Interdisciplinary Description of Complex Systems 23(3), 250-261, 2025

IMPROVING RECLAIMED WASTEWATER QUALITY IN JORDAN USING THE SIX SIGMA APPROACH

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DOI: 10.7906/indecs.23.3.6
Regular article

Received: 20 February 2024.
Accepted: 1 November 2024.

ABSTRACT

This study analyzed the high rates of (out of specification) samples observed in Jordan and proposed solutions and monitoring practices for sustainable wastewater treatment using the DMAIC methodology, one of the Six Sigma tools. Across its five phases – Define, Measure, Analyze, Improve, and Control – the analysis yielded key findings on addressing high "out-of-specification" samples in wastewater treatment plants (WWTPs) using data from 2016 to 2018. The research revealed that private WWTPs and linked industries exhibited growing non-compliance, while public WWTPs improved over time. Using the fishbone diagram, root causes were identified in five main areas such as outdated equipment, inadequate staff training, inconsistent monitoring, and weak oversight. In the IMPROVE phase, solutions such as enhancing training, monitoring, introducing penalties and incentives were identified and prioritized using an impact-effort matrix, as well as long-term actions such as upgrading treatment technologies were suggested. The CONTROL phase established comprehensive monitoring, real-time adjustments, and periodic audits. This study provides a framework for addressing wastewater quality in Jordan, ensuring long-term regulatory compliance and environmental improvement.

KEY WORDS

wastewater, wastewater treatment, reclaimed water, six sigma, DMAIC

CLASSIFICATION

ACM: G.3, I.6.5

JEL: C8, Q25

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INTRODUCTION

The Sustainable Development Goals (SDGs) were formulated by the United Nations General Assembly in 2015 to address global challenges and promote sustainable development by 2030. They aim to end poverty, protect the planet, and ensure prosperity for all through a shared framework for action [1]. SDGs also play a vital role in the field of wastewater (WW) treatment and reuse by providing a framework for addressing global water challenges. SDG 6, which focuses on clean water and sanitation, highlights the critical importance of sustainable WW management. Achieving SDG 6 not only ensures access to healthy drinking water and proper sanitation but also promotes responsible WW treatment and reuse practices. This is essential for mitigating water scarcity, especially in arid regions, reducing environmental pollution, preserving ecosystems, and advancing public health. It also encourages countries to prioritize efficient WW management as an essential part of their sustainable development. SDG 6 holds particular significance for water-scarce countries like Jordan, which has been facing increasing pressure on its water resources since the 1960s due to rapid population growth, economic expansion, urbanization, technological development, rising water consumption, and changes in precipitation, runoff, and evapotranspiration rates driven by climate change. This has made the search for alternative water resources such as the treatment and reuse of reclaimed WW essential. Consequently, Jordan has started utilizing treated WW as a water source in certain sectors, and today properly treated WW sustains the country's water supply and reduces the demand for freshwater. Reclaimed WW is used mainly in the agricultural sector, and it helps supporting sustainable practices and enhancing food security, while also preserving public health and the ecosystem when it is not discharged into water bodies [2, 3].

According to the World Health Organization, in 2022, 76.83% of domestic wastewater from households and the service industry was safely treated in Jordan, either at the source or through centralized wastewater treatment plants before being discharged into the environment. This share is notably higher than the global average which is 57.79% [4].

