BUILDING CLIMATE RESILIENT AND SUSTAINABLE SANITATION INFRASTRUCTURE THROUGH INNOVATIVE TECHNOLOGIES TOWARDS A CIRCULAR ECONOMY

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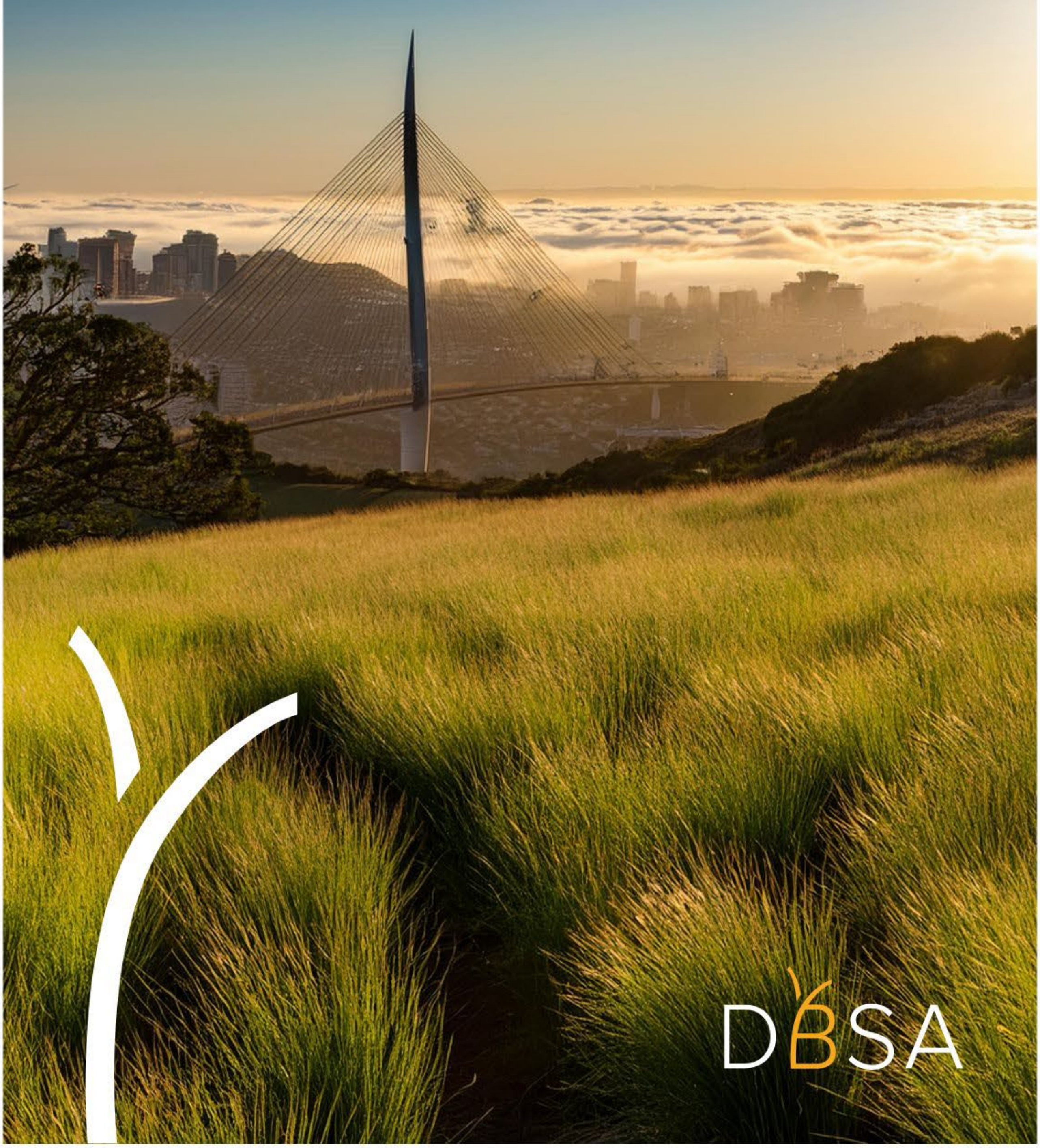

