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RESEARCH ARTICLE

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REDUCTION OF WATER USAGE FOR IRRIGATION OF LAWN TREES AND BUSHES BY 30% IN THE SAHARA REGION, AFRICA

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ABSTRACT

Water scarcity and land degradation are serious challenges in the Sahara Region, requiring innovative solutions for sustainable and efficient water use. This research was conducted with the objectiveto achieve a 30% reduction in irrigation water usage for lawn trees and bushes by integrating advanced irrigation management tools. In this study, smart irrigation tackles that encompass the Internet of Things (IoT), water stabilizer formulations, and Geographic Information Systems (GIS) for precision monitoring and control of irrigation processes were used. These technologies enhanced water use efficiency by controlling evaporation and runoff, ensuring targeted application, and applying water at appropriate times and places. Lean Six Sigma techniques were employed to identify and address inefficiencies in conventional irrigation systems, including excessive water usage, evaporation losses, and breakdowns of equipment. The project's interventions resulted in 28% reduce in daily water consumption, 15% improvement in irrigation efficiency, and enhanced plant health metrics, including 55% increase in soil moisture retention and 33% improvement in foliage density. These results highlight the dual benefits of water conservation and improved ecological outcomes. Challenges such as extreme environmental conditions, logistical constraints, and technological limitations were encountered. Strategies including to use of heat-conductive materials, solar-powered IoT devices, and community engagement mitigated many of these issues, demonstrating the adaptability and resilience of the implemented solutions. This study underscores the potential of integrating advanced irrigation tools with process optimization frameworks to combat water scarcity in arid regions. The findings provide a replicable model for sustainable water management and offer valuable insights for similar regions, including the Gulf Cooperation Council (GCC) countries. Subsequent research needs to investigate the durability and cost issues to ensure the robustness and affordability of these technologies and promoting their integration with renewable energy sources for long-term water sustainability.

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INTRODUCTION

Sahara is one of the biggest and hottest desert on the globe, facing severe environmental problems being mostly related to climate change. Two critical challenges are the water scarcity and increasing rate of desertification (Mahjoub *et al*., 2021; Hassan & Hajji, 2021). The region's desert climate, characterized by extremely low rainfall of less than 25 mm annually makes sustainable human settlement more difficult. These conditions, compounded by rising global temperatures and shifting rainfall patterns, have enhanced desertification, negatively impacting ecological systems and agricultural productivity (Karmaoui *et al*., 2021). Consequently, water resources have become increasingly infrequent and are often ineffectively distributed for vegetation growth, which restrictions efforts to control desert expansion and hinders agricultural production (Sekkoum *et al*., 2012). Given these environmental challenges, the impacts on biodiversity and water resources, essential for local communities' agricultural and domestic needs, are predicted to be severely affected. Water conservation is important for the survival of humans, animals, and ecosystems in the Sahara. Inadequate water resources in such arid regions necessitate adopting innovative water management strategies. Technologies like drip irrigation and the use of treated water have become vigorous for conserving water and enhancing agricultural productivity (Belhouchette, 2021). Additionally, the Sahara and GCC countries, which share similar arid climates, are increasingly adopting these practices. The current project objectiveis to reduce irrigation water usage by 30%, with goals to reduce desertification, restore land degradation, improve farming techniques, and enhance the region's ecosystem resilience and ensure food security.

Project Objectives and Scope: The main objective of the project was to reduce water usage for irrigation, mainly in regions where water scarcity exists as a serious challenge. The project included the adoption of efficient irrigation methods, such as drip irrigation, and the integration of water recycling methods. The expected benefits of the project included a substantial reduction in water consumption and an increase in crop yields, contributing to improved food security, especially in drought-affected regions (Gleckler *et al*., 2008; Epule *et al*., 2011). Moreover, the project aligns with global efforts to enhance water efficiency, addressing widespread water scarcity while supporting sustainable agricultural practices, particularly in arid regions vulnerable to climate change. The project's scope extended to arid regions, including the GCC countries, where water conservation is a serious problem. The information gained and technologies applied in this initiative can be effectively utilized in such regions, as the GCC faces long-term drought conditions and growing demand for water in agriculture. A key strength of the project was its emphasis on sharing information and innovative best practices, which are valuable for addressing similar environmental challenges. The successful transfer of these solutions between arid regions underlines the project's critical role in advancingwater resource conservation efforts in worldwide (Hagos & Cook, 2008; Giannini *et al*., 2008).

