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Emergency On-Site Greywater Treatment Systems: A Lifeline Resource for Infrastructure Devastation on the Gaza Strip

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Abstract

The Gaza Strip has been suffering from problems of water scarcity and wastewater management due to the prolonged blockade imposed and the limited entrance of the required materials for the operation of wastewater treatment plants. The authorities had established on-site greywater treatment Units (GWTUs) to reduce the volumes of discharged wastewater and to reuse the treated water for agriculture and non-potable uses. The aim of this study is to assess the economic, environmental, technical, social, and health impacts of applying GWTUs and highlight the obstacles and facilitators to their implementation. Through two questionnaires administered to 52 households and WASH sector experts, the study shows that irrigation reuse was the principal motivation for GWTU adoption (86% of users), leading to 71.4% overall beneficiary satisfaction. Nonetheless, considerable operational obstacles endure as 35% of GWTUs were inoperative due to maintenance issues, reliance on electricity, and insufficient user knowledge. A significant economic obstacle is the 600% rise in operational expenses associated with private generators ($0.90/kWh) relative to the municipal grid ($0.15/kWh), leading 89% of beneficiaries to identify financial strain from operation and maintenance as a principal concern, while 75% report issues with leakage. However, GWTUs are acknowledged as a crucial emergency alternative, facilitating decentralized water management and contributing to resilience in disaster settings. The results highlight the essential requirement for flexible economic measures, including energy-efficient designs and community-oriented financing, to guarantee the enduring sustainability of GWTUs in conflict-impacted areas.

Keywords: Emergency Water Management; Greywater Treatment Systems; Conflict Zones; Water Reuse; Socio-economic Impact; Sustainability.

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Graphical abstract

1. Introduction

Effective wastewater management is important for maintaining communities' public health, especially in water-scarce regions. Decentralized systems have attracted interest especially in low and middle-income countries, also in conflict zones, due to low capital costs, low energy need, easy installation, and durability (de Simone Souza *et al.*, 2023; Khaki, Kumar and Kumar, 2026). Thereby, decentralized systems, namely Greywater Treatment Units (GWTUs) proved their reliability in comparison to centralized systems. Where, source-separated systems improve resource recovery by categorizing wastewater into blackwater from toilets and greywater from other household sources, which are subsequently treated independently (Kobayashi *et al.*, 2020). Low and middle-income countries that have been suffering from improper wastewater management and the subsequent health and environmental impacts, are spotting the light on greywater management as it can be used in agriculture, which ultimately improves their food security and public health (Hamidi, 2025). GWTUs utilizes technologies within two treatment stages. First, primary treatment is used to remove physical pollutants through screening, filtration, sedimentation, and floatation. While the secondary treatment is used to remove pollutants and organic matter through aerobic and anaerobic degradation (Hamidi, 2025). These technologies led to the reduction of the per capita water usage by 50% while reducing environmental contamination (Ángel *et al.*, 2016; Hamidi, 2025). (Subramanian *et al.*, 2020) conducted a study in rural India using GWTUs and utilized biofiltration, aeration, and ozonation achieving high removal efficiencies (up to 99% for turbidity, TSS, and >99.99% for pathogens). Also, (Subramanian *et al.*, 2020) tested a low-cost adsorbent-based GWTUs in rural schools of north-central Chile, particularly using modified HAC, and it showed near-complete sCOD removal and effective reduction of turbidity and TDS.

The Gaza Strip in particular has been suffering from water and sanitation issues for a long time due to the recurring conflict with Israel, which causes severe damage to the infrastructure of water, sanitation, and hygiene (WASH) (Efron *et al.*, 2018; Sarsour and Nagabhatla, 2026). This destruction of WASH infrastructure compounded by insufficient resources' management, and rapid population growth had exacerbated sanitation problems (UNICEF, 2020). Furthermore, the blockade imposed on Gaza since 2006 has further deteriorated the situation through the restrictions on the entrance of fuel, materials, and equipment that has hindered the operations of wastewater treatment plants (OXFAM, 2017; World Bank, 2020; UNRWA, 2026). Thereby, the raw and partially treated wastewater is directly released into the sea, Wadi Gaza, and stormwater reservoirs, with 40% of wastewater contaminating the sea and fouling 75% of Gaza's coastline (Al Mezan Center for Human Rights, 2018). Alarmingly, 97% of groundwater is unfit for drinking due to excessive withdrawal and the leakage of wastewater and agricultural runoffs to the groundwater (Al Mezan Center for Human Rights, 2018; Palstinian Water Authority, 2018).

The recent conflict has exacerbated the destruction of centralized water infrastructure making access to water a matter of survival, highlighting the imperative for decentralized solutions. In this extreme context, GWTUs offer a viable and sustainable lifeline solution to provide basic sanitation and food security. Also, their affordability, simplicity of upkeep, and capacity for prompt deployment enhance their significance in rural settings and emergencies (Subramanian *et al.*, 2020; Yimenu and Gemechu, 2026). Initiatives financed by entities such as the Palestinian Hydrology Group and Secours Islamique France (SIF) have evidenced the viability of establishing GWTUs in Gaza, with units constructed in locales such as Khan Younis and additional governorates. Based on studies conducted on Gaza GWTUs which has examined acceptance and barriers (Thaher *et al.*, 2020), public attitudes (Alkhatib, 2022), and environmental optimization (Mizyed, 2024), this study offers a more robust empirical basis for understanding the applicability of GWTU in the Gaza Strip and presents several novel contributions. It provides a scientifically validated, reframed, and solution-focused analysis of GWTUs as a vital lifeline in the Gaza Strip, going beyond descriptive studies. It presents a survival-driven framework for GWTU deployment in conflict areas which aligns with recent studies (Walle *et al.*, 2023; Gholipour, Hassanabadi and Gayh, 2026), and incorporates a multifaceted analysis of economic, environmental, technical, social, and health impacts. Compared to single-focus studies, this offers a more comprehensive picture and suggests adaptable economic options for crisis situations. This strategy guarantees that the study functions not only as a local case study but also as a scalable, empirically supported model for the application of greywater treatment in crisis situations across the globe.