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BUILDING CLIMATE RESILIENT AND SUSTAINABLE SANITATION INFRASTRUCTURE THROUGH INNOVATIVE TECHNOLOGIES TOWARDS A CIRCULAR ECONOMY

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ABSTRACT

It is becoming increasingly recognised that poorly managed sanitation and wastewater systems are not only a significant contributor to greenhouse gas emissions (GHGs), but climate change also poses a serious threat to existing sanitation infrastructure and the public health progress made over the years. Households that have gained access to basic or safely managed sanitation services risk losing them during extreme climate-related disasters such as floods, droughts, and rising temperatures. This vulnerability will continue to prevail unless there is a shift towards emphasising that the design, selection, and implementation of sanitation systems must incorporate considerations for mitigating potential risks. There is an urgent need to research, develop, and demonstrate innovative sanitation technologies that are climate-resilient, environmentally sustainable, and promote circular economy principles within the sanitation value chain. Recognising this, the Water Research Commission (WRC) has prioritised research and innovation linking climate change and sanitation through the South African Sanitation Enterprise Programme (SASTEP). Through SASTEP, the WRC is actively evaluating and demonstrating cutting-edge sanitation technologies that are off-grid, climate-resilient, and support a circular economy by promoting water efficiency, wastewater reuse, and nutrient recovery from human waste. Most of these technologies are highly rated for climate resilience and are both mitigative and adaptive in addressing climate change challenges. These innovative solutions should be considered when selecting sanitation systems, particularly as part of long-term strategies that take future climatic projections into account. Doing so will ensure the establishment of sustainable, resilient sanitation systems that protect public health in the face of climate change.

Keywords: Sanitation, Sustainable, Circular Economy, Climate Change, Wastewater

INTRODUCTION

It is becoming increasingly recognised that poorly managed sanitation and wastewater systems are not only a big contributor to carbon emissions, but also that climate change threatens existing sanitation systems and public health progress made over the years. Households that have gained access to basic or safely managed sanitation services risk losing them during extreme climate related disasters. This will prevail until we consider and emphasize that the design, selection, and implementation of sanitation systems should consider mitigation of potential risks and shocks related to climate change. There is a need to research, develop and demonstrate innovative sanitation technologies that are climate resilient and promote circular principles within the sanitation value chain.

Climate change is a worldwide crisis. As temperatures and sea levels rise, people around the globe are increasingly experiencing heat waves, droughts, foods, cyclones, and wildfires. The effects of climate change are not equal, the poorest and most marginalised communities of our society feel the impact. Weather patterns are increasingly becoming less favourable and the frequency as well as severity of extreme events is increasing as temperatures are projected to continue rising and rainfall patterns are expected to shift. This will result in frequent flooding, heatwaves, droughts, storms, and sea level rise all of which have ripple effects on people and the environment.

Climate change impacts water availability which is going to have a negative impact on people, ecosystems, and the economy. At the same time, it exacerbates risks for water security which has negative effects on those sectors heavily dependent on water such as agriculture, electricity generation, mining, and industrial activities. Water is becoming increasingly polluted by human activities due to inadequate sanitation and open defecation practices. Also, many wastewater treatment plants are discharging sub-standard effluent as they are in critical condition (Green Drop Report, 2022)

According to the Intergovernmental Panel on Climate Change (IPCC, 2008), sanitation systems will be increasingly vulnerable if the design standards do not account for changing climate conditions and non-climate-resilient sanitation systems will expose the public to health hazards. In the event of severe flooding, damaged toilets and sanitation systems can spread waterborne disease across communities and settlements. In areas affected by drought, non-resilient sanitation systems contribute to water stress or can stop functioning, causing people to settle for open defecation. The impact of climate change will result in regression on the progress made over the years in the sanitation sector, hence the need for sanitation systems to be resilient to ensure universal access to safely managed sanitation for all as per the Sustainable Development Goals (SDGs).

The IPCC has stated that “the relationship between climate change mitigation measures and water is a reciprocal one” (IPCC, 2008). This relationship between climate change and water means that investing in climate resilient water and sanitation services is a vital part of solving the worldwide climate crisis. Supporting adaptation and climate resilient water and sanitation services makes sense from a financial point of view for both governments and users. It was indicated in COP27, recently held in Egypt, that for every dollar spent on water and sanitation services, resilience equates to 21 dollars in return and for every dollar spent on water flood, resilient upgrades equate to 62 dollars saved in flood restoration costs.