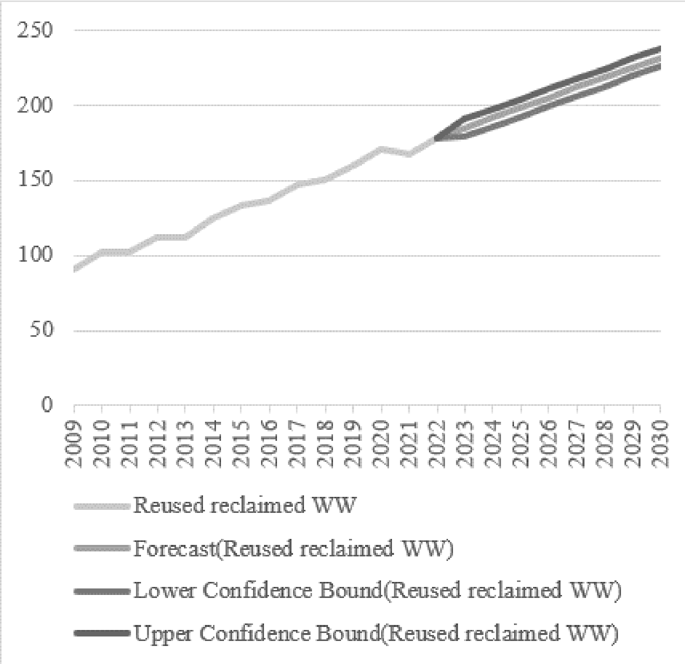
According to the literature, raw WW is biologically overloaded in developing countries due to low average per capita domestic water consumption and population growth [5]. As a result, most wastewater treatment plants (WWTPs) are highly loaded with organic materials beyond the normal levels on the specification which imposes operational problems on WWTPs. Additionally, Jordan's raw WW is considered more contaminated than that of other countries due to high salinity, high concentration of heavy metals, and toxic organic compounds [6, 7].

The adapted treatment technology plays a significant role in the efficiency of WWTPs as several studies on WWTPs in Jordan indicate that the highest efficiency index values were recorded in activated sludge WWTPs, followed by trickling filter treatment technology, while the lowest values were found in plants employing waste stabilization pond treatment technology. This highlights the crucial role of treatment technology in WWTPs' efficiencies, in addition to some other factors that also influence WW characteristics, including the type of the sewer collection system (combined or separated), the presence of industrial waste in the sewer system, the quality of domestic freshwater, and the standard of living of the consumers' communities [6, 8].

Therefore, ensuring that WW is treated properly is a vital matter. The Jordanian standards for reclaimed domestic WW (JS893/2021) and reclaimed industrial WW (JS202/2007) aim to ensure the safe usage of reclaimed WW by specifying the characteristics of the effluent WW for reuse, whether for irrigation or for discharge into streams or water bodies.

These standards categorize reclaimed water based on its quality, with each category designated for specific purposes. In the case of irrigation, reclaimed WW can be used either mixed with freshwater to enhance its quality or used directly, depending on the type of crops to be irrigated [9].

In 2022, 177 million cubic meters (MCM) of reclaimed WW was reused. Based on historical data from the Jordanian Department of Statistics (DoS), it is estimated that by 2030 approximately 231 MCM of reclaimed WW will be reused, Figure 1. This prediction assumes that the increase in influent flow and treatment efficiency will remain at the same level [10].



Year	Reused reclaimed WW quantity (MCM)	Forecasted reused reclaimed WW quantity (MCM)
2009	91	
2010	102	
2011	102	
⋮	⋮	
2020	170	
2021	167	
2022	177.48	177.48
2023		184.74
2024		191.44
2025		198.13
2026		204.83
2027		211.53
2028		218.22
2029		224.92
2030		231.62

Figure 1. Prediction of quantities of reclaimed wastewater to be reused. Elaborated by the author based on data from the Jordanian DoS.

This article aims to investigate the challenges caused by the high rates of non-complaint (out-of-specification) wastewater samples observed in Jordan and to offer solutions and monitoring practices using the DMAIC (Define, Measure, Analyze, Improve, Control) methodology. Through a structured approach, the paper wants to identify the root causes of the problem, and propose targeted interventions for improvements. The study also tries to outline possible long-term strategies to enhance the efficiency of WWTPs and ensure sustained compliance with quality standards.

CASE STUDY

This study focuses on Jordan, a country in the Middle East with a population of approximately 11.5 million people. Jordan's arid climate and limited rainfall place Jordan among the most water-scarce countries in the world as more than 93% of the country receives a rainfall of less than 200 mm [11].