Conventional academic literature frequently assesses decentralized systems in terms of long-term environmental sustainability; nonetheless, it is imperative to comprehend their deployment as a survival-oriented action to immediate crises. This study, consequently, analyzes the implementation of GWTUs in the region not as a conventional technological shift, but as a crucial emergency measure. While it was not possible to conduct a long-term quantitative water quality testing which was a limitation of this study, the qualitative assessment investigated the systems implementation and analyzed their function as an emergency solution for alleviating water and sanitation issues in the context of extensive infrastructure devastation, offering crucial insights into the adaptation of decentralized WASH (Water, Sanitation, and Hygiene) solutions to sustain human survival when centralized systems fail.

1.1. *Study area*

The Gaza Strip is located on the eastern coast of the Mediterranean Sea with a total area of 365 km^2, a length of 41 kilometers, and a width between 6 to 12 kilometers. The region consists of five governorates: North Gaza, Gaza City, Deir Al-Balah, Khan Younis, and Rafah. The population-to-area ratio indicates that the Gaza Strip is one of the highly condensed areas in the world with a population that exceeded two million according to Statista Research Department (Statista, 2024). Figure 1 shows the map of the Gaza Strip.

2. Methods

The research employed a case study methodology with an analytical descriptive framework to evaluate the feasibility of on-site GWTUs in the Gaza Strip. Primary data were collected in 2021 utilizing two structured questionnaires supported by secondary data from official project reports.

The first questionnaire targeted specialists, professionals, and engineers in the Water and Sanitation (WASH) sector specifically those directly involved in greywater management, sanitary infrastructure, or project management and implementation. A purposive expert sampling method was employed to guarantee that participants had significant technical and practical knowledge. The questionnaire was disseminated to 40 experts, yielding 36 responses showing a response rate of approximately 90%. This questionnaire examined the technical, economic, environmental, and health dimensions of GWTUs, encompassing criteria for selecting greywater technology and assessing the merits and drawbacks of the systems.

Figure 1. Map of the Gaza Strip (AI Generated)

The second questionnaire was distributed to 65 households with on-site GWTUs under the Secours Islamique France (SIF) project, yielding 56 responses, showing a response rate of approximately 86%. Also, the questionnaire included both single-response and multiple-response questions. The sample size was determined based on accessibility and operational feasibility of the installed GWTUs at the time of data collection. This questionnaire collected data on household satisfaction, system monitoring, environmental and health implications, and the economic dimensions of GWTUs.

Quantitative data analysis was performed with SPSS. Descriptive statistics, including frequencies and percentages, were employed to summarize the responses. Chi-square tests were utilized to investigate the relationships between socio-economic characteristics (e.g., income level, household size) and the acceptance or adoption of GWTUs, as well as to uncover perceived obstacles to ascertain perceived obstacles to implementation. Statistical significance was assessed at a 95% confidence interval.

Additionally, official reports from SIF, encompassing design specifications, expenses of GWTU components, and water quality assessments, were also gathered to support and contextualize the research findings.

Following the outbreak of October 2023 war, the initial data obtained from the questionnaires were reexamined using a contextual and thematic reanalysis approach. The initial datasets from household surveys and expert questionnaires were reexamined to assess the possible function of on-site GWTUs as an emergency and resilience-focused water management solution. The analysis utilized SPSS to perform chi-square testing to assess the adoption of GWTUs and identify potential impediments to their deployment amid the ongoing conflict, including logistical, technical, and resource limitations. The results were utilized to advocate for GWTUs as an effective emergency option for water management in Gaza, highlighting their swift implementation and durability in crisis situations.

2.1. *Case Study Description*

2.1.1. Current WASH Status in the Gaza Strip

The Gaza Strip is suffering from unprecedented WASH (Water, Sanitation, and Hygiene) catastrophe resulting from the wars and prolong blockade, infrastructural destruction, and environmental deterioration (World Bank, European Union and United Nations, 2024). Groundwater, the main water source for the region, is 97% polluted and unsuitable for use (World Bank, 2018; PCBS, 2023a; American Near East Refugee Aid, 2024). In response to the shortage of clean water, the region has depended on more than 150 brackish water desalination plants, with 80% being privately managed (United Nations International Children's Emergency Fund, 2018). Nevertheless, most of these units have halted operations owing to fuel shortages. Prior to the war, the average per capita water use was 80 liters daily (American Near East Refugee Aid, 2023). This figure has decreased by 90%, resulting in receiving only 1.5–2 liters per day, well below the emergency threshold of 15 liters per day recommended by the United Nations and the survival requirement of 3 liters per day (United Nations International Children's Emergency Fund, 2023). The World Health Organization (WHO) establishes the standard daily water requirement at 100 liters per individual (American Near East Refugee Aid, 2024).

The sanitation services provided to all the Palestinian Territories are high, but the Gaza Strip has more connections to the sewage system than the West Bank. In which 78% of the households and facilities in the Gaza Strip are connected to sewage networks while the remaining 22% are still using the on-site systems. The West Bank has 94% access to improved sanitation. However, only 30% of the population are connected to sewage networks. Also, more than 60% of the West Bank population depends on cesspits that are emptied and the contents are discharged to the sewage networks, dump sites, and other open locations (World Bank, 2018). The percentage of untreated wastewater in the Gaza Strip is about 90% of the total amount of wastewater. In which, 80% of the untreated wastewater goes to the sea, and the remaining 20% seeps into the aquifer polluting the water and soil (Euro-Med Monitor, 2021). Due to the war, the sanitation infrastructure is in collapse. All five wastewater treatment facilities have stopped operations due to insufficient fuel and structural damage, leading to the daily release of over 100 million liters of untreated sewage and wastewater into the soil and the Mediterranean Sea (United Nations Environment Programme, 2024). Within six months of the war, over 18 billion liters of wastewater have been discharged, presenting substantial risks to the environment and public health (Price, 2024). This has further intensified the public health crisis in the region, particularly affecting children under five and mothers, who are the most susceptible. The humanitarian ramifications of this catastrophe are profound. Public health is declining due to prevalent communicable diseases, such as hepatitis, dysentery, upper respiratory infections, meningitis, skin rashes and lice, scabies, and chickenpox (Kearney *et al.*, 2024) resulting from inadequate sanitation and the buildup of over 270,000 tons of uncollected waste in urban areas.