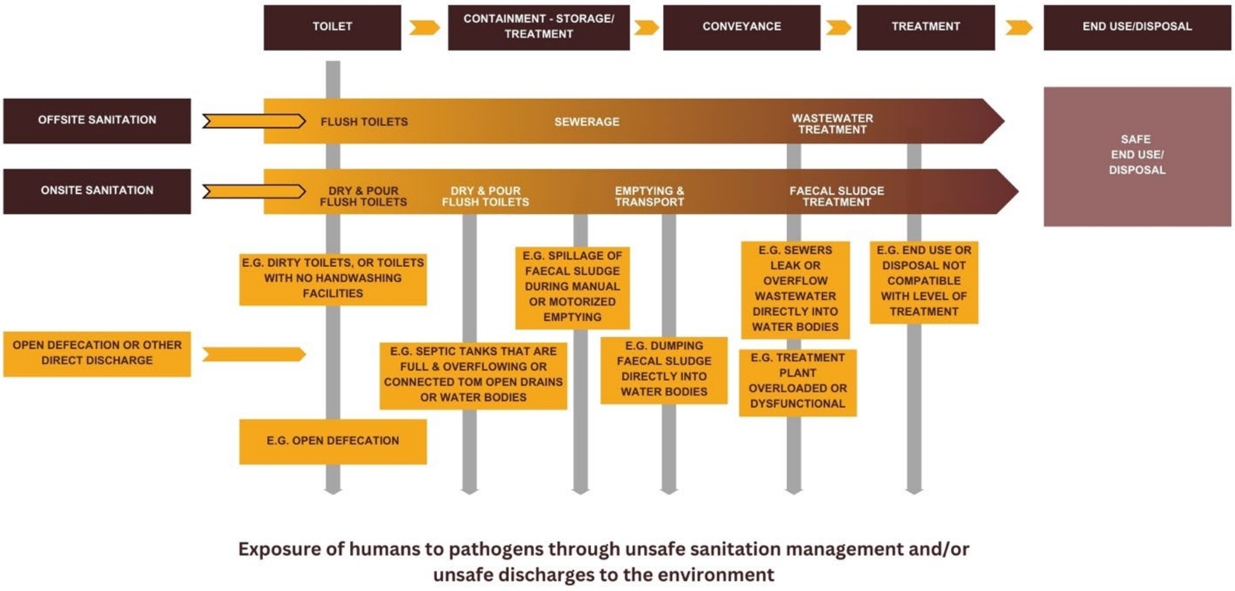

Figure 1: Excreta flow diagram showing examples of climate related hazardous events at each step of the sanitation service chain (adapted from Peal et al., 2014).

LITERATURE REVIEW

Impact of climate change on the sanitation value chain

The sanitation value chain comprises of collection/storage, transport/conveyance, treatment, and discharge/disposal or recycle/re-use as shown in Figure 1 above. Each area of the chain is highly vulnerable to the effects of climate change. Examples of some of the vulnerabilities are discussed briefly below:

Collection/storage

In areas that are not connected to sewer systems, on-site sanitation systems (septic tanks, conservancy tanks, pit toilets) are used and these systems are highly susceptible to adverse weather conditions and climate change as they can become flooded, overflow, and pollute the environment (USAID, 2015). Flooding may also result in the areas with on-site sanitation becoming isolated, as they may not be accessible during floods.

Transport/conveyance

In urban areas, sewage is conveyed through a system of pipes, pumps, and other associated infrastructure to a centralised wastewater treatment plant. These sewer systems may be damaged by extreme climatic events and cause uncontrolled discharge of raw wastewater into water resources (DEFRA, 2012), which can lead to pollution of the water resources (Howard et al., 2016). This was experienced in eThekwini Municipality during the floods in April 2022 where sanitation infrastructure was damaged.

Overflow of wastewater discharge onto streets or open ground poses a health risk to people and animals (DWS, 2016; EPA, 2004). Extended periods without any rainfall cause the degradation of sewers and the resulting accumulation of solid waste sediments can cause blockage which can result in backflow of raw sewage.

