

DEVELOPMENT OF AN URINE EVAPORATION SOLUTION FOR INNOVATIVE RE-ENGINEERED SANITATION SYSTEMS

Deliverable 5 Final report

A Report
to the Water Research Commission

by

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EXECUTIVE SUMMARY

In the sector of wastewater management and sustainable sanitation, the practice of urine separation and valorisation can offer reuse water and nutrients for crop production. However, the effective realization of urine separation necessitates the concurrent development of urine treatment systems. While membrane filtration techniques have been employed to concentrate urine, these options are unable to concentrate urine beyond a certain threshold. This limitation underscores the imperative of exploring alternative approaches, such as evaporation, for further urine concentration. Nonetheless, the evaporation process presents an energy demand, so it is therefore imperative to consider the development of an evaporator that is designed based on urine characteristics and to be the most efficient possible to reduce the operating costs.

This project focuses in developing and validating a cost-effective urine evaporator proof-of-concept tailored for decentralized urine systems that could be applied in two distinct scenarios: re-engineered toilets and decentralised treatment plants. The project investigates two distinct types of urine to ensure a comprehensive assessment: hydrolysed stored urine and urine treated with lime (calcium hydroxide) for its stabilisation avoiding urea hydrolysis. The project is conducted at the Water, Sanitation & Hygiene (WASH) Research & Development (R&D) Centre, University of KwaZulu-Natal (UKZN), and involves collaborative efforts with other institutions.

The first part of this project consisted in the characterisation of urine evaporation properties at the laboratory to better understand the process for the evaporator design (WP1). The results revealed that urine physiochemical properties (thermal conductivity, water activity, viscosity, and electrical conductivity) exhibited relative stability with constant values or smooth variations during the majority of the evaporation process. Notable variations in properties occurred only after achieving 60% to 80% urine evaporation (leading to a solid concentration of 4 to 6%). This suggests that evaporation predominantly occurred under steady-state conditions for the major part of the process. Only in the final stages, the solutes concentration significantly influenced urine properties, which would subsequently influence the overall process.

The heat consumed during urine evaporation was similar than the latent heat of vaporization of pure water for the majority of the process, accompanied by a similar vapor pressure. However, after evaporating 80% of the urine and achieving a 4% TS, vapor pressure decreased, and consequently the energy demand would increase to evaporate the remaining urine.

Evaporation properties of stabilised and hydrolysed urine were found to be similar, with the only exception being the pH evolution. Hydrolysed urine exhibited pH decrease during evaporation due to ammonia volatilization, leading to neutralization. In contrast, stabilised urine maintained a stable alkaline pH, showcasing the efficacy of lime pre-treatment for nitrogen recovery. Ammonia volatilization in hydrolysed urine resulted in apparent faster evaporation kinetics compared to stabilised urine.

The liquid state of urine was maintained even after achieving high levels of evaporation (up to 98%). This characteristic is advantageous for the developed evaporator, which was not designed to desiccate urine to a solid state. Evaporation did not degrade organic matter. However, it was observed that lime-treatment could have led to the degradation of a part of urine organic fraction.

The second part of the project witnessed the successful construction of the urine evaporator (WP2). The urine evaporator consists in a heated packed column where urine flows from the top to the bottom. The urine is introduced inside the column as small droplets through a spraying mechanism and flows downwards through the packing material, which is expected to increase the surface area by creating a urine thin-film. An air stream is introduced at the bottom of the column and expelled at the top to induce a counter-flow contact with the urine for a higher mass transfer. After traversing the column, urine is returned to the recirculation tank where the liquid fraction of urine is recirculated to the evaporator. The cycle is repeated until concentrating the urine at a given solids concentration, and the concentrated urine is then discharged into an outlet collection tank. Various sensors are integrated into the system to monitor critical parameters (temperature, relative humidity, pH, electrical conductivity).

Preliminary tests were conducted using both water and saltwater. The urine evaporator demonstrated functioned as intended, validating the envisioned proof-of-concept. The optimal conditions for the urine evaporator were identified: ventilation pre-heating activated, maintaining a temperature range of 30-40°C, and utilizing pall rings as filling material in the evaporation column. Despite successful functioning, there is room for improvement and optimization in the evaporator design and operation. Notably, energy consumption was found to be comparatively high when compared to reverse osmosis. The challenge lies in reducing both capital and running costs to enhance the commercial viability of the urine evaporator.