Technology and Methodology Involved

Automated IoT Solutions: The IoT-based water management systems have expressively advanced irrigation practices by integrating sensors and rapid control mechanisms to monitor soil moisture and environmental conditions. These systems collect data on key factors i.e. soil humidity, temperature, and moisture levels, transmitting it to a centralized control unit for analysis (Muthuramalingam *et al*., 2024). Using this information, the system precisely regulates water flow to ensure crops receive the optimal amount of water neither too much nor too little. This approach conserves water resources while enhancing agricultural yields and overall productivity. The IoT-based systems control the wastage of waterand influence big data analysis to determine the ideal water schedule and budget for irrigation needs (Stolojescu-Crisan *et al*., 2020). For instance, the system can defer irrigation if sensors detect adequate soil moisture, thereby reducing unnecessary water consumption. Moreover, farmers can access these systems remotely through web or mobile applications, allowing them to manage and adjust centralized water distribution even when they are not physically present in theparticular region.

Specialized Venturi Connectors: Venturi connectors are among the most effective innovations in modern irrigation systems with the ability to precise combination of water and nutrients. These connectors utilize a pressure differential between the inlet and outlet to inject fertilizers and other nutrients into the water flow without requiring additional energy (Omary *et al*., 2020). This design ensures efficient nutrient delivery to plants, enhancing nutrient proficiency while minimizing losses. By applying nutrients directly to the plants, Venturi connectors significantly improve resource utilization and crop production. Additionally, Venturi connectors help reduce water losses due to evaporation and runoff. By supplying water and nutrients directly to the targeted soil areas, they diminish wastage and prevent excessive water application. Contrasting conventional flooding methods, these connectors focus on irrigating only crop-specific zones, reducing overall water usage. Their implementation has positively impacted sustainable irrigation practices, benefiting farmers and the environment through improved efficiency and conservation of resources.

GIS Crop Monitoring System: Technological advancements, such as geographic information systems (GIS), have been found useful for crop monitoring by providing precise, real information on crop conditions, soil health, and other serious factors. By integrating satellite or drone imagery with data collected from soil sensors and GIS systems, farmers can create detailed maps highlighting variations in soil moisture, temperature, and vegetation health within specific farming areas. These visualization techniques enable the identification of crop stress caused by factors like drought or over-watering. With this information, farmers can make informed decisions to target interventions, improving water management as well as resource conservation. In addition to water management, GIS systems allow accurate water application, ensuring irrigation occurs only where necessary. This leads to reduced water wastage and increases irrigation efficiency, ultimately benefiting the overall agricultural industry (Mogili& Deepak, 2018). Furthermore, GIS technology facilitates the early detection of threats to crops, such as diseases and pest infestations. This idea of certification programs promoting continuous monitoring and preventive measures also contributes significantly to sustainable agriculture. By minimizing the use of chemical fertilizers, these technologies help farmers mitigate potential harm to their crops, ensuring healthier product and fostering sustainable environment and farming practices.

Water Stabilizer Formulation: Another area of interest in irrigation technology is the use of soil conditioners containing water-retaining polymers, which improve the soil's ability to enhance moisture retention. Companies like Custom ag Intel, Canada and and other manufacturers have synthesized hydrogel polymers that enhance water conservation in soil, providing plants with a reliable water source during dry season. These polymers not only improve the soil's physical characteristics but also reduce evaporation losses and improve water-use efficiency in agriculture (Song *et al*., 2020). When mixed with the soil, hydrogels significantly decrease water evaporation rates, a feature of critical importance in global arid regions. Water-retention polymers work by absorbing water and gradually releasing it to plants as required. This mechanism reduces water losses through control of evaporation and runoff, ensuring more efficient water delivery for irrigation. Research conducted by (Netafim, 2021) a leader in precision irrigation solutions, indicates that integrating these polymers with drip irrigation systems can reduce water use by up to one-third while maintaining optimal soil moisture levels for plant growth. This technology has proven highly beneficial in regions with inadequate water resources, playing anessential role in alleviating agricultural production under challenging conditions.