Treatment

Wastewater treatment plants are mostly located on low-lying areas as sewer systems rely on gravity, however this makes them vulnerable during flooding or sea-level rise. Declining annual rainfall or drought leads to the unavailability of water required to flush adequately and accompanying higher temperatures can have an impact on how sewage systems operate. Every extreme climate event (flooding or drought) affects the influent water quality of the wastewater treatment plants and that negatively impacts the operating efficiency and treatment ability of the plants (Howard et al., 2016).

Discharge/disposal

Flooding and drought affect the water quality of the receiving water bodies as the quality of the effluent is dependent on the volume of effluent discharge in the water resources (Miller & Hutchins, 2017). Drought has been observed to reduce the capacity of surface water to dilute, attenuate and remove pollution (DWA, 2013).

ClimateFirst Framework for rating overall resilience of sanitation technologies

The University of Technology Sydney's Institute for Sustainable Futures (UTS-ISF) developed ClimateFirst to provide guidance on assessing how the design features of sanitation systems can reduce the risks of failure during climate related hazardous events. The design features in ClimateFirst are based on a literature review of the latest thinking in resilient technological design across sanitation and other sectors and the opinions of sanitation experts. The development of the framework was supported by the Bill and Melinda Gates Foundation (BMGF). According to UTS-ISF, climate resilient sanitation service delivery includes institutional, technological, governance, service, financial, and social aspects. As such, ClimateFirst is not a complete guide to developing climate-resilient sanitation. It, however, should be considered as a resource focused on technologies and to be used as part of a wider shift towards resilient sanitation for all. Through use of ClimateFirst, sanitation designers and implementers can be equipped to rate overall climate resilience of a sanitation technology and select the best technology for the scenario at hand. The framework has 25 design features that are grouped into six categories as follows (See figure 2 also):

A. Avoiding exposure to hazards

Design features that reduce the likelihood that critical components and processes of the sanitation technology become directly exposed to a climate hazard.

B. Withstanding exposure to hazards

Design features that enable the sanitation technology to continue functioning "as normal" (i.e. no changes in hardware or operations) even when exposed to climate hazards.

C. Enabling flexibility
Design features that enable the adaptation or reconfiguration of a sanitation technology's hardware components or that enable changes to a sanitation technology's processes or operations so that the sanitation technology can continue providing services when exposed to climate hazards.

D. Containing failures
Design features that enable a sanitation technology to continue providing services (albeit potentially degraded) that meet user needs despite damage caused by climate hazards.

E. Limiting consequences of complete failure
Design features that minimise the negative consequences of a sanitation technology failing due to a climate hazard.

F. Providing benefits beyond resilience
Design features that enable the sanitation technology to provide other benefits to people or to other systems that aid in broader community or system resilience.

Category	Resilience design feature
A. **Avoiding exposure to hazards**	1. Raising
	2. Burying
	3. Portability
	4. No/low inputs
B. **Withstanding exposure to hazards**	5. Armouring and strengthening
	6. Oversizing
	7. Shapes that distribute pressure
	8. Circumvention
	9. Sealing and Barriers
C. **Enabling flexibility**	10. Adaptability
	11. Modular design
	12. Platform design
	13. Redundancy and diversity
	14. Signaling
D. **Containing failures**	15. Frangibility
	16. Fail-operational
	17. Decentralisation
E. **Limiting consequences of complete failure**	18. Safe disposal
	19. Reusable materials
	20. Fail-silence
	21. Repair speed
	22. Accessibility for rapid flaw detection and repair
F. **Providing benefits beyond sanitation technology resilience**	23. Reciprocity
	24. Hybridising
	25. Transformative capacity

Figure 2: ClimateFirst Framework resilience design features.
Source: UTS-ISF

RESEARCH METHODOLOGY AND METHOD

The Water Research Commission has prioritized research and innovation that links climate change and sanitation through the South African Sanitation Enterprise Programme (SASTEP). Through SASTEP, the WRC is evaluating and demonstrating non-sewered sanitation (NSS) technologies that are off grid and promote a circular economy within the sanitation value chain through water efficiency, water reuse and nutrients recovery from human waste. The technologies are described below:

Clear

The Clear NSS is a closed loop recycling and off-the-grid flushing toilet system. The system that treats wastewater and kills pathogens by means of a natural biological process, without the need for sewer connections, continuous water, or electrical mains supply with the uptake of the solar option. The waste stream from the toilet is initially stored in a black water collection tank. The tank provides residence time for the wastewater to equalize. The tank inventory is then pumped to the treatment section of the system where it is first treated to remove suspended solids and then it undergoes anoxic and aerobic biological treatment to remove organic and nitrogen, respectively. A special aerobic media is placed in the aerobic reactor and proprietary bacteria, specifically developed for treating wastewater is attached on the media as a biofilm. This biofilm can effectively biodegrade the organic pollutants and reduce its concentration. The treated stream is then passed through the membrane biological reactor (MBR). The MBR membranes serve as microbial barriers that can capture most of the biomass for recirculation inside the bioreactor. The MBR has exceptionally good solids/liquid separation effects and produces water that can either be reused for toilet flushing or discharged into downstream sewer directly or be reused as irrigation water. The water is dozed with ozone to further treat it and ensure it is pathogen free.

Schematic Flow

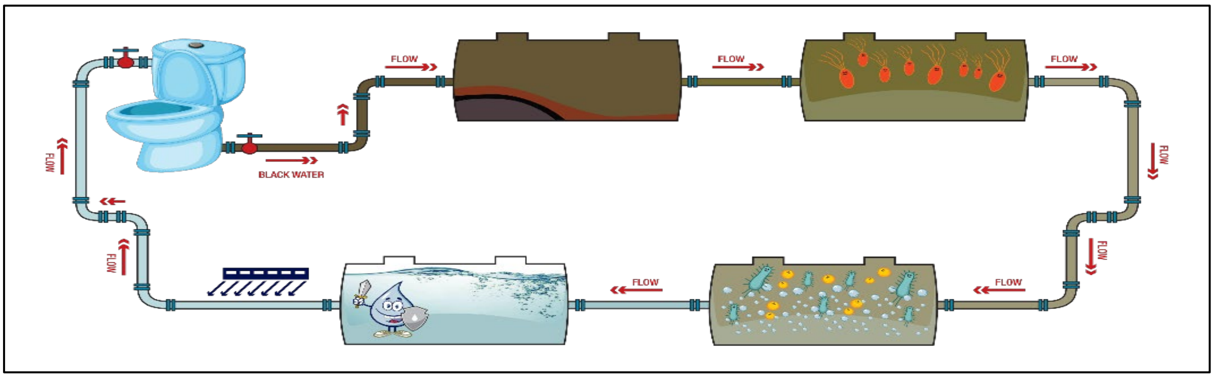

Figure 3: Schematic flow diagram of Clear NSS.
Source: American National Standards Institute

NEWgenerator

The NEWgenerator is a modular off-grid sewage treatment system that has been developed by the University of South Florida (USF). It treats sewage using an anaerobic membrane bioreactor, nutrient capture system, and electro-chlorination to produce treated water, biogas, and liquid fertilizer. Treated water can be recycled for toilet flushing to reduce the external water demands. It is supplied with a solar system to provide all power required for the off grid running of the system.

Schematic flow

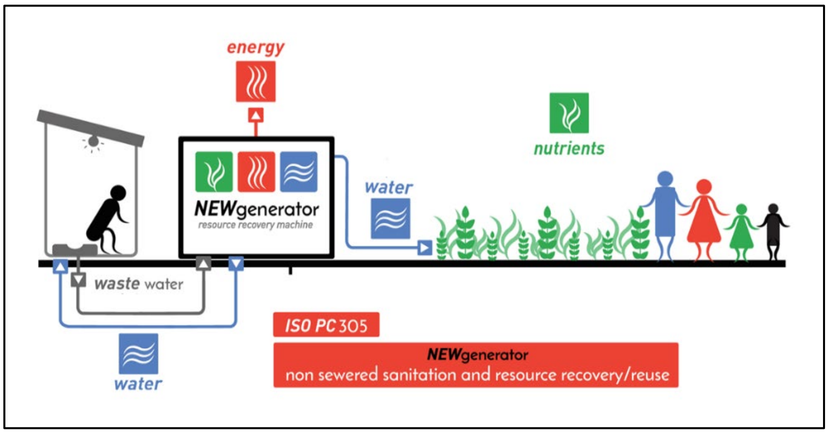

Figure 4: NEWgenerator schematic flow diagram.
Source: Wec Projects

Aquonic

Aquonic system is an onsite sewage treatment technology which treats grey and blackwater to a reusable quality for toilet flushing and/or irrigation utilizing biological and electrochemical processes. It is modular, an ideal solution to retrofit existing septic tank to improve overflow water quality output. It uses low energy and can be installed above ground or underground and it is suitable for use in public and private sector markets.