Preliminary estimates indicated an energy consumption of 3 kWh/l, translating to an estimated running cost of R225/month/person. This underscores the need for further efficiency improvements. An encouraging finding was the positive impact of integrating a solar thermal energy collection system into the evaporator. Despite a higher initial investment, the long-term cost was found to be less than half of the expenses incurred when running the evaporator using electricity from the grid.

Preliminary discussions took place with EnviroSan regarding the potential integration of the urine evaporator into the re-engineered toilets backend. Conversations also occurred with Teddy Gounden, the former Executive Manager at eThekweni Water & Sanitation, exploring the possibility of establishing a urine centre at the Newlands-Mashu sanitation research facility. The envisioned centre would allow the evaporator to be relocated for testing and optimization. Furthermore, it could be connected to other urine-related projects, e.g. the continuation of the VUNA project if it happens.

As the continuation of this project, a new Mechanical Engineering final year project is slated to commence in March to October 2024, focusing on the development and construction of a second version of the evaporator. This iteration aims to incorporate improvements based on lessons learned from the current project. During this phase, increased communication with sanitation technology developers (such as EnviroSan, SLU – Sanitation 360 and VUT – BAAS) is anticipated to promote the adoption of the urine evaporator technology.

After this, the exploration of opportunities for a project proposal to extend the current initiative will be undertaken. The foundation for this continuation will be built upon the data acquired in the laboratory and the development of the two versions of the urine evaporator. The new project will aim to delve into the integration of solar thermal energy into the technology and the combination with a membrane process. The intended applications include the incorporation of this technology in re-engineered toilets with urine diversion and decentralized urine treatment plants.

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ACRONYMS & ABBREVIATIONS

DEWATS	Decentralised Wastewater Treatment System
DSC	Differential Scanning Calorimetry
EC	Electrical conductivity
IWA	International Water Association
NSS	Non-Sewage Sanitation
R&D	Research & Development
RH	Relative humidity
RO	Reverse osmosis
RUNRES	RURal-urban Nexus – Establishing a nutrient loop to improve city region food system RESilience
SDG	Sustainable Development Goal
SEC	Specific Energy Consumption
TC	Thermal conductivity
TGA	Thermogravimetric analysis
TS	Total solids
TSS	Total suspended solids
UKZN	University of KwaZulu-Natal
VS	Volatile Solids
VUT	Vaal University of Technology
WASH	Water, Sanitation & Hygiene
WISA	Water Institute of Southern Africa
WP	Work Packages
YWP	Young Water Professional

1. INTRODUCTION

1.1 BACKGROUND

In the realm of wastewater management and sustainable sanitation, the practice of urine separation and valorisation has emerged as a crucial facet. Recognizing its significance, this interest delves into the multifaceted aspects of urine separation, exploring the benefits it offers and the transformative potential it holds for a variety of challenges. If treated adequately, urine valorisation can offer reuse water and fertilizers due to its high content in chemical elements with relevant nutrient value for crop production, such as nitrogen, phosphorous and potassium. Urine separation can therefore address a range of issues, including the impending water scarcity resulting from climate change-induced droughts and flooding. It also plays a pivotal role in ensuring food security, countering the scarcity of fertilizers attributed to mineral depletion and supply chain disruption. Moreover, its practice aligns with Sustainable Development Goal (SDG) 6, contributing to the implementation of an improved sanitation system and sustainable water supply, as well as SDG 2 to ensure food security worldwide.

To facilitate the practical implementation of urine separation, innovative pedestal designs have surfaced, as the one developed by the Austrian company EOOS (<https://www.eoos.com/>). This pedestal technology enables urine separation by the tea drop effect with a user interface similar than the conventional toilets (i.e. without a physical separation of the toilet bowl for urination and defecation), allowing a better public acceptance. South Africa has ventured into urine diversion initiatives, as evident from the implementation of urine diversion toilets with the EOOS design and manufactured at low-cost by the local company EnviroSan (<https://envirosan.co.za/>) with financial support from the Water Research Commission. However, the effective realization of urine separation necessitates the concurrent development of urine treatment systems, specifically tailored for re-engineered toilets and decentralised treatment plants. While membrane filtration techniques have been employed to concentrate urine, in particular reverse osmosis, these options are unable to concentrate urine beyond a certain threshold. This limitation underscores the imperative of exploring alternative approaches, such as evaporation, for further concentration of urine or the production of a solid fertilizer. Nonetheless, the evaporation process presents an energy demand difficult to afford, due to the high latent heat of water vaporisation and the additional energy input required to break the electrostatic interactions of water molecules with the solutes in a urine solution. Besides, to the best knowledge of the authors, almost no evaporation technologies have been specifically designed to deal with urine, which highlights the need to bring efforts in this crucial area. It is therefore imperative to consider the development of an evaporator that is designed based on urine characteristics and to be the most efficient possible to reduce the operating costs. The energy consumption is a critical factor in South Africa due to the current energy crisis leading to frequent loads heeding episodes and power outages, and an increase of the electricity rate.