2.1.2. Gaza Strip Household Grey Water Treatment Projects

In the Gaza Strip, the Palestinian Hydrology Group (PHG) in partnership with Bani-Suhaila municipality, Coastal Municipal Water Utility (CMWU) and water specialists initiated a project in 2015 that aimed to construct on-site grey water treatment units in Bani-Suhaila area in Khan Younis governorate to prevent using household cesspits and reuse the treated water for irrigation (PHG, 2016). The project's major purpose was to solve the absence of conventional sewerage systems in Bani Suhaila, where hardly 15% of the 40,000 residents possessed acceptable sanitation facilities (PHG, 2016). Residents predominantly depended on cesspits or septic tanks for wastewater disposal, resulting in environmental and health complications from overflow and groundwater contamination. The initiative sought to appropriately, effectively, and safely collect and treat greywater, accounting for approximately 55% of daily domestic consumption, using on-site small-scale treatment units (PWA *et al.*, 2017). The processed wastewater was subsequently utilized for irrigation through drip systems, aiding in water conservation and alleviating stress on the over-exploited aquifer.

According to PHG case study, the specific objectives encompassed offering alternatives to cesspits for 135 families, enhancing public health and hygiene awareness, ensuring that the treated greywater conformed to WHO and Palestinian Water Authority standards for agricultural irrigation, and diminishing the reliance on chemical fertilizers by employing the nutrient-rich treated greywater. The project's outcome was the construction of 135 on-site GWTU's in Bani-Suhaila area where around 1350 people benefitted from the project and reuse greywater in toilet flushing and for irrigation purposes (PHG, 2016). The quality of the treated grey water was regularly tested to ensure its compliance with the WHO and Ministry of Environment (MoE) standards. Another project funded and implemented in 2018 by the Secours Islamique France (SIF) aimed to install 100 on-site GWTUs in different governorates in the region. The project constructed around 100 on-site GWTU's in rural areas of Khan Younis, Middle area, Gaza city, and North Gaza.

2.1.3. Description of the Onsite Grey Water Treatment Units

The system is based on the separation of the black water and grey water streams, where the blackwater is discharged to the households' cesspits or septic tanks. While the grey water is discharged to the on-site Grey Water Treatment Units (GWTU). The illustration of the Onsite Grey Water Treatment Unit is shown in Figure 2.

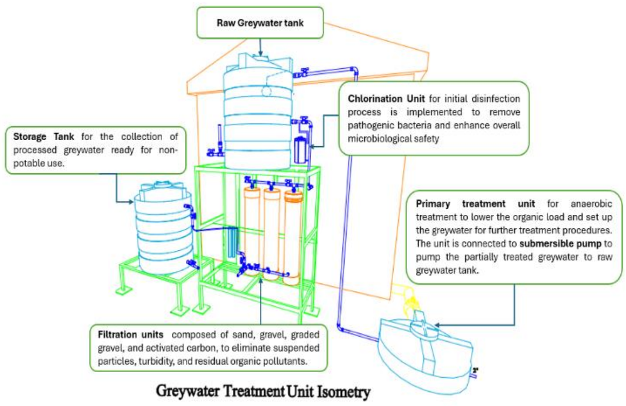

Figure 2. Illustration of the on-site GWTU (CMWU, 2021)

In the GWTU system, the conveyed greywater first goes through anaerobic treatment in the first tank, which serves as the primary treatment unit. This tank retains greywater under anaerobic conditions, facilitating the partial decomposition of organic materials and the sedimentation of denser suspended particles. This preliminary phase lowers the organic load and sets up the greywater for further treatment procedures. A submersible pump located in this tank elevates the partially treated greywater to a higher raw greywater tank, facilitating gravity-fed flow to the subsequent treatment units.

The untreated greywater flows by gravity from the upper tank into a chlorination unit, where an initial disinfection process is implemented to remove pathogenic bacteria and enhance overall microbiological safety. After chlorination, the greywater flows through three filtration units to eliminate suspended particles, turbidity, and residual organic pollutants. These filtering devices are composed of stratified media, including sand, gravel, graded gravel, and activated carbon. The sand and gravel strata mainly remove fine particles and suspended solids, whilst the activated carbon adsorbs dissolved organic compounds, smells, and residual disinfectants.

In the final stage, the processed greywater is gathered in a storage tank and subsequently allocated for non-potable reuse, particularly for agricultural irrigation and toilet flushing. This multi-phase treatment system guarantees that the processed greywater complies with applicable health and environmental regulations, while preserving a straightforward, low-energy design appropriate for decentralized and emergency water management scenarios.

According to reports from CMWU, samples from the projects were collected regularly from the GWTU's to monitor the quality of the greywater treated. Table 1 shows the results of water quality tests from samples of the SIF project in 2021.

Table 1. Results of treated grey water quality (CMWU, 2021)

Parameter	Results	Unit
pH	7.57	-
Color	< 1	-
TSS	35	mg/l
COD	100	mg/l
BOD	30	mg/l
DO	1.5	mg/l
FC	Nil	CFU

The results of grey water quality tests from samples obtained from the GWTU's showed its compatibility with the Palestinian standards for wastewater reuse and WHO standards for grey water reuse. The results of treated grey water quality reflect the high efficiency of the installed treatment units.

Grey water treatment unit costs consist of a combination of capital, operation and maintenance costs. Household GWTU's are preferred to be low-cost treatment systems to ensure the continuity of projects. However, according to CMWU, the projects executed in the Gaza Strip were completely funded by international and national organizations, and the construction of each Grey Water Treatment Unit costs around 2000$. While the operation and maintenance costs were covered by the donors in the first phase (the first year of operation) and after that the O&M costs were covered by the beneficiaries.

2.1.4. The Role of On-Site Greywater Treatment in Emergency Response

A key advantage of on-site GWTUs is their decentralization. In Gaza, where centralized sewage networks are frequently compromised or unattainable owing to bombardment or resource deficiencies, decentralized systems provide autonomy from impaired infrastructure. They can offer prompt assistance to communities by facilitating the reuse of greywater for irrigation, or toilet flushing, hence diminishing dependence on limited freshwater resources which was proved by several studies that stated the reuse of greywater have reduced the potable water consumption by 30-50% (Yu *et al.*, 2015; Siang *et al.*, 2018). For an average large family in Gaza, consisting of around 10 individuals according to our study, this corresponds to a possible greywater reuse volume of 500-700 liters per day, depending on an average greywater production of 50-70% of total domestic wastewater (Ghrair, 2011; Exchange, 2025).