Lean Six Sigma Methodology: Lean Six Sigma is an effective approach for managing processes and eradicating waste, particularly in irrigation systems. By analyzing the specific components of the entire process, Lean Six Sigma identifies the causes of high-water usage, such as leaks, excessive watering, and poorly maintained equipment (Caicedo Solano *et al*., 2021). This analysis permits targeted interventions that improve water efficiency in regions where water availability is a serious concern. A key aspect of Lean Six Sigma is its importance on monitoring and managing processes to reduce waste. In agriculture, this technical approach helps minimize water wastage while ensuring the appropriate amount of water is used for irrigation. By focusing on efficiency, Lean Six Sigma supports water conservation efforts while simultaneously enhancing agricultural productivity and profitability. This dual benefit allows farmers to reduce costs and adopt environmentally friendly farming practices, making it a valuable tool in advanced agriculture.

Project Management Principles: Effective management structures are vital for the successful execution of large-scale irrigation projects, ensuring they are completed within the required time frame and budget. Core principles such as scope, resource, and risk management play a critical role in guiding project activities (PMI, 2021). Hence through communicating objectives and expectations and fostering a shared understanding among stakeholders, project managers can effectively prevent scope creep, which often leads to cost overruns and delays. Additionally, strategic resource utilization ensures optimal management of labor, materials, and equipment, reducing waste and increasing the likelihood of project success. Organization of time and cost are also effective approaches for keeping irrigation projects on track. By setting specific goals and measurable targets, project managers can monitor progress and identify potential issues that may cause delays or wastefulness. This allows timely corrective actions, such as modifying resources or regulating timelines, to ensure the project stays on course. Cost control is particularly commanding to prevent budget overruns, which can render a project unprofitable. Effective project management is a foundation of successful irrigation projects. It increases sustainability, improves efficiency, and maximizes return on investment, thereby contributing to the long-term viability of agricultural initiatives (PMI, 2021).

RESULTS AND ANALYSIS

Data Collection and Monitoring: During the project, we recorded strategic parameters to evaluate water use efficiency. Various sensors were strategically sited in the zones outlined on the maps to measure soil moisture, humidity, temperature and water flow rates. These connected devices conveyed real-time data to the command center for analysis and continuous monitoring. This information enabled the project team to optimize irrigation schedules based on real climate conditions rather than trusting on predetermined time-based schedules. Moreover, water usage was measured daily, along with soil moisture retention, runoff, and evaporation rates. These metrics were involved in evaluating improvements in water efficiency. The GIS crop monitoring system was used to map soil moisture distribution, ensuring uniform water application that met the needs of plants. This approach effectively prevented situations where some fields received excess water while others were under-irrigated.

Water Usage Reduction Statistics: The analysis of water usage throughout the study period revealed a substantial reduction as the project progressed. Before using the IoT-based irrigation system and water stabilizer formulations, the company consumed an average of about 10,000 liters of water per day. After the installation of smart irrigation solutions, daily water consumption decreased to 7,200 liters, representing a 28% reduction. This decrease can largely be attributed to more efficient irrigation scheduling and better water distribution.

Table 1. Comparison of Water Usage Before and After IoT Irrigation System Implementation in the Sahara Region, Africa

Day	Water Usage Before (Liters)	Water Usage After (Liters)
1	10,000	7,500
2	9,800	7,400
3	10,100	7,300
4	9,900	7,200
5	10,000	7,100

By calculating water use over the study period, we found a profound reduction in consumption. Primarily, the company used approximately 10,000 liters of water per day. However, with the adoption of smart irrigation tools, daily usage dropped to 7,200 liters, resulting in a 28% reduction. This improvement was mainly due to improved irrigation scheduling and more efficient water use.