1.2 AIM

The aim of this project was to present the development of a cost-effective urine evaporator proof-of-concept, intended for integration within decentralized systems. This transformative endeavour held the potential to significantly advance the field of sustainable sanitation, specifically in terms of urine management.

1.3 SPECIFIC OBJECTIVES

This project originally encompassed the following set of specific objectives:

- Objective 1: characterizing the properties of urine evaporation at the laboratory;
- Objective 2: conceptualization and design of a urine evaporator;
- Objective 3: construction of the urine evaporator, followed by rigorous testing to validate its efficacy;
- Objective 4: exploration of the integration of the urine evaporator into existing innovative sanitation systems, particularly emphasizing its placement in the back-end of these systems;
- Objective 5: investigation of the viability of harnessing solar energy to power urine evaporator;
- Objective 6: Study concerning the fertilizer potential of dried urine, as well as the potential presence of contaminants.

1.4 SCOPE OF THE PROJECT AND INITIAL STRATEGY

The project was conducted at the Water, Sanitation & Hygiene (WASH) Research & Development (R&D) Centre, University of KwaZulu-Natal (UKZN), and involved collaborative efforts with other institutions. The project focused in developing a cost-effective urine evaporator tailored for decentralized urine systems that could be applied in two distinct scenarios: re-engineered toilets and decentralised treatment plants. The design criteria emphasized simplicity, low-cost implementation, energy efficiency, and compatibility with renewable energy sources. The project investigated two distinct types of urine to ensure a comprehensive assessment: hydrolysed stored urine and urine treated with lime (calcium hydroxide) for its stabilisation avoiding urea hydrolysis.

The project advanced through several phases divided into 4 Work Packages (WP):

- WP1: The project started with a literature review to better understand urine properties and conceptualize the urine evaporator. After this, the urine evaporation properties were characterised at the laboratory which were meant to be used for the design and optimization of the evaporator as part of an MSc project. This part of the project was conducted in collaboration with SLU (Swedish University of Agricultural Sciences), which gave advice on the type of experiments to undertake.
- WP2: The conceptualisation, design, construction and testing of the urine evaporator was carried through a mechanical engineering undergraduate students project.
- WP3: As the project would reach its culmination, a discussion was envisaged to be initiated regarding the integration of the urine evaporator within current sanitation technologies, including the EnviroSan pedestal based on the EOOS design, the Sanitation360 toilet (developed by SLU), Vapoorize Toilet (developed by BAAS Technology and Consulting and Vaal University of Technology (VUT)) and the decentralised wastewater treatment plant in in eThekweni municipality where urine separation is practiced.
- WP4 (OPTIONAL): The project's holistic approach extended to evaluating the application of the final product, namely the dried urine, in agricultural settings, in collaboration with the UKZN Crop Science discipline. This part of the project could be linked to the "RUrban-urban Nexus – Establishing a nutrient loop to improve city region food system RESilience", an initiative funded Swiss Agency for Development and Cooperation for the valorisation of waste for food production, project where UKZN is involved.

Note that WP4 was optional and could not be conducted since further funding was not obtained for this WP.

The interlinkage between the different WP is summarised in Figure 1.1. The participation of the collaborators in the different WP of the project is shown in Table 1.1.