The flexibility of on-site solutions renders them optimal for emergency response. In the study area, similar systems have been implemented in residences and public buildings to maintain fundamental hygiene practices during and following escalations. Their compact design and reduced expenses render them viable for extensive application in resource-constrained regions, such as refugee camps, which accommodate a substantial segment of Gaza's displaced population. The case study in this work (Section 3) illustrates that beneficiaries preferred greywater reuse for agricultural and sanitation uses, particularly in regions where the municipal water supply is characterized by high salinity and inconsistent Availability. These findings underscore the economic benefits of GWTUs; For example, the reuse of greywater can decrease household water bills by around 10% (as indicated in our study) and, importantly, avoid the expensive costs associated with emergency water trucking, which can be 10 to 20 times more costly than municipal supplies during crises.

The ongoing war in Gaza highlights the necessity for robust and flexible WASH solutions. Data from the case study demonstrates that GWTUs enhance immediate water availability and foster long-term resilience by diminishing reliance on cesspits, decreasing operational expenses, and ensuring water access during crises. These findings, though centered in Gaza, provide considerable generalizability and transferability to other emergency situations. The measurable outcomes, represented in the form of the reduction in freshwater demand and significant cost savings relative to emergency alternatives, offer a justification for promoting decentralized WASH interventions in any conflict-affected, displaced, or water-scarce region worldwide. The observed patterns of user acceptance, alongside the obstacles associated with operations and maintenance and external supply chains, are prevalent in humanitarian situations, rendering the insights gained from Gaza particularly useful for shaping policy and practice in analogous contexts.

3. Results and Discussion

3.1. *Pre-War Households' Questionnaires*

3.1.1. General Information on Households

Fifty-two households in rural areas of the Gaza Strip were surveyed. The results of the community questionnaire showed that the average family size who had an on-site GWTU is around 10.3 which is considered a large family size compared to the average in the region that was 5.5 in 2022 (PCBS, 2023b). Also, the average number of children in the study sample was 4.5. The average income of the onsite GWTUs' owners ranged from 60-600 US$. While official Palestinian statistics in 2017, showed that 53% of Gaza citizens were considered poor according to the national poverty standard (PCBS, 2017).

3.1.2. Monitoring the On-site GWTUs

The results showed that 35% of the total treatment units constructed by SIF were not operating anymore, due to many reasons including the need for maintenance, the need for electricity, and the beneficiaries' lack of adequate understanding of operation and maintenance. Also, the data showed that 73.2% of the units were only monitored by the implementing agency during the first phase after the units started operating, while only 26.8% of them monitor the units by regular visits to ensure the performance of the units. Therefore, a training program must be provided for the beneficiaries on how to operate and maintain the GWTUs, because raising awareness of the system is crucial for its continuity as highlighted by recent UN-Water findings (WHO and UNICEF, 2025).

The questionnaire also covered the commitment of the implementing agency for testing the quality of the treated water. The results showed that 28.6% of them do not monitor the quality of water, while 71.4% monitor the treated water quality only in the first phase of operation. The results showed that there is no continuous monitoring for the treatment units from the implementing agency, and the owners who do not have sufficient knowledge or training are responsible for the monitoring and evaluation process. Also, the results showed that 44.6% of the beneficiaries were unsatisfied with the performance of the implementing agency, the dissatisfaction percentage is not low and reflects that the responsibility and performance of the implementing agency adversely affecting the sustainability of the treatment units.

Additionally, the beneficiaries mentioned several points that the implementing agency had mistakenly made during the construction and operation. Among these problems is the design of the treatment system, in which the capacity of the storage tank was small, in addition to the inappropriate discharge of greywater through the manhole, leakage from the treatment unit, and the lack of monitoring from the implementing agency.

3.1.3. Satisfaction and Acceptance of GWTUs

The results of the questionnaire showed that the main reasons behind the beneficiaries' acceptance of using the on-site GWTUs differ.

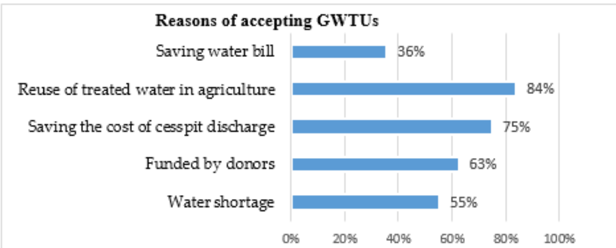

Figure 3. Main reasons for beneficiary acceptance of on-site GWTUs based on a multiple-response question.

Figure 3. shows the reasons for beneficiaries for accepting the installation of GWTUs in their households. The main reason for accepting the installation of the treatment system is to cover the water demand for agricultural purposes, as the treated water is preferred for irrigation over the municipal water that is highly saline in most of the region. Saving the costs of discharge of cesspits is the second main reason for accepting GWTUs. Another factor influencing the acceptance is the external funding for the construction of the on-site GWTUs and coverage of operation and maintenance cost for the first year. Water shortage that is exacerbating and affecting all life aspects is another important reason for accepting GWTUs. Reducing water bills was seen as the least significant effect, especially in households with smaller family units.

Hereby, the beneficiaries showed a high percentage of satisfaction of 71.4%. While 28.6% showed their dissatisfaction due to the problems they faced with their treatment units like the small capacity, leakage, odors emission, and other problems.

Table 2. Acceptance of providing GWTPs for reuse in irrigation

Acceptance of GWTBs for reuse in irrigation		
Independent variables	Asymp. Sig. (2-sided) Value	Status
Family size	0.024*	Significant
Job	0.054	Insignificant
Income	0.013*	Significant
Owner satisfaction	0.043*	Significant
Level of noise	0.964	Insignificant
Aesthetic effect	0.159	Insignificant

Table 3. Acceptance of GWTUs for reuse in irrigation versus monthly income

Monthly income (New Israeli Shekel, NIS)	Monthly income (Dollars $)	Acceptance of GWTUs (%)
< 500	< 160	87%
500 - 1000	160 – 320	73%
1000 - 1500	320 – 480	67%
1500 - 2000	480 - 640	60%
≥ 2000	≥ 640	40%

Acceptance of providing GWTUs for reuse in irrigation varied according to many reasons as mentioned in **Table 2**.

The above table showed that there is a statistically significant relationship between the dependent variable (acceptance of GWTBs for reuse in irrigation) and the independent variables (family size, income, and owner's satisfaction).

