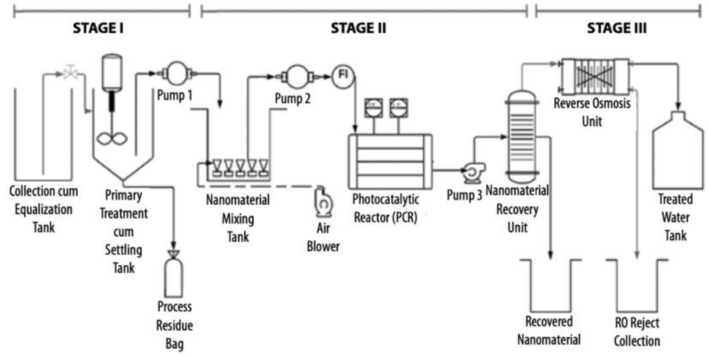


Figure 2. IAOP Schematic

Wastewater is passed through Stage I (the primary treatment stage) where the physical matter settles in the settling tank. Once Stage I is complete, the water passes through a nanomembrane to a photocatalytic reactor. In this reactor, the water is exposed to ultraviolet rays where it reacts with titanium oxide for the oxidation of contaminants. Once disinfection in Stage II (the secondary treatment stage) is complete, the water passes through Stage III (the tertiary treatment stage). This entails the water undergoing reverse osmosis to desalinate the water and further improve water quality to meet surface water quality standards. Finally, the treated water is collected in a reservoir.

ANNEX 4. Methodology

4.1 Content Analysis

Researching literature was the first step to lay the groundwork for the research on wastewater and its treatment. It is through this step that the following was identified:

a) The current status of WWT in MIC developing countries.

b) The health and environmental implications of insufficient WWT associated with water sanitation systems in these cities.

It is through content analysis that IAOP was identified as an emerging technology and, thus, further research was conducted to examine how this technology could potentially address the WWT problems. Other key research topics included WWT technologies for various WWTS, the implications of improper treatment, and disposal of wastewater and sludge.

4.2 Expert Interviews

IAOP is in its pilot stage and thus, published information on IAOP was limited. Additionally, information in the context of cities in developing countries varied. As such, these interviews helped to identify environmental and health implications in these contexts and the barriers to implementation as well as potential solutions.

Interviews were semi-structured and open in nature. This encouraged the interviewees to express their opinions and insights more freely. Each interviewee received an introduction to the project and IAOP. The interviews were conducted by two IEPC consultants; one acted as an interviewer while the other was a notetaker and/or translator. Interviews were recorded and transcribed for future reference.

Interviewees were selected based on varying parameters, including expertise in WWT, advanced oxidation, as well as several other expertise in the field of wastewater. Through these interviews, the current state of WWT, associated health and environmental implications, and IAOP were identified. Additionally, the information gathered in these interviews helped to identify driving forces (or drivers) for the scenario analysis.

Scenario analysis accounts for the complexity and uncertainty of the environment and projects possibilities for the future implementation of IAOP. Scenarios were developed based on the main drivers identified through content analysis and expert interviews. The scenarios are explorative scenarios which had equal chance of occurring, but the implementation of IAOP ultimately lies in the hands of various actors, including policymakers [see Annex 4].

ANNEX 5. Barriers to Implementation

The awareness of **end-of-pipe users** on issues related to wastewater and WWT is low.[9,14] This could be attributed to the fact that people pay for the water that they use and not its treatment.[14]

Energy supply, particularly in the developing country context, can inhibit the effective operation of energy intensive systems, such as WWTS. Although cities have more efficient energy grids than rural areas, WWTS can provide an additional burden on already strained systems. However, if the current trend of moving towards more renewable energy sources continues, contingencies need to be put in place to ensure sustained power supply.[23]

The UV-catalysis stage of the IAOP is not chemically selective and highly reactive and can produce undesired compounds which would show up in the output water. These undesired compounds would then have to be removed subsequently, which would take away from the efficiency of the technology.[21]

Water system engineers, who are responsible for the design and technologies used in WWT, are described as generally being conservative in their decision-making. Resultantly, the implementation of innovative technologies, such as IAOP, can be slow.[23]

ANNEX 6 Scenario Analysis

Scenario analysis was conducted by identifying relevant driving forces and assigning a scale to each driver. Each driver was ranked based on their relevance with reference to expert interviews and content analysis. The most relevant driving forces were chosen and used in the four-scenario axis [see Figure 1]. Finally, narratives for each scenario were conceptualized and a name was assigned to each scenario.