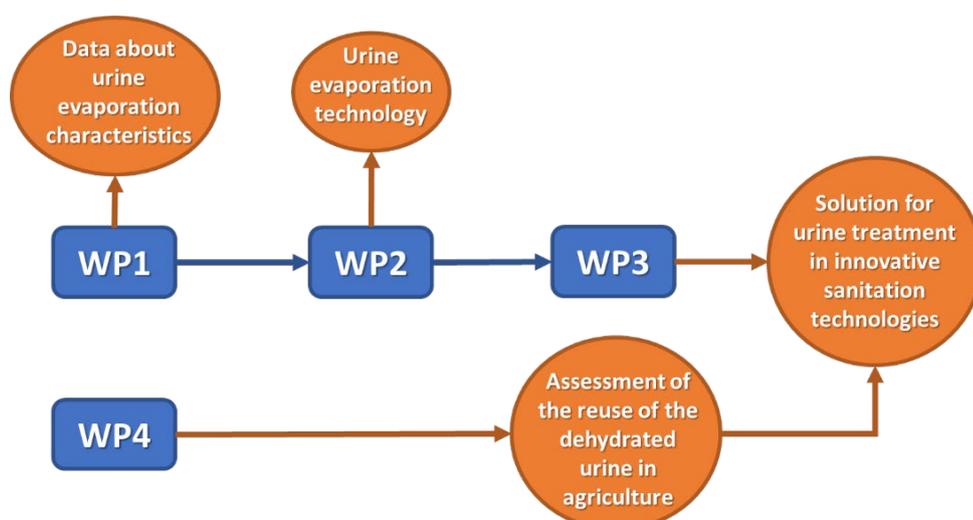


Figure 1.1. Summary of the strategy of the project

Table 1.1. Participation of the collaborators in the different WP

WP1	WP2	WP3	WP4
WASH R&D Centre			
UKZN Chem Eng			
	UKZN Mech Eng		
		UKZN Crop Science	
VUT / BAAS			VUT / BAAS
SLU / Sanitation 360			SLU / Sanitation 360
			EnviroSan

1.5 SUMMARY OF PREVIOUS DELIVERABLES

The project milestones encompassed the following deliverables:

- Deliverable 1: An inception report that outlined the project strategy and introduced initial concepts for the urine evaporator;
- Deliverable 2: A comprehensive literature review exploring evaporator technologies and various concepts applicable to the design of the urine evaporator.
- Deliverable 3: Presentation of the experimental plan detailing urine evaporation characteristics in the laboratory, along with preliminary test results. This deliverable also included an overview of the urine evaporator design with the latest construction progress updates.
- Deliverable 4: A draft final report providing insights into the progress of experimental work for urine evaporation characterisation in the laboratory. Additionally, it included a description of the urine evaporation construction process and testing results.
- Deliverable 5: The final report (current report) consolidating the results from urine evaporation characterisation at the laboratory and the entire process from the urine evaporation design to construction and testing, including a preliminary techno-economic analysis. Moreover, it describes the next steps that will be undertaken for the continuation of this project.

The Deliverable 1 to 4 can be consulted from **Supporting Documents A** (including the presentations and minutes from the Reference Group meetings).

1.6 OUTLINE OF THE REPORT

This project is structured as follows:

- Chapter 1 (current chapter) provides a comprehensive background of the project, outlining the motivation to carry out this investigation, the aim, objectives, scope, and initial strategy.
- Chapter 2 focuses on the experimental work conducted to characterise urine evaporation in the laboratory, as part of WP1. This chapter includes a detailed presentation of the methodology and results.
- Chapter 3 delves into the development and testing of the urine evaporator, integral to WP3. It encompasses the conceptualization, design, testing methodology, results from initial tests, a techno-economic analysis and a study about how solar energy could be integrated into this technology.
- Chapter 4 concludes the project, offering insights into the outcomes and the way forward. This chapter provides a summary of the project's achievements, including capacity building and knowledge dissemination. It also discusses any milestones that could not be achieved, along with the remaining final activities to close project. Additionally, the chapter outlines the strategy for the project's continuation.

2. EXPERIMENTAL WORK TO CHARACTERISE URINE EVAPORATION

In this Chapter, the methodology employed to accomplish the objective of characterizing urine evaporation properties as part of work package 1 (WP1) is outlined. The comprehensive experimental plan designed to investigate various thermodynamic, chemical, mechanical, physical, and thermal properties during urine evaporation is elaborated upon. Furthermore, the specifics of urine collection and the subsequent analyses are detailed to provide a clear understanding of the research approach.

The documentation with the detailed information from this work can be consulted in **Supporting Documents B**.