According to Jordan's Ministry of Water and Irrigation's annual reports for 2016, 2017, and 2018, WWTPs in the country experienced a high number of "out-of-specification" samples (failing to meet the required quality parameters). These samples were collected from the effluent discharges of public WWTPs, private WWTPs, and industries linked to the WW system. In 2016, a total of 903 samples were collected from the previously mentioned sources, from which 617 (68.3%) did not meet Jordanian standards (out-of-specification) [12]. In 2017, 1543 samples were collected from the aforementioned sources, with 802 samples (52%) being classified as "out-of-specification" [13]. In 2018, 1204 samples were tested, with 804 samples (66.8%) falling into the "out-of-specification" category [14]. This shows that the biggest challenge is the persistent condition of the WWTPs as it may indicate inadequate treatment processes, inefficiencies in handling industrial effluents, or a variability in influent quality, potentially posing risks to public health, to the agriculture, and to ecosystems.

The research questions are as follows.

- What are the key factors behind the high rates of the (out-of-specification) WWTPs?
- What solutions can be implemented to improve compliance in wastewater treatment processes, and how they can be prioritized based on their impact and effort?
- What monitoring and control practices could be effectively established to ensure long-term compliance and operational efficiency in wastewater treatment plants?

METHODOLOGY

Six Sigma, developed by Motorola in the 1980s, is a data-driven methodology aimed to be used for quality and process improvement. One of the Six Sigma tools is the DMAIC approach, which is an acronym for the five phases: Define, Measure, Analyze, Improve, and Control. It is a structured, five-step approach that defines and addresses a problem, and also provides solutions for improvements linked to underlying causes, and establishes best practices to ensure the solutions remain in place. This standardized improvement model provides a roadmap through a logical process that focuses on optimizing the process. DMAIC aims to deliver permanent solutions for process improvement across various sectors, including industries, healthcare, education, and more [15-19].

Firstly, in the *DEFINE* phase, the primary objective is to clearly identify and quantify the problem, pointing out its severity. This step provides a high-level overview of the process. Subsequently, in the *MEASURE* phase, the problem's extent is determined by examining the state established in the *DEFINE* phase. These baseline measurements serve as standards for comparison in the next phase. The *ANALYZE* phase identifies the root causes of the problem, which are organized and investigated a cause-and-effect diagram, known as the fishbone or Ishikawa diagram, which was first developed and applied by Dr. Kaoru Ishikawa in 1950 in the field of quality management, particularly in the manufacturing industry, by categorizing the potential factors causing a problem into five primary areas: Environment, Measurement, Machinery, Method, and Personnel. These main areas represent the fundamental components of most processes in manufacturing, services, or any organizational systems, serving as a comprehensive framework to ensure that all potential causes of a problem are considered [20]. Following this, the *IMPROVE* phase focuses on finding potential solutions and classifying them according to their impact on improving the process, and the corresponding effort or cost required for the implementation, using the impact-effort matrix. Finally, the *CONTROL* phase concentrates on preserving the improvements achieved through solution implementation [21].

RESULTS

In the first phase of the DMAIC process, *DEFINE*, the problem was identified as a significant and persistent issue with non-compliance in wastewater treatment across public and private WWTPs, as well as in the industries linked to the wastewater system during the years 2016, 2017, and 2018 (Figure 2). Over the period from 2016 to 2018, a large proportion of samples tested from these sources were found to be out of specification, with the highest rates observed in private WWTPs and linked industries.

In 2018, 91.3% of tested samples from private WWTPs and 92% from linked industries were non-compliant, indicating a critical and escalating problem. This high rate of non-compliance poses environmental risks and threatens to breach regulatory standards, necessitating immediate corrective actions to improve wastewater treatment processes and reduce out-of-specification samples. The problem has been clearly defined as the failure to consistently meet wastewater treatment specifications, particularly in private facilities and linked industries, which highlights the need for targeted improvement efforts, Figure 3.