6.1 Drivers

Through content analysis and expert interviews, several drivers were identified and defined:

<u>End user Involvement</u>: This basically defines the level of involvement of the consumer and the extent of their relationship with treated WW. These are of two types. Consumers that have no direct relationship with the treatment of the wastewater or municipal treatment units that only need to treat water to reach discharge standards. The second type is of consumers that also reuse the water treated.

- <u>Decentralized Systems</u>: Decentralized WWTS include industries, hospitals, agricultural units, schools, and offices with WWTS. These systems need to adhere to surface water quality and water reusability standards.
- <u>Centralized Systems</u>: Centralized WWTS include conventional WWT facilities and communities that depend on a common municipal system of WWT. Conventional WWT facilities meet the bare minimum surface water quality standards for discharge and directly affect end-of-pipe users as they use the water output. However, these users tend to be unaware of issues regarding wastewater and WW.

<u>Retrofitting</u>: Retrofitting refers to the addition of a new technology or feature to an older existing system. In case of wastewater treatment plants IAOP can be retrofitted in existing WWT units easily. The point at which the IAOP can be retrofitted into the existing system depends on the source of wastewater, its components, the degree of treatment needed and sophistication of existing biological treatment unit.

- <u>After primary treatment:</u> Ideally the most preferable point for retrofitting would be after the secondary treatment however, there is a possibility that this would vary depending on the existing type of system.
- <u>Polishing stage</u>: All other points of retrofit would be less ideal; however, this still may depend on the existing system type.

Energy Consumption: The amount of energy that would be utilized to run IAOP depends on two factors. A) If an entire treatment system (IAOP) is retrofitted or a part of it. B) if the point of retrofit of the system is most or least preferable.

- High energy consumption: A higher consumption in energy is noted in two cases, a) if an entire system is retrofit b) if the point at which the IAOP is retrofit is not optimum.
- Low energy consumption: A low consumption in energy is noted in two cases, a) if only a small part of the IAOP id retrofit b) if the point of retrofit is most optimum.

Investment: The investment covers the installation, operations and maintenance costs. These costs can be high or low depending on the catalyst used and how frequently it needs to be replenished. The maintenance and replacement of membranes and cost of energy.

- New funding: These costs are attached to a more expensive catalyst. The implementation costs can be high if an entire 3-step IAOP is installed.
- Covered under existing budget: These costs are low if only a part of the IAOP is retrofit. Also, IAOP being more sophisticated it reduces the load on the following treatment systems and thus, frequency and costs of maintenance reduce.

Source of Wastewater: The source of wastewater dictates the types of pollutants that can be found in it and the level of treatment needed.

- Municipal: This is from wastewater from households which usually has faecal and organic content as well as antibiotic, microbial and personal care product residue.
- Industrial: Depending on the industry the wastewater can vary in composition. It usually has a high nutrient and inorganic compound content. The wastewater from hospitals can have high biomedical residues. Wastewater from the textile industry can have high turbidity, colour and organic compound content.

Level of contaminants: Sludge is a by-product of biological treatment of wastewater. Sludge is usually highly toxic and contains high concentration of nutrients, heavy metals, toxins and pathogens.

- Heavy metals and toxins: Found mostly in industrial systems.
- Organic compounds and pathogens: These toxins are found in higher amounts in municipal wastewater.

Age of the System: The age of the system is very important. The older the system the less effective it is due to new emerging pollutants.

- Old and not updated: WWTS are old and have not been updated to include the latest versions of the treatment processes. Fixing IAOP for such systems is more important, easier and cost effective.
- New and latest: For WWTS that have been updated to include the latest treatment for conventional systems it may not be required, important or cost effective to add IAOP treatments.