2.1 METHODOLOGY

The experimental work from this project aimed at the characterisation of urine evaporation properties that have not been explored in literature and that are deemed to be relevant for the design of a urine evaporator. The following aspects were identified to guide the experimental work:

- Determination of the process thermodynamic properties, specifically the heat required for evaporation as a function of urine concentration.
- Determination of the process kinetics to estimate the urine evaporation rate.
- Identification of the changes in urine chemical, mechanical, physical, and thermal properties along evaporation. This includes monitoring the water activity, pH, density, viscosity, thermal conductivity, and heat capacity.
- Detection of the urine solutes precipitation through the measurement of the total suspended solids, electrical conductivity, and particle size distribution (PSD);
- Tracking the changes in consistency through qualitative observations.

The experiments were carried out with hydrolysed stored urine and urine stabilised with lime (calcium hydroxide). A comparative analysis of urine evaporation behaviour was performed between the two types of feedstock at 40°C, maximum temperature permitted for the lime-stabilised urine to avoid urea thermal degradation. Evaporation was tested at 100°C, corresponding to the water boiling point at ambient conditions, for hydrolysed urine only.

2.2 URINE COLLECTION

The process of urine collection was the first step in the experimental work. The following subsections elaborate on the methods and details of urine collection.

2.2.1 Hydrolysed stored urine

Urine was collected from the urine diverting toilets from a taxi rank located in Greyville, Durban (Figure 2.1). The collected volume consisted around 20 L. The urine was then subjected to storage in a refrigerator at 4°C to maintain its integrity for further analysis.



Figure 2.1. Photograph from urine collection

2.2.2 Fresh urine

Fresh urine was obtained through voluntary donations done at the facilities from the WASH R&D Centre. Most of the donors were part of the staff from the WASH R&D Centre, consisting in a pool of healthy male and female individuals in the age range of 20 to 60 years old.

At the end of each day of donation, 10 g of lime was added to 1 L of urine. After lime addition, the urine pH was measured to check it reached alkaline levels to inhibit urea hydrolysis. The total collected volume was around 20 L, and measures were taken to store the samples in a refrigerator at 4°C for subsequent testing.

2.2.3 Urine characterisation

Most of the properties of the initial urine samples were measured in the laboratory following the standard operating procedures from the WASH R&D Centre. The results from the analyses are displayed in Table 2.1.

Table 2.1. Initial properties of the hydrolysed and lime-stabilised urine

	TS (g/L)	TSS (g/L)	VS (g/L)	COD (g/L)	pH	EC (mS/m)	Density (kg/L)	Heat Capacity (J/kg/K)	Water activity
Hydrolysed urine	13.53 ± 0.01	0.99 ± 0.00	6.53 ± 0.01	9.4 ± 0.1	8.77 ± 0.03	30.3 ± 0.2	0.98 ± 0.01	5278 ± 284	1.01 ± 0.04
Lime stabilised urine	14.43 ± 0.04	3.52 ± 0.02	6.07 ± 0.01	3.9 ± 0.6	12.44 ± 1.04	19.0 ± 0.1	1.00 ± 0.01	5246.62 ± 296	1.03 ± 0.00

Both urine samples had the same water activity, density and heat capacity. Their water activity was equal to 1, showing that the water in the raw urine solution behaved thermodynamically as pure water with the same vapour pressure. The density of the urine samples was also very similar to that from pure water. Nonetheless, the urine heat capacity was considerably higher than pure water, probably due to the effect of the solutes.

The electrical conductivity was higher for the hydrolysed urine compared to the one stabilised with lime. This result was probably attributed to the higher ammonium ions concentration in the hydrolysed urine, resulting from the degradation of urea into ammonium ions that increased the electrical conductivity of the solution. The lime addition in the stabilised urine stopped urea hydrolysis, hence avoiding the formation of ammonium ions. The pH of the stabilised urine was higher than that of the hydrolysed urine probable because of the addition of lime, which alkalinised considerably the urine. The pH of the hydrolysed urine was as expected after urea has been hydrolysed into ammonium, leading to a rise of the pH until achieving the pKa of the acid-basic ammonium ions / ammonia pair around 9.