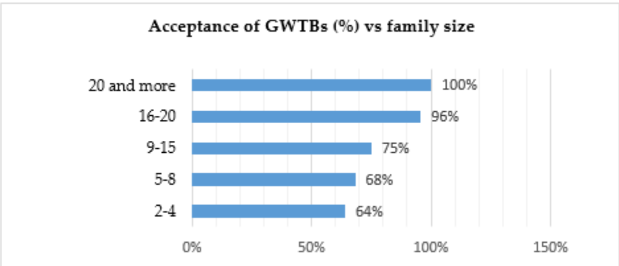

Figure 4. Acceptances of GWTUs for reuse in irrigation per family size.

- Family size: from Figure 4. It is noticed that the acceptance of GWTUs for reuse in irrigation differs between different family sizes, in which the acceptance increases in large families.
- Monthly income: Acceptance of GWTPs was different for people who have different average monthly income as seen in Table 3, where the high percentage was for the people who have the less income, while people with high incomes have less interest in having the GWTUs.
- Owners' satisfaction: 87.5% of people who were satisfied with their GWTUs accepted the reuse of the treated greywater for irrigation, while 81.25% of people who were dissatisfied with their GWTUs accepted the GWTUs for the reuse in irrigation.

3.1.4. Economic Viability and Life Cycle Considerations

The results of the survey showed that in the majority of households, the water bill decreased after operating the GWTUs by an average of 10%. Where 86% of respondents stated the decrease in their water bills, while 14% responded did not witness a decrease. Additionally, 66.1% of the beneficiaries stated that they financially benefited from the GWTUs and their benefits varied, in which 66.1% benefitted by increasing their savings, 17.9% benefited by providing a new source of income, and 16.1% benefitted by increasing their income.

It is important to acknowledge that the economic evaluation is mainly founded on reductions in water bills and perceived financial advantages through savings. However, the sustainability of these savings is threatened by operational costs. The most frequently reported barrier to GWTU application was the financial burden of operation and maintenance (O&M), cited by 89% of beneficiaries as mentioned in section 2.1.7. The cost of energy is the most critical factor in the system's life cycle, as shown in **Table 4**.

Using private generators as a solution to operate the GWTUs in times of blackouts has increased energy expenses by 600% constituting a financial cliff, thereby threatening the long-term sustainability of GWTUs especially in post-war contexts. Additionally, as 73.2% of units being supervised by the implementing agency in the first-year, this resulted in the 35% abandonment rate noted in this study. In contrast to traditional systems with centralized operations and maintenance, GWTUs transfer this responsibility to the user, in which (Muzioreva *et al.*, 2022) identify it as a known failure point in low income countries.

3.1.5. Environmental Impact of On-site GWTUs

Despite the high satisfaction with the GWTUs, people have stated some environmental problems related to odor, noise, insect presence and aesthetics. Odor emission was the most reported issue with 21.4% of beneficiaries complained about frequent odor emission while 48.2% of respondents mentioned occasional odors. On the other hand, 19.6% stated that the system rarely emits odors, while 10.7% said they never noticed odor emission form their treatment units. Moreover, for those who experienced bad odor emission, 51.8% stated that the treatment units produce a medium odor, 19.6% said the omitted odors are strong, while 28.6% said the odors are light and negligible.

Table 4. Life Cycle Cost Considerations for GWTUs in Gaza

Cost Component	Relative Cost	Impact on Sustainability
Initial Capital	Medium	Initial barrier; but covered by grants
O&M (Grid Power)	Low ($0.15/kWh)	Sustainable for low-income households
O&M (Generator Power)	Very high ($0.90/kWh)	Primary cause of system abandonment
Maintenance/Parts	Medium	Significant burden after grant period ends

Table 5. Comparison with International Environmental Standards

Parameter	WHO/FAO Guideline for Irrigation (WHO, 2006)	Gaza GWTU Status
BOD5	<240 mg/L	30 mg/L, compliant as long the system is kept maintained.
Total Coliforms	<1000 CFU/100ml	Nill; but there is high risk during leakage.
Odor/Insects	Minimized	Reported Issue (21–48%)

The noise produced by the treatment units was regarded as negligible. The majority of respondents (58.9%) stated that there is no noise coming from their treatment units, whilst 30.4% said they rarely hear the noise. Merely 10.7% stated that sometimes they hear noise from the pump. Consequently, the level of noise is rather negligible for 69.6% of the beneficiaries, while 21.4% said the noise is acceptable, and 8.9% expressed their annoyance with the noise and considered it high especially at night.

Regarding biological nuisances, 71.4% of households reported an absence of insect infestation linked to the treatment units, while 28.6% noted a minor presence of insects. Concerning the aesthetic impact of the treatment units in the beneficiaries' houses, 80.4% stated that the treatment units did not have any effect on their properties, 7.1% said the system positively affected the view of the house, while 12.5% stated a bad impact.

Despite the reported issues, comparing the results of the samples taken from Gaza GWTUs, in Table 1, and WHO Guideline for Irrigation in Table 5, showed environmental compliance to the international standards. This compliance shows the ability of the system to operate well, but it still needs to be maintained to keep up with the standards.

3.1.6. Health Outcomes of On-site GWTUs

The data obtained from the questionnaire showed that the GWTUs were safe for the health of beneficiaries if no malfunctions occur in the system. In which 58.9% of beneficiaries said that family members have no contact with the untreated grey water, while 23.2% stated that it is a weak probability for family members to be exposed to untreated grey water. However, 17.9% of respondents said that in the case of leakage there is a possibility for exposure to the untreated grey water. However, 51.8% of respondents did not know if the treatment system contributes to the reduction of disease occurrence by reducing pollution, while 26.8% stated that it does reduce diseases by reducing the accidents of wastewater seepage from the cesspits. On the other hand, 21.4% stated that the treatment system has no effect on reducing diseases.

Additionally, 66.1% of respondents denied the potential of being physically harmed by accessing the treatment unit, while 23.2% stated they were rarely exposed to physical harm, 10.7% did not know if the system causes physical harm or not as they did not experience a similar situation. Moreover, most respondents with a percentage of 87.5% stated they never noticed any spread of epidemic diseases after the use of the GWTUs, while 12.5% stated they had suffered from gastrointestinal viruses and parasitic roundworms.