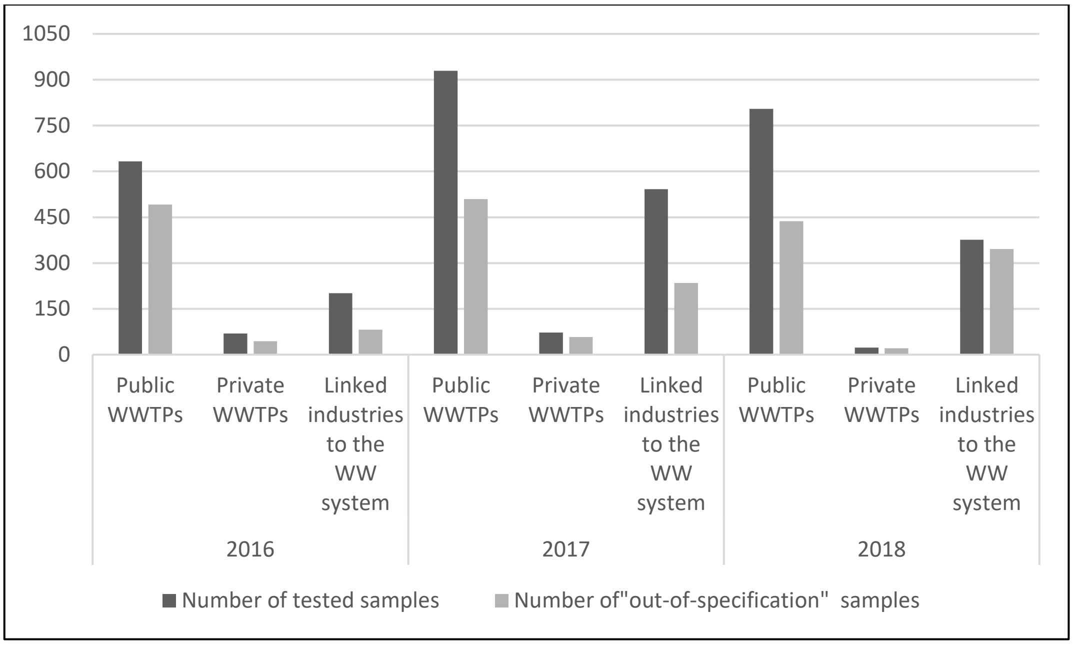
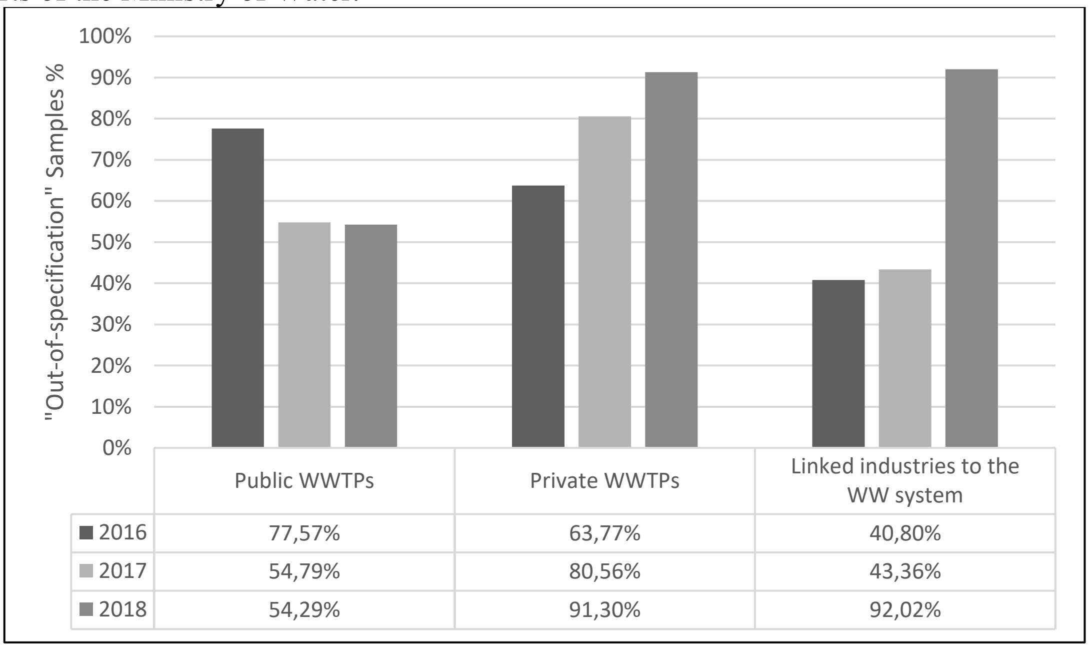