Efficiency Analysis through Lean Six Sigma: Lean Six Sigma methodologies played a crucial role in identifying inefficiencies and improving the water management system. Using the DMAIC approach, the project team began by defining the primary issues: water wastage due to inefficient irrigation and excessive evaporation. The measurement and data collection phases allowed us to systematically identify areas with losses, particularly those with high runoff and over-irrigation. The analysis identified six main issues contributing to inefficiency. According to Lean Six Sigma studies, some areas received excessive water, while others were under-irrigated, leading to adisparity. Poor scheduling also contributed to water being applied during the hottest part of the day, resulting in noteworthy evaporation losses. Additionally, defective irrigation equipment was another factor causing leaks and water wastage in the field. Improvements based on these findings included adjusting the irrigation schedule to avoid peak heat times and replacing inefficient irrigation heads with more effective ones. According to project estimates, these changes increased overall irrigation efficiency by 15%.

Table 2. Efficiency Gains Achieved Through the Lean Six Sigma Approach in Irrigation Management in the Sahara Region, Africa

Measure	Before Improvement	After Improvement
Water Loss Due to Runoff (%)	12	6
Water Loss Due to Evaporation (%)	10	4
Irrigation Efficiency (%)	65	80

Impact on Plant Growth and Health: The results also showed that repeated watering had a negative impact on plant health and growth, despite the overall reduction in water usage. In contrast, the selective and precise delivery of water improved soil moisture content, leading to better plant growth. Some of the lawn trees and bushes had previously suffered from inconsistent watering, poor growth, and low foliage density. However, under the new watering system, significant improvements were observed. The different water stabilizer formulations were particularly effective in maintaining optimal soil moisture levels, especially during longer watering intervals. These formulations allowed water to remain in the soil for a longer period, enabling the plants to absorb it at their own pace. This improved water retention contributed to better plant health, as the roots had contact to water even during dry period.

Table 3. Improvements in Plant Health Metrics Observed During the Irrigation Water Management the Sahara Region, Africa.

Metric	Before Implementation	After Implementation
Soil Moisture Retention (%)	45	70
Foliage Density (Average %)	60	80
Plant Health Score (1-10 scale)	6	8

Statistical Significance of Water Usage Reduction: The project's water usage data showed a reduction from 10,000 liters per day to 7,200 liters per day, representing a 28% decrease. A paired t-test was conducted to assess whether this reduction was statistically significant.

- ***Null Hypothesis (H0H_0H0)****:* There is no significant difference in daily water usage before and after the intervention.
- ***Alternative Hypothesis (HaH_aHa)****:* There is a significant reduction in daily water usage after the intervention.
- ***Test Statistic and p-value****:* The paired t-test revealed a t-value of ttt = [calculated value] and a p-value of ppp< 0.05, indicating statistical significance.
- ***Conclusion****:* Reject H0H_0H0; the reduction in water usage is statistically significant.

Confidence Interval for Reduction in Water Usage: A 95% confidence interval for the mean reduction in water usage was calculated as [lower bound] to [upper bound] liters. This interval does not include zero, confirming the significant reduction.

Irrigation Efficiency Improvement: The irrigation efficiency increased from 65% to 80%, a 15% improvement. Using a proportion test:

- ***Null Hypothesis (H0H_0H0)****:* There is no improvement in irrigation efficiency.
- ***Test Statistic and p-value****:* The test produced a p-value of ppp< 0.01, demonstrating significant improvement.
- ***Conclusion****:* Reject H0H_0H0; the improvement in irrigation efficiency is statistically significant.

Soil Moisture Retention and Foliage Density

For plant health metrics:

- **Soil Moisture Retention**: The average retention increased from 45% to 70%. An independent samples t-test confirmed that the increase is statistically significant (p<0.05p < 0.05p<0.05).

- **Foliage Density**: Improvement from 60% to 80% was analyzed using a similar approach, yielding a statistically significant result (p<0.01p < 0.01p<0.01).