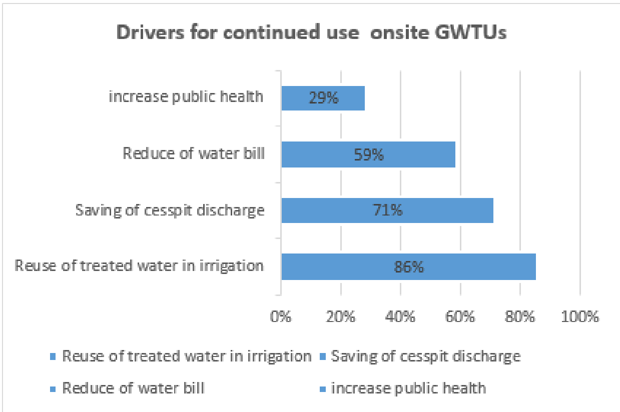

Figure 5. Drivers for continued use of on-site GWTUs based on a multiple-response question

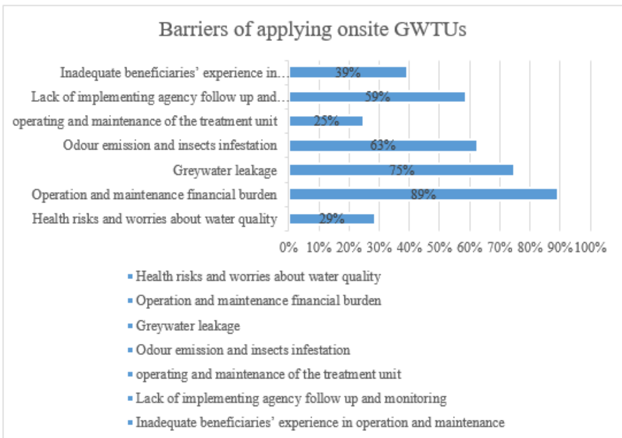

Figure 6. Main barriers to the application of on-site GWTUs based on a multiple-response question

3.1.7. Drivers of Applying Onsite GWTUs

The beneficiaries from the onsite GWTUs stated their drivers for continuing using the GWTUs based on a multiple-response question as shown in Figure 5. The main driver was the reuse of greywater treated for agricultural purposes (86%). Followed by reducing the costs spent on the discharge of cesspits by 71%, as the greywater form 80% of the domestic wastewater and the separation and treatment process cause only blackwater to be discharged to the cesspits, thereby the time for filling the cesspit is longer than before establishing the GWTUs. The third driver is reducing the water bill, and the least driver is to raise public health with a percentage of 29%. These results indicate operational motivations rather than initial acceptance criteria. Although there is a substantial intersection between acceptance factors and drivers of application, the two concepts represent two distinct decision phases: initial acceptance and long-term operational motivation.

Table 6. Demographic characteristics of study sample.

Demographic data		Frequency	%
Gender	Male	31	86
	Female	5	14
years of experience	less than 5 years	16	44
	5 - <10	12	33
	10 years and more	8	22
Position	Manager	9	25
	Civil Engineer	12	33
	Site Engineer	5	14
	WASH Engineer	6	17
	Consultant	4	11

3.1.8. Barriers of Applying On-site GWTUs

Despite the systems' benefits, the GWTUs is still facing many several technical, financial, and institutional barriers and Figure 6 shows the main barriers identified by the beneficiaries.

The most frequently reported barrier was the financial burden on operation and maintenance with 89% of beneficiaries showing their concern about these costs. The second barrier was the greywater leakage with a percent of 75% because of the limited capacity of the raw greywater tank that cause overflow and lead to the leakage of pipelines into the manhole. The third barrier was odor emission and insects' infestation that result mainly from the leakage of greywater. The fourth barrier identified was the lack of implementing agency's follow up after the end of phase one (The first year of operation). The less frequent barriers mentioned by the respondents were the inadequate beneficiaries' experience in operation and maintenance, concerns about health risks and water quality, and the operation and maintenance processes of the treatment unit. Even though these barriers were reported in a lower frequency, they are considered important as they have long-term effect on the system's performance and beneficiaries' confidence.

3.2. *Experts' Questionnaire*

3.2.1. General Information on Study Sample

The study population included the following demographic variables: (Gender, years of experience in the WASH sector, positions of the respondents), Table 6 showed the demographic characteristics that distinguish the study sample.

The respondents were divided between three water sectors. In which, 47% of the respondents work in the regulation and operation sector, 31% work in regulation sector, and 22% work in operation sector.

3.2.2. Sustainability of the On-site Grey Water Treatment Units

The results of the questionnaire showed that applying the on-site GWTUs is sustainable in terms of economic, technical, environmental, and health aspects.

3.2.2.1 Economic Aspects of On-site GWTUs

The results showed that 80% of respondents agreed that the on-site GWTUs require lower operational costs than the WWTPs. While 11.1% showed a neutral response and 8.3% disagreed with it. Regarding maintenance costs, 91.7% of respondents agreed on the lower maintenance costs in comparison to WWTPs. Additionally, 72.2% expressed their agreement on the lower requirement for construction costs, while 19.4% showed a neutral response, and 8.3% disagreed with it. The neutral response and disagreement come because of the fluctuating conditions in the region and the siege imposed for more than a decade, in the peak of events, the prices of construction materials were doubled and sometimes tripled. The results also showed 83.3% agreement that the GWTUs projects Attract grants that align to water resource initiatives, while 16.7% expressed their neutral opinion as they see that there are more important humanitarian projects that attract external grants.

From the results, we can conclude a general agreement on the economic sustainability of the on-site GWTUs projects despite the challenges facing the water and sanitation sector in the region.

3.2.2.2 Technical Aspects of On-site GWTUs

The results showed that 83.3% of respondents agreed on the lower demand of the GWTUs for municipal infrastructure, while 13.9% stated their neutral response, and 2.8% disagreed. Regarding the need for training the operators and supplying them with information resources, 97.2% of respondents expressed their agreement while only 2.8% disagreed.

Due to the high population density in the Gaza Strip, the questionnaire included land availability and its sufficiency to construct the GWTUs. The results showed 47.2% of respondents agree that the available lands areas in the region are sufficient to construct the treatment units, while 38.9% stated their disagreement and 13.9% stated a neutral response. The differences in respondents' opinions result from the limited land in the region. However, the design of the GWTU is small and includes underground and above ground tanks to minimize the land used for constructing the treatment unit. Moreover, the majority of GWTU are installed for houses in the rural areas far from the condensed city. Therefore, the area of land available is sufficient to be used for the treatment system.