Figure 2. Tested Samples and "Out-of-Specification" Samples from Public WWTPs, Private WWTPs, and Linked Industries (2016-2018), elaborated by the authors based on the annual reports of the Ministry of Water.



	Public WWTPs	Private WWTPs	Linked industries to the WW system
2016	77,57%	63,77%	40,80%
2017	54,79%	80,56%	43,36%
2018	54,29%	91,30%	92,02%

Figure 3. Share of "out-of-specification" samples from different sources in 2016, 2017 and 2018, elaborated by the authors based on the annual reports of the Ministry of Water.

Then the *MEASURE* phase of the DMAIC process revealed that public WWTPs had decreasing rates of out-of-specification samples from 77% to 54% over the years. On the other hand, private WWTPs showed a critical increase in non-compliance rates, reaching 91.3% in 2018, and industries linked to the wastewater system also had rising non-compliance rates from 40.8% in 2016 to 92% in 2018. This clearly quantifies the extent of the problem and highlights that private facilities and linked industries are the primary sources of concern, but public WWTPs improved, with a significant drop in performance over time. This measurement provides the foundation for deeper analysis in the next phase.

In the *ANALYZE* phase of the DMAIC process, a fishbone diagram was applied to identify the root causes of the high non-compliance rates in wastewater treatment. This tool is used to categorize the potential factors contributing to the problem into five primary areas; Environment, Measurement (Samples' Testing), Machinery (Treatment Facilities), Method (Treatment Technology), and Personnel, as suggested by the tool's inventor.

By illustrating these causes as shown in Figure 4, it became clear that issues such as outdated or malfunctioning equipment, inadequate staff training, inconsistent monitoring processes, and lack of stringent oversight in private WWTPs and linked industries were the primary drivers of non-compliance. These potential causes were primarily derived from previous studies and literature on WWTPs noting that the available literature did not differentiate between the three specific sources highlighted in this article – public WWTPs, private WWTPs, and linked industries [6, 8, 9, 22, 23-30].

In the *IMPROVE* phase, a range of solutions were identified and then evaluated using the impact-effort matrix (Figure 5) in order to prioritize the solutions with the highest impact relative to their cost and effort. These solutions are linked to their unique IDs to be used later in the matrix.

Enhancing the capacity of personnel through collaborative training initiatives with educational institutions and industry experts about WW treatment processes, sampling, testing, and their adherence to the Jordanian standards (ID 1) is crucial for improving compliance [24, 30]. Developing a comprehensive, long-term wastewater master plan that involves municipalities, urban planners, environmental consultants and industries (ID 2), and implementing a robust monitoring and reporting system that allows tracking the plants' compliance (ID 3) will ensure that these plants will consistently meet the Jordanian standards [31]. Additionally, introducing penalties for non-compliant facilities while offering incentives for those meeting the standards consistently (ID 4) can enhance better adherence to regulations. Encouraging public reporting of violations (ID 5) would further enhance transparency and accountability [29].