Schematic flow

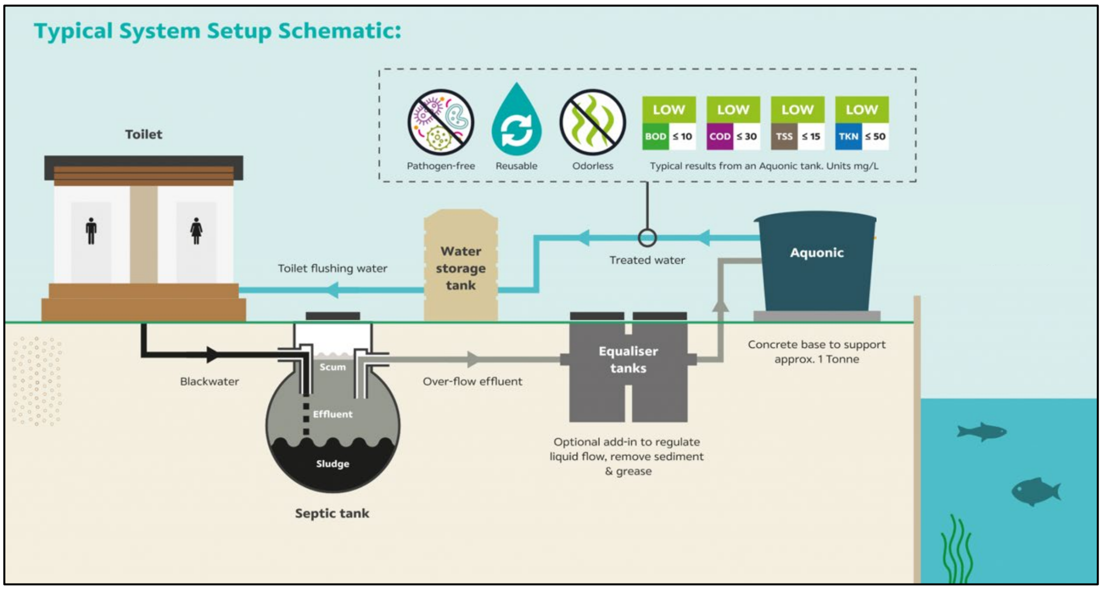

Figure 5: Aquonic schematic flow diagram.
Source: Prana Water and Sanitation

Dewdrop

The Dewdrop is a decentralized ecological wastewater treatment system with a modular design that provides convenient harvesting and reuse of domestic greywater. It can recycle up to 250L of greywater per day to produce safe, odour free non potable water for toilet flushing, car washing and garden watering. The system consists of anaerobic baffled reactor (ABR), planted gravel filter, tree filter and biochar filter for polishing of the final effluent.