The results show the great effect of the blockade on the sustainability of the on-site GWTUs projects, while the land availability issue can be solved by the design of the treatment unit. Also, it is very important to provide technical support in the form of training and information resources to the operators to avoid mistakes that can hinder the performance of the treatment units.

Even though this study did not perform laboratory analysis of the systems, the qualitative data can be used for benchmarking against global standards as shown in **Table 7.**

Table 7. Technical Benchmarking of GWTUs

System Type	Removal Efficiency (BOD/COD)	Reference	Energy Dependency	Suitability for Conflict
On-site GWTU (Gaza)	50–70% (Estimated)	This study	High	High
Constructed Wetland	95-96%	(Gizi´nska-Górna, Jó´zwiakowski and Marzec, 2020)	Low	Medium
Slow Sand Filter	70–80%	(Fitriani, Fatikasari and Affandi, 2025)	Low	Medium
Centralized WWTP	90–98%	(Yusrina *et al.*, 2024; Wang *et al.*, 2025)	Very High	Low

Table 8. Comparison matrix and weighting factors of success criteria

No.	Criteria	Weight (%)
1	Initial investment and running costs	26%
2	Skilled staff required to design, construct and maintain	24%
3	Quality of the untreated greywater	21%
4	Land space required for construction	15%
5	Familiarity of technology among people in the city	14%

GWTUs provides a high crisis resilience solution when compared to WWTP as they function as an essential buffer in the times of infrastructure breakdown. However, 75% of beneficiaries had indicated greywater leakage as barrier, mostly because of the insufficient capacity of the raw greywater tank, resulting in overflow. However, many projects still encounter strong social and political issues that affect maintenance and reliability, according to recent studies of greywater use in buildings (Niewitecka, 2025; Franco-quintero, Rizo-maestre and Andújar-montoya, 2026). According to 88.9% of experts, the blockade in Gaza makes this more difficult by limiting access to replacement parts, and 97.2% stated the effect of the blockade on the availability of construction materials.

3.2.2.3 Environmental Aspects of On-site GWTUs

The results of the questionnaire showed that 36.1% of respondents agreed that several GWTUs have a problem of leakage. While 52.8% of respondents disagreed and 11.1% neither agreed nor disagreed, because the leaking greywater can be filtered by the layers of the soil before reaching the groundwater. Additionally, 50% of respondents stated that the GWTUs does not cause soil contamination, while 36% agreed that the system causes soil contamination, and 13.9% neither agreed nor disagreed. The percentage of agreement comes from the reports that some treatment units leak, and the leaking of raw greywater can cause soil contamination around leakage. In respect of the reuse of treated greywater in irrigation, 86.1% of respondents stated their agreement on its role in improving the agricultural sector. However, 5.6% disagreed and 8.3% neither agreed nor disagreed.

Most results indicate that the GWTUs are environmentally sustainable, as they did not cause groundwater and soil contamination unless there was a defect in the system, it also played a role in improving the agricultural sector by providing a water source with an acceptable quality for irrigation. This also contributed to saving freshwater and reduced the demand for it.

The obtained "Knowledge Gap" in our findings underscores that 97.2% of experts consider that operator training is the primary factor for environmental sustainability. In the absence of such training, the localized health hazards associated with greywater exposure may compromise the overall public health advantages of the system.

3.2.2.4 Health Aspects of On-site GWTUs

The results of the questionnaire showed that 52.8% of respondents did not agree with the possibility of the transmission of pathogens to people. While 30.6% expressed their agreement and 16.7% neither agreed nor disagreed. The variation in the respondents' opinions result from their observations during the implementation of the project, where the transmission of pathogens resulted from the contact with untreated greywater, and this contact is possible in the case of pipes leakage or the overflow of the tanks if there is a problem in the discharge to the manhole.

In the same context, 63.9% of respondents did not agree that the propagation of odors could affect people with health issues. While 25% agreed and 11.1% neither agreed nor disagreed. The high percentage of disagreement was because beneficiaries rarely complained from strong and noticeable odors. While for the respondents who agreed, their opinion came from their experience during the monitoring and maintenance of the treatment units in the first phase of the project. As the treatment units with leakage problem and filter clogging could cause disturbing odor emission. The results also showed that 72.2% of respondents expressed their agreement on the effect of GWTUs in reducing diseases occurrence through reducing pollution. While 27.8% neither agreed nor disagreed.

3.2.2.5 Success Criteria of Grey Water treatment Projects

The success criteria for greywater treatment projects were established based on experts' response gathered from the first questionnaire. Experts were requested to evaluate the significance of predetermined criteria employing an established rating scale. The average relevance score for each criterion was calculated and then normalized to produce weighting factors, which were assembled into a comparison matrix (Table 8). This weighting method, grounded in expert judgment, is frequently utilized in environmental and water management research, especially in data-limited and exploratory case studies.

The weighting results show that initial investment and operation and maintenance costs are the most significant success criterion (26%), highlighting the financial limitations characteristic of low-income and conflict-affected environments. The availability of trained technical personnel (24%) and the quality of untreated greywater (21%) both directly influence system performance and long-term reliability. Land availability (15%) and community familiarity with technology (14%) were assessed as comparatively less impactful, however still significant for project acceptance and viability.

The researchers examined the relationship between the sustainability of the On-site GWTUs and the identified success criteria using spearman's rank correlation coefficient test. This non-parametric test was used because of the ordinal characteristics of the questionnaire data and the restricted sample size. The results showed that there is a statistically significant relationship between the sustainability of the On-site GWTUs and the success criterion of greywater treatment projects. This relates to the fact that the availability of these criterions improve and accelerates the implementation of the project and ensures its long-term sustainability. On the other hand, these results demonstrate that the feasibility of GWTUs in Gaza is primarily an institutional and economic issue, rather than a technological one. The blockade markedly intensifies these problems, with 97.2% of experts concurring that it critically restricts the availability of construction materials and spare parts.