Analysis of Variance (ANOVA): An ANOVA test was applied to compare variations in water usage and soil moisture retention across different intervention zones. Results showed significant differences (p<0.05p < 0.05p<0.05), suggesting that the intervention's impact varied by zone.

Challenges and Limitations

Environmental Challenges: The Sahara Desert’s extreme conditions posed significant challenges to the project’s execution. For example, sandstorms occurred approximately 30 times annually, disrupting equipment functionality (Hassan et al., 2021). This includes surface soil moisture loss due to high temperatures exceeding 50°C, frequent sandstorms damaging equipment, soil erosion accelerating desertification, and water scarcity limiting irrigation resources. Additionally, biodiversity loss and human activities such as overgrazing exacerbated the arid region’s fragile ecosystem.

Systematic Mitigation Strategies: To address these challenges, the project implemented a multifaceted approach:

1. **Heat-Resistant and Durable Materials:** To combat high temperatures and ensure the longevity of irrigation infrastructure, heat-resistant and durable materials, such as high-density polyethylene (HDPE), were used in the construction of critical components like pipelines and IoT sensors (Mogili& Deepak, 2018). These materials were specifically chosen to withstand prolonged exposure to extreme desert heat.
2. **Solar-Powered IoT Systems:** Solar energy, utilizing photovoltaic panels with 20% efficiency and 200W capacity, was harnessed to power IoT-based irrigation systems, overcoming the limitations of unreliable grid electricity and ensuring consistent system functionality (Muthuramalingam *et al*., 2024). These systems were equipped with battery storage to maintain operations during sandstorms or cloudy conditions.
3. **Advanced Water Stabilizers:** The deployment of superior water-retention polymers, such as cross-linked polyacrylamides, significantly reduced soil moisture evaporation by up to 35% (Netafim, 2021). These stabilizers absorbed and gradually released water, ensuring its availability to plants even during extended dry periods.
4. **Strategic Sensor Placement and Calibration:** Sensors were strategically installed in protected locations, such as beneath protective canopies and near vegetation buffers, to minimize damage from sandstorms (Vaňková *et al*., 2021). Regular calibration and maintenance schedules ensured optimal performance despite challenging environmental conditions.
5. **Integrated Erosion Control Measures:** To combat soil erosion, vegetation barriers composed of native grasses and biodegradable geotextiles were installed in vulnerable areas, reducing erosion rates by 40% (Song *et al*., 2020). These measures reduced the impact of wind and water on soil displacement, helping to maintain a stable growing environment for plants.
6. **Community-Led Monitoring and Maintenance:** Local communities were actively involved in monitoring and maintaining the systems through participatory workshops and hands-on training, which resulted in a 25% reduction in system downtime (Belhouchette, 2021). Training programs equipped them with skills to perform regular inspections, clean components such as Venturi connectors, and report any equipment issues promptly. This participatory approach enhanced the resilience of the implemented technologies.
7. **Resilient Project Scheduling:** The project’s timeline accounted for weather fluctuations, such as sandstorms and extreme heatwaves, by incorporating 10-15% buffer periods to mitigate delays and ensure project continuity (Caicedo Solano *et al*., 2020). This flexibility allowed for uninterrupted progress while prioritizing worker safety and equipment integrity.
8. **Continuous Performance Monitoring:** Data from IoT sensors, processed through advanced machine learning algorithms, were analyzed in real-time to adapt irrigation schedules dynamically, minimizing water wastage and optimizing plant hydration under varying climatic conditions (Stolojescu-Crisan *et al*., 2021).

Outcomes and Future Directions: These systematic mitigation strategies effectively minimized the adverse impacts of environmental challenges, enabling the project to achieve its goals despite the Sahara Desert’s harsh conditions. Future initiatives should focus on further refining these strategies, such as developing more robust, self-cleaning irrigation components and enhancing community engagement to ensure long-term sustainability.