Schematic Flow

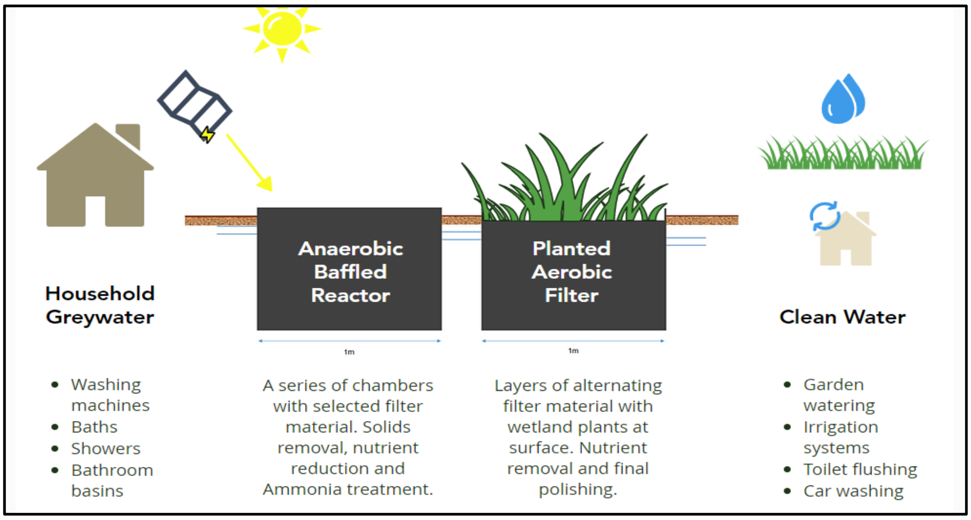

Figure 6: Dewdrop schematic flow diagram
Source: Wader Technologies

The above-described technologies were assessed for climate resilience using the ClimateFirst framework, which is a climate framework for improving resilience of sanitation technologies. ClimateFirst was developed by ISF-UTS funded by BMGF. The framework offers a process to consider how climate-related hazards can affect a sanitation technology and how the risks of these hazards can be reduced through technology design by incorporating climate resilient design features (ISF-UTS, 2023).

RESEARCH RESULTS

The detailed results of the ClimateFirst resilience framework for each of the NSS technologies are shown in Table 1 below:

Table 7: Overall climate resilience rating for non-sewered sanitation technologies

Category	Resilience design feature	Clear	NEWgen	Aquonic	Dewdrop
A. Avoiding exposure to hazards	1. Raising	Y	Y	Y	Y
	2. Burying	Y	Y	Y	Y
	3. Portability	N	N	N	N
	4. No/low inputs	Y	Y	Y	Y
B. Withstanding exposure to hazards	5. Armoring and strengthening	Y	Y	Y	Y
	6. Oversizing	Y	Y	Y	Y
	7. Shapes that distribute pressure				
	8. Circumvention	N	N	N	N
	9. Sealing and Barriers	Y	Y	Y	Y
C. Enabling flexibility	10. Adaptability	Y	Y	Y	Y
	11. Modular design	Y	Y	Y	N
	12. Platform design	Y	Y	Y	Y
	13. Redundancy and diversity	Y	Y	Y	Y
	14. Signaling	Y	Y	Y	Y
D. Containing failures	15. Frangibility				
	16. Fail-operational				
	17. Decentralisation	Y	Y	Y	Y
E. Limiting consequences of complete failure	18. Safe disposal	Y	Y	Y	Y
	19. Reusable materials	Y	Y	Y	Y
	20. Fail-silence				
	21. Repair speed	Y	Y	Y	Y
	22. Accessibility for rapid flaw detection and repair	Y	Y	Y	Y
F. Providing benefits beyond sanitation technology resilience	23. Reciprocity	Y	Y	Y	Y
	24. Hybridising	N	Y	N	N
	25. Transformative capacity	N	Y	N	N
Overall Resilience Rating		High (17/25)	High (19/25)	High (17/25)	High (16/25)

NB: Y - Yes and N – No

Source: Author's Work

Clear and Aquonic systems

Both systems have the same overall rating and resilient design features both scoring 17 out of 25 resilient design features. These systems are considered to be avoiding exposure to hazards (A), withstanding exposure to hazards (B), Enabling flexibility (C) and limiting consequences of complete failure (E) due to each having scored at least 75% of these categories of resilient design features. Both systems scored 33% in the resilient design category of containing failures (D) and providing benefits beyond sanitation technology resilience (F).

NEWgen

The NEWgen system had the highest overall rating and resilient design features scoring 19 out of 25 resilient design features. The system is considered to be avoiding exposure to hazards (A), withstanding exposure to hazards (B), Enabling flexibility (C), limiting consequences of complete failure (E), and providing benefits beyond sanitation technology resilience (F) due to the NEWgen having scored at least 66% of these categories of resilient design features. The system scored 33% in the resilient design category of containing failures (D).

Dewdrop

The Dewdrop system had a scoring of 16 out of 25 resilient design features. The systems are considered to be avoiding exposure to hazards (A), withstanding exposure to hazards (B), Enabling flexibility (C) and limiting consequences of complete failure (E) due to each having scored at least 75% of these categories of resilient design features. The system scored 33% in the resilient design category of containing failures (D) and providing benefits beyond sanitation technology resilience (F).