Relevant drivers for scenarios:

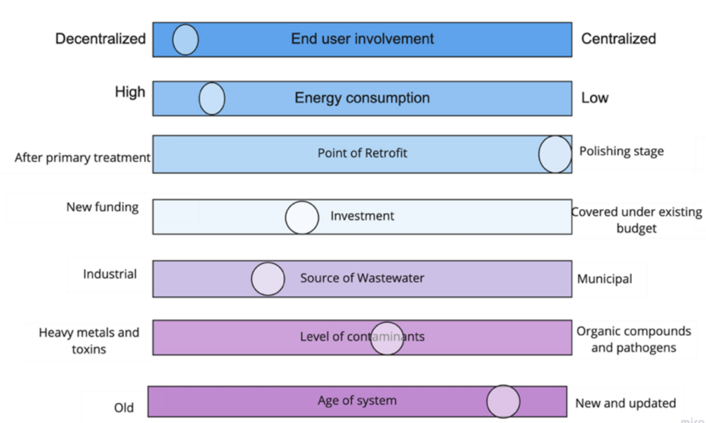
1) End user Involvement

2) Energy Requirement

6.2 Micro Scenarios

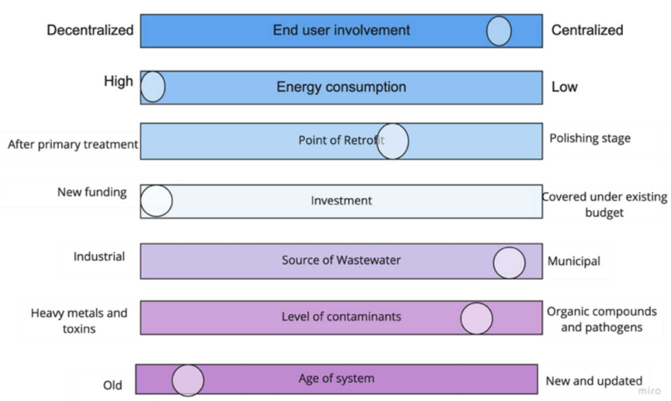
In this scenario, the stage in which IAOP is implemented into existing WWTS could vary. However, the outcome would be high energy consumption. Decentralized WWTS, such as industrial, agricultural, hospital, etc. systems, would not be incentivized to invest in IAOP as high energy consumption would increase maintenance costs and investors would see little financial return. Thus, the environmental impact would be high as decentralized systems would not be incentivized to implement IAOP, causing high energy consumption and lower water and sludge quality output.

Figure 3. Scenario 1: Power Hungry



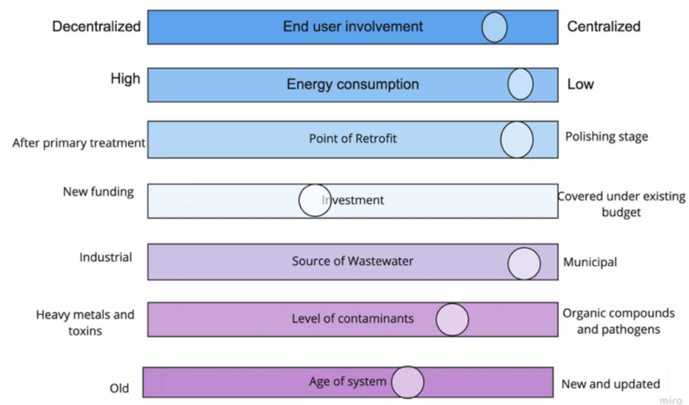
In this scenario, the stage in which IAOP is implemented into existing WWTS could vary. Centralized WWTS, such as conventional municipal systems, would be less incentivized to implement IAOP as they only have to meet bare minimum surface water quality standards and energy consumption costs would be high. The extent of investment would be low as centralized WWTS tend to have less funding than decentralized systems and high energy consumption would increase operational costs. Thus, the environmental impact would be high as centralized systems would not be incentivized to implement IAOP, causing high energy consumption and low water and sludge quality output.

Figure 4. Scenario 2: Mind the Costs



In this scenario, IAOP would be implemented into existing WWTS after the secondary treatment; energy consumption at this point of retrofit is low. Centralized WWTS, such as conventional municipal systems, would be less incentivized to implement IAOP as they only must meet bare minimum surface water quality standards. Investment would be low as centralized WWTS tend to have less funding than decentralized systems.

Figure 5. Scenario 3: Slow and Steady



In this scenario, IAOP would be implemented into existing WWTS after the tertiary treatment; this would be a polishing treatment and can be the point of retrofit where energy consumption is at its lowest. Decentralized WWTS, such as industrial, agricultural, hospital, etc. systems, would be incentivized to investment in IAOP as low energy consumption would decrease operational costs. Likewise, the environmental impact would be low as IAOP would produce cleaner sludge and higher water quality output. This would also lead to a higher rate of water reuse.

Figure 6. Scenario 4: Bang for your Buck