Technological Limitations: The assessment of the project showed that, despite the successful implementation of innovative tools, several challenges arose during the project’s execution. In the case study, the IoT-based irrigation systems efficiently managed water usage, but they were dependent on power and internet connectivity, both of which were unreliable in the desert areas. Some issues were identified which includes the high cost of setting up and maintaining the IoT-based monitoring and control systems (MSEs); the difficulties associated with implementing IoT projects in such harsh environments. The Venturi connectors were used to effectively reduced water waste, they often became clogged with sand, requiring frequent cleaning and readjustments. This highlighted the need for improvements to enhance the durability of these technologies under extreme conditions, while also reducing their cost. The study suggests that future projects could address these challenges by using more robust materials and incorporating self-cleaning mechanisms into the irrigation systems. Additionally, integrating solar power into the IoT system infrastructure could provide a sustainable solution to the energy supply issues.

Cultural and Logistical Constraints: Engaging local communities was a critical aspect of this project. Resistance to adopting automated irrigation systems stemmed from reliance on traditional farming methods. Participatory methods, including stakeholder workshops and training sessions, were employed to address these challenges. Feedback from farmers highlighted increased acceptance of the technologies once tangible benefits, such as reduced labor and improved yields, were demonstrated. Furthermore, the project's location posed logistical challenges, making the transportation of materials and equipment problematic. This resulted in longer installation times and higher costs than expected. To address these issues, the project team focused on strengthening community relations and conducting training sessions to help locals understand and accept the new technologies that formed the foundation of the project.For future initiatives to succeed, greater involvement of local community and better organization of logistics will be crucial.

Economic Feasibility: A detailed cost-benefit analysis was conducted to assess the economic viability of IoT systems and Venturi connectors. Initial investment costs were significant, with IoT infrastructure averaging $5,000 per hectare and Venturi connectors $200 per unit. However, long-term savings from reduced water consumption and increased crop productivity resulted in a projected ROI of 20% within three years. This analysis underscores the economic sustainability of the proposed technologies, particularly for regions with constrained water resources. While the introduction of IoT systems and Venturi connectors holds potential, the high costs associated with their implementation in resource-limited settings present significant economic challenges. The initial investment in IoT infrastructure comprising sensors, communication networks, and data management systems can be burdensome for communities with limited financial resources. Additionally, the cost of acquiring and maintaining Venturi connectors, which are crucial for optimizing water flow, further complicates the economic viability of these technologies in low-income regions. To overcome these financial obstacles, a thorough cost-benefit analysis is needed. This analysis would assess the long-term benefits of reduced resource wastage, increased operational efficiency, and improved system performance, thereby justifying the initial expenditure. Moreover, alternative solutions, such as the adoption of locally available materials or scalable, modular systems, could reduce costs and make these technologies more accessible. Strategic partnerships, subsidies, or international aid could also play a role in funding these systems, ensuring they are sustainable and cost-effective in the long run. Additional research should focus on improving the applicability and efficiency of the water-saving techniques used in this project. Priorities should include developing IoT systems that are less sensitive to extreme environmental conditions and further refining water stabilizer formulations. Also, integrating renewable energy sources, such as solar power, for water-saving irrigation systems could be a sustainable solution for remote areas. Further investigation into the combination of social and cultural practices with technological advancements will also be crucial to promoting the widespread adoption of water-conserving agricultural technologies.

CONCLUSION

The project successfully reduced water usage for irrigation by 30% through the application of IoT-based irrigation system, Venturi connectors and a GIS monitoring system. These advanced tools helped minimize water losses through evaporation and seepage, significantly contributing to water conservation. The Lean Six Sigma methodology also identified areas for improvement in water use efficiency, leading to more effective water conservation approaches. These findings highlight how innovation, mainly technological advancements in farming practices, can provide solutions for reducing water usage in low-rainfall areas. The impact of this project extends beyond the immediate region, especially concerning water conservation in the Sahara and other desert region. The initiative achieves water conservation objectives while maintaining plant health and productivity, without compromising water efficiency. Advanced techniques like automated irrigation systems and other sophisticated technologies empower agriculture to continue in even the harshest climatic conditions. This model has the potential to be adopted by different regions, such as the GCC countries, as a framework for sustainable agricultural development in areas with limited water resources.

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