Upgrading treatment technology is another possible solution, which means transitioning from less efficient treatment technologies to more effective ones and selecting the technology based on the desired efficiency would lead higher performance (ID 6) [26, 27]. Installing advanced pre-treatment facilities for industrial and slaughterhouse effluents and collaborating with industries to control influent WW quality (ID 7) would also improve plant efficiency. The introduction of advanced control systems to maintain consistent treatment parameters (ID 8), along with verifying treatment parameters and chemical dosages through automated control systems and ensuring the procurement of chemicals from reputable suppliers and conducting quality tests upon receipt (ID 9) would help ensure stable operation [32]. To reduce pressure on larger plants, decentralized wastewater treatment plants (ID 10) could be established in high-demand areas (high density urban districts) and over-loaded WWTPs and systems to manage peak flows or installing the surge storage to accommodate peak flows without bypassing treatment processes (ID 11) could prevent overloading during peak periods [29].

Since the spatial distribution of population and economy is very uneven, a collaboration among larger admirative units (governorates) to align the expansion of treatment plants with population growth and urbanization trends (ID 12) would ensure that the capacities of the WWTPs meet existing demand. Additionally, managing and mitigating illegal discharges into the system (ID 13) and forecasting future wastewater generation based on urbanization trends, population growth, industrial expansion, and environmental conditions (ID 14) would support sustainable growth.

Furthermore, implementing a digital data entry system for each plant and connecting them with the laboratories (ID 15), as well as conducting regular testing (ID 16), and performing in certified and up-to-date laboratories (ID 17) would help improve compliance and accuracy [30, 33]. A systematic facility maintenance, a scheduled maintenance program with regular inspections