3.2.3. Post-War Adaptive Economic Strategies for Sustained Operation

Considering these significant environmental and survivability advantages, the economic assessment of GWTUs in Gaza must go beyond traditional cost-benefit analysis and embrace a disaster resilience approach. Although initial setup and operational expenses may be substantial, the cost of inaction evident in public health emergencies, the deterioration of agricultural livelihoods, and irreversible ecological harm, is clearly more severe. To guarantee the enduring affordability and sustainability of these systems in a dynamic environment, we offer the following strategic solutions:

1. Cost Reduction by means of Energy-Passive Design: The primary operational challenge highlighted is the six-fold escalation in expenses associated with the use of private generators during power outages ($0.9/kWh compared to $0.15/kWh). To address this, subsequent GWTU implementations must emphasize gravity-fed filtering systems or use economical solar photovoltaic (PV) modules. Separating treatment from the unstable power grid via energy-passive or renewable energy solutions is essential for attaining operational autonomy and removing the primary recurring cost, thereby rendering the environmental advantages economically viable (Oyedepo *et al.*, 2019; Garrido-baserba *et al.*, 2024)
2. Adaptive Financing Mechanisms: The shift from external humanitarian assistance to beneficiary-led maintenance frequently results in a significant "financial catastrophe". To address this disparity and guarantee the sustained attainment of environmental advantages, we propose the creation of community-oriented revolving maintenance funds. These techniques, effectively employed in other relocation contexts (UNHCR, 2024), provide resource aggregation for significant repairs and regular maintenance, thereby dispersing the financial load and alleviating the immediate impact on individual households.
3. Local Material Procurement and Capacity Development: To decrease capital expense, mitigate logistical difficulties under blockade conditions, and improve repair efficiency, GWTU designs must be modified to incorporate locally sourced or salvaged materials. Simultaneously, strong local capacity-building initiatives are crucial to provide communities with the knowledge and skills necessary for system operation and maintenance (Yimenu and Gemechu, 2026). This strategy guarantees that technical malfunctions do not result in the irreversible

abandonment of systems due to insufficient specialized imported components or experience, therefore preserving environmental and public health advancements.

By incorporating these adaptive economic strategies, GWTUs can evolve from donor-dependent initiatives into resilient, survival-focused infrastructure that is environmentally advantageous and economically sustainable for the region's population, even amidst severe crisis conditions.

3.3. *Success and Failure Lessons*

The performance of GWTUs in Gaza Strip provides valuable information and lessons to the WASH sector in humanitarian agencies for future plans and projects.

3.3.1. Drivers of Success

The water scarcity issue is the main driver for the adoption and success of the GWTUs, as the beneficiaries use the treated greywater for irrigation in the form of necessity-driven acceptance. The GWTUs provide a solution for the high water demand, and provide a good quality water alternative for the people. Additionally, the presence of external funding for the construction, operation, and maintenance of the treatment system in the first year of operation, encouraged people to accept the treatment system, highlighting the need for institutional support before the system can be community-managed.

3.3.2. Root Causes of Failure

The Failure of the GWTUs is related mainly to technical and nstitutional challenges more that technology-realted issues.

1. Construction Quality: Failure resulted from the inappropriate construction of the treatment units that caused the leakage of the untreated greywater, thereby causing localized health problems. This highlight broader problem where emergency interventions can compromise technical standards (Yimenu and Gemechu, 2026).
2. Monitoring and support: the absence of monitoring and technical support from the implementing agency let to system ignorance. Research conducted on Community-Managed Decentralized Wastewater Systems (DEWATS) frequently highlights the failure of technical support as a pivotal failure point (World Bank, 2013).
3. Knowledge gaps: Failure can be due to the beneficiaries' lack of knowledge and understanding of the system operation and maintenance. This reflects the critical need for capacity building among communities to ensure long-term viability of the system (Tuan et al., 2026).

4. Conclusions

This study shows that the on-site greywater treatment Units (GWTUs) have demonstrated significance in mitigating the water and sanitation issues encountered in regions hit by war such as the Gaza Strip. The findings indicate that the GWTUs systems have demonstrated tangible environmental, technological, health, and socio-economic advantages, especially in emergency settings with infrastructure damage and chronic water scarcity. The use of GWTUs has significantly benefited the region, encompassing the reuse of treated greywater for irrigation as reported by 86% of beneficiaries, and 71.4% overall user satisfaction.

Nonetheless, despite their benefits, these systems have problems that constrain system performance and long-term sustainability. A significant 35% of GWTUs were identified to be non-operational, mostly due to the substantial financial burdens associated with operation and maintenance (O&M) on beneficiaries, which was a source of concern expressed by 89% of respondents. When there are repeated power blackouts, people have to rely on private generators, which makes the cost of electricity go up by 600%. This makes the financial burden even worse. Also, 75% of the units leaked, which caused problems like bad smells and bugs. The fact that 73.2% of units were only monitored during the initial phase and not afterwards, along with the fact that users had inadequate experience with O&M, further compromises system reliability and public health concerns.

These issues underscore that mere technological deployment is inadequate; ongoing institutional support, user training, and contextually relevant system design are crucial to maintain functionality, especially under prolonged crisis situations. The reexamination of pre-war data considering the current crisis highlights the significance of GWTUs as an emergency and resilience-focused intervention. Their decentralized characteristics, swift implementation, and capacity to function autonomously from centralized sewage systems render them particularly appropriate for regions facing recurrent infrastructure disturbances. Scaling up these systems necessitates specific enhancements, including:

- Cost-reduction strategies: Emphasizing energy-efficient designs or incorporating renewable energy sources to reduce excessive operational expenses.
- Adaptive designs: take into consideration household size and usage patterns, while addressing important aspects like tank capacity and discharge mechanisms.
- Reinforced monitoring and training frameworks: Providing ongoing technical assistance, routine water quality assessments, and thorough user education to improve system efficacy and protect public health.

The findings, though based on a Gaza-specific case study, possess broader applicability to other conflict-affected, displaced, and water-scarce environments. This research synthesizes technical performance, user perceptions, and institutional barriers to provide evidence-based direction for funders, humanitarian actors, and policy makers pursuing sustainable WASH solutions that connect immediate disaster relief with long-term recovery. With suitable design, financial frameworks, and governance assistance, on-site GWTUs can significantly contribute to improving water security, safeguarding public health, and bolstering community resilience during extended crises.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Availability of Data and Materials

The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Declaration of Using Artificial Intelligence (AI) in the Writing Process

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