DISCUSSION

Climate Resilience Rating of NSS

The NSS technologies being demonstrated by WRC had 64 - 76% (16-19 out of 25) climate resilient design features in the climate resilient framework developed by UTS. Each system had at least one resilient design feature under all the 6 climate resilience design categories and thus all the technologies were rated high in terms of overall resilience. The Clear and Aquonic systems had the same scoring of 17 out of 25 for resilient design features whilst Newgen and Dewdrop scored 19 out of 25 and 16 out of 25, respectively. All the systems scored 33% in the resilient design category of containing structures which should be the areas of optimization and improvements in the future by designers and implementers.

Willingness of stakeholders

SASTEP has partnered with municipalities and the Department of Basic Education (DBE) to demonstrate new sanitation technologies, recognizing them as key early adopters. Currently, SASTEP is highlighting NSS technologies in 11 schools and 3 municipal sites. Additionally, the Department of Human Settlements has been engaged to update the design guidelines to include NSS as an option for sanitation provision. To date, DBE through its implementing agent, has procured the 48 NSS system for schools in the Eastern Cape, Kwa-Zulu Natal and Limpopo indicating their willingness to adopt these NSS.

Improvements to previous prototypes

The NSS systems has offered the following improvements from previous prototypes:

Climate resilience: All the technologies scored high on the ClimateFirst Framework for resilience.

Water efficiency: The systems are designed to be off-grid and reuse treated water for flushing, reducing reliance on external water sources.

Energy efficiency: All the NSS systems have solar options.

Integration of tools

The ClimateFirst Framework tool is used to assess the climate resilience of these sanitation technologies, though this should be harmonised with other existing tools for various aspects like design, implementation, and cost analysis, etc.

Integration with existing/traditional sanitation systems

The focus of SASTEP is on NSS technologies. These are designed for areas without existing sewer infrastructure. Integration with traditional sewer systems might not be a primary goal. However, these NSS technologies could potentially serve as alternatives in areas where traditional systems are failing or not feasible.

Addressing odor issues

NSS technologies use biological treatment processes that efficiently break down waste, thereby reducing the production of odour-causing compounds and minimising sludge accumulation, which are common issues in conventional sanitation systems. Furthermore, many of the demonstrated NSS units have been installed near users, and surveys indicate that users themselves report no odour from these systems.

Funding source for operation and maintenance

SASTEP is promoting the procurement of NSS technologies with integrated Operation and Maintenance (O&M) plans included upfront. This approach ensures that the capital expenditure (CapEx) also covers the costs of O&M through a Service Level Agreement (SLA) for a specified period. By doing so, the long-term sustainability and functionality of the sanitation systems are secured, reducing the risk of system failures, and ensuring continuous, effective operation. For schools, the cost is borne by the Department of Basic Education (DBE), while for informal settlements, the municipalities bear the cost.

CONCLUSION

WRC is demonstrating NSS technologies which have a high-rating for-climate resilience and these technologies address both climate adaptation and mitigation pathways simultaneously by being water or energy efficient, reducing greenhouse gas emissions and being off-grid.

These technologies could have at least 64% of the resilient design features embedded into their designs and be considered when selecting sanitation systems that consider future climatic projections to ensure sustainable sanitation systems in the face of climate change. NSS systems improve upon previous prototypes by emphasising climate resilience, water efficiency through off-grid design and water reuse, and energy efficiency with solar options. They mitigate odour issues through biological processes and include upfront O&M plans funded by respective stakeholders, ensuring long-term sustainability.

RECOMMENDATIONS

It is especially important that the selection of appropriate sanitation technologies also be based on screening their vulnerability and adaptability to different climate scenarios apart from technical, financial, economic, social, and environmental considerations. The selected sanitation technologies should have a high-rating for-climate resilience and high adaptability to climate change. Existing infrastructure and technologies should be assessed for climate change resilience and where feasible, be modified to reduce the adverse impacts of climate related events. Further efforts should focus on integrating NSS systems into existing sanitation frameworks where feasible and ensuring comprehensive O&M plans are included from the outset to sustain functionality and reduce operational risks.

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