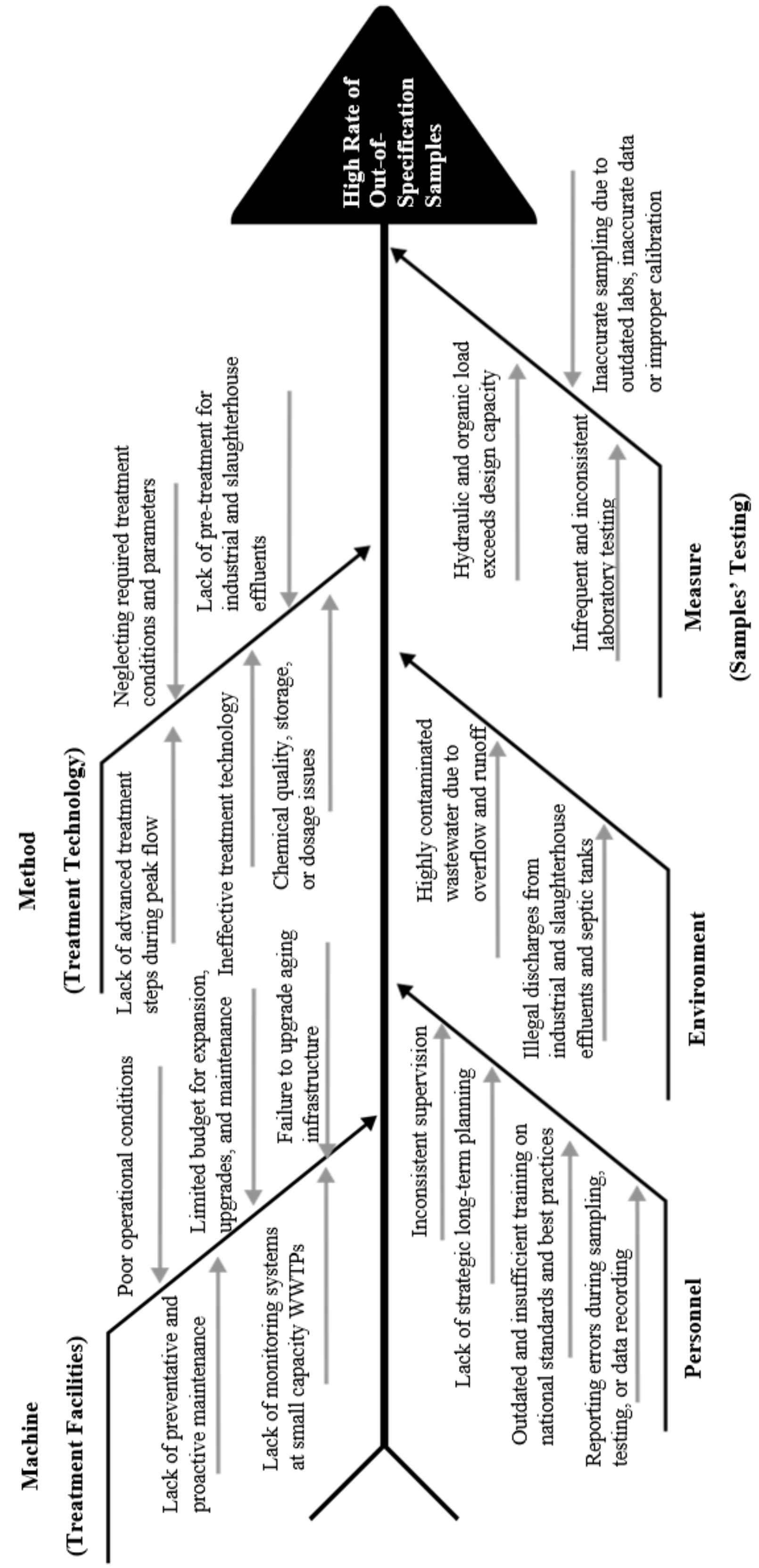


Figure 4. Fishbone diagram.

(ID 18) and maintaining an inventory of critical spare parts (ID 19) would prevent breakdowns and extend the lifespan of equipment. In addition, an increase of budget resources and the involvement of external funding (ID 20) would also ensure that the plants are well-maintained. Investing in clean energy solutions (ID 21) can provide additional cost savings that can be reinvested in more efficient treatment technologies [27]. Each solution mentioned above has been strategically placed in the impact-effort matrix, with its corresponding ID denoting its placement. This approach ensured that high-impact, low-effort solutions were prioritized for immediate implementation, while high-effort, high-impact solutions were considered for more long-term planning. By leveraging the matrix, the solutions that deliver maximum benefit while optimizing resource allocation were identified, ensuring a practical and effective approach to improving wastewater treatment processes.

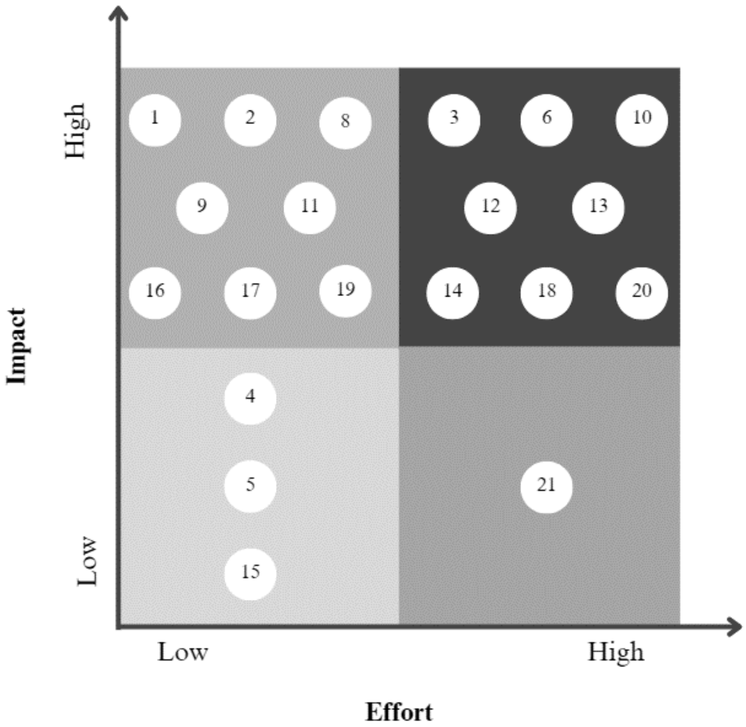


Figure 5. Impact-Effort Matrix.

In the *CONTROL* phase, a comprehensive monitoring plan was established to ensure the continued success of the implemented solutions and maintain the improved performance of the wastewater treatment facilities. This plan includes generating detailed quality reports for each facility, which assess both the quality of effluent discharge and operational efficiency, as well as conducting regular inspections of facility operations by designated personnel at specified time intervals to ensure that the system continues to operate within the standards. Implementing continuous environmental monitoring systems, leveraging advanced technology to quickly detect and responding to changes in influent water quality or other external factors would lower future risks and make the control more efficient [25, 26, 29]. Additionally, monthly effluent testing could be carried out to ensure that the quality consistently meets regulatory standards, the collected data could be used to adjust processes as necessary to prevent any changes. Employees productivity should be continuously assessed, with ongoing training programs to foster the development of staff knowledge, ensuring their knowledge extends to the latest technologies and regulatory requirements [29]. A detailed emergency response plan should be developed, outlining specific actions and solutions to be taken in the event of any process disruptions, such as equipment failure or sudden changes in WW quality. Feedback from stakeholders from industries and communities affected by the improperly treated effluent WW quality could also be actively integrated into these improvement plans and efforts [34, 35]. To ensure full transparency and facilitate future analysis, detailed records of inspections, testing results, process adjustments, and any deviations from standards should be documented in a centralized digital system. Finally, periodic audits and review cycles could ensure that the control measures remain effective, and opportunities for further optimization could be identified [36].

CONCLUSIONS

This study provided a systematic analysis on the high rates of "out-of-specification" samples observed in Jordan, and elaborated solutions and monitoring practices for sustainable wastewater treatment using the DMAIC methodology. The analysis performed across the five phases – DEFINE, MEASURE, ANALYZE, IMPROVE, and CONTROL – has yielded important findings to address the issue of high "out-of-specification" samples in WWTPs. The study, based on data from the years 2016, 2017, and 2018, identified key challenges in both public and private WWTPs, as well as industries linked to the wastewater system. Unfortunately, the annual reports from the Ministry of Water and Irrigation has not provided data on "out-of-standard" samples after 2018, which poses a limitation on assessing trends beyond the investigated period.

Based on the analysis, clear responses can be formulated to the research questions listed in the introduction section. Using the fishbone diagram, the study identified that the primary causes of non-compliance include outdated equipment, insufficient staff training, inconsistent monitoring, and a lack of stringent oversight. These issues are more pronounced in private facilities and linked industries where non-compliance rates kept growing over the years compared to public WWTPs, which showed significant improvement over time.

In the IMPROVE phase, various solutions were proposed and prioritized based on their impact and effort. Immediate high-impact, low-effort solutions include improving staff training, enhancing monitoring systems, and introducing penalties for non-compliant facilities alongside incentives for compliant ones. Longer-term solutions, such as upgrading treatment technologies and establishing decentralized wastewater treatment plants, were also identified as essential steps for sustained improvement, particularly in areas with high demand or overloaded systems.

To ensure continued success, the CONTROL phase established a comprehensive monitoring and control plan. This plan includes regular inspections, monthly effluent testing, and continuous training for personnel. The introduction of advanced environmental monitoring systems would allow real-time adjustments in treatment processes and maintain detailed records along with periodic audits, which can ensure transparency and further optimization opportunities.

Overall, this study provides a systematic framework for addressing the wastewater quality challenges in Jordan, ensuring long-term compliance with regulatory standards. By identifying root causes and implementing targeted, prioritized solutions, Jordan's wastewater treatment processes could be significantly improved, which would contribute to better environmental and health conditions.

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