The COD and VS was lower in the stabilised urine maybe because the lime oxidised organic matter leading to the organic content decrease. The stabilised urine exhibited a higher TS and TSS content than that from the hydrolysed samples, which could be due to the addition of lime to the urine. Indeed, the lime added up to the solids already present in urine. Besides, it was observed that a fraction of the lime did not dissolve into the urine, increasing the TSS. The non-dissolved lime settled at the bottom of the beaker, which could explain the more limpid look of the stabilised urine in comparison to the hydrolysed sample. The latter exhibited a more dark and turbid aspect probably because the solid particles were suspended in the solution (Figure 2.2). Note that the difference of composition between the two samples could be partially explained from where the urine was originated.



Figure 2.2. Stabilised (right) and hydrolysed (left) urine samples

2.3 EXPERIMENTAL PLAN

The experimental plan encompasses various tests aimed at achieving the experimental work goal. The methods employed for different types of tests are elucidated in the following subsections.

2.3.1 TGA-DSC tests

The *Artisan SDT-Q600 Simultaneous* TGA-DSC tests enable to determine the simultaneous heat and mass variations during the evaporation of the urine samples. The data generated from these tests aid in determining the process kinetics and the heat consumed by evaporation along the process. The tests were undertaken at the Mechanical Engineering Department from the Durban University of Technology. During the tests, the samples were heated at rate of 10°C/min until reaching the set temperature (40 or 100°C). The initial mass of sample was around 90 µL. An air stream flowed around the crucible holding the sample.

2.3.2 Evaporation rate tests in the moisture analyser

The evaporation rate of urine was determined using a *Radwag Max 50* Thermal Moisture Analyser. The device allows to measure the water content of the sample after heating it at 40 or 100°C.

2.3.3 Evaporation in oven

For this experiment, urine was left to evaporate in an oven at temperatures of 40°C or 100°C (depending on the test). The first stage consisted in determining the evolution of the total solids content as a function of time. Once this relationship was established, a small portion of the sample was taken out of the furnace during

evaporation for the analyses of various properties at different total solids contents. The various analyses carried out are displayed in Table 2.2.

Table 2.2. Urine properties measured during evaporation in the oven

Property to measure	Instrument / method	Significance
Total solids	<i>Radwag Max 50</i> Thermal Moisture Analyser	Verification of the amount of water evaporated
Total suspended solids	Filtration + oven drying of the solid residue	Detection of precipitation of the urine solutes during evaporation
Water activity	<i>AquaLab Tunable Diode Laser-TDL</i> water activity meter	Measurement of the binding energy of water with the solutes in urine, vapor partial pressure and osmotic pressure
Thermal properties (thermal conductivity, heat capacity)	<i>C-Therm TCI™</i> thermal conductivity analyser	Determination of the thermal behaviour of urine during evaporation
Electrical conductivity	Probe Hach MM150	Detection of precipitation of the urine solutes during evaporation
pH	Probe Hach MM150	Detection of the changes in chemistry during evaporation
Density	Measurement of mass of a given volume	Characterisation of the relationship between mass and volume at different stages of evaporation
Viscosity	Capillary tube viscometer (<i>Ametek Brookfield</i> rotation viscometer for low viscous fluids)	Characterisation of the flow behaviour of urine at different stages of evaporation
Visual observation	Photographs	Detection of solutes precipitation, consistency modifications and phase changes

2.4 RESULTS AND DISCUSSIONS

2.4.1 Preliminary results

Evaporation trial tests were conducted in the oven at 40°C for 1 L of hydrolysed and stabilised urine. After 5 consecutive days in the oven, the sample volume was reduced to 100 mL, representing 90% of reduction, as it can be appreciated in Figure 2.3 compared to Figure 2.3. Salt precipitation could be observed after taking out the urine from the beakers (Figure 2.4).



Figure 2.3. Stabilised (right) and hydrolysed (left) urine samples at the after 5 days evaporation at 40°C



Figure 2.4. Precipitated salts remaining in the beaker after taking out the urine

The evaporation process occurred slowly with a mass loss of around 3-4 g/h, which could be explained by the low urine interfacial surface area and large headspace volume from the beakers employed for these tests, limiting the mass transfer of water vapour molecules from the urine to the environment. Therefore, new tests were conducted with new containers offering a considerably higher surface area and a good exchange with the surrounding air. The results show that urine evaporated at a considerably higher rate and evaporation was completed within a few days. The evaporation tests were carried out with these containers from this point.

2.4.2 Evaporation rate and heating flux

The TGA-DSC tests were completed but the data needs to be further analysed. For the moment, the evolution of the mass of the stabilised and hydrolysed urine samples during evaporation at the different temperatures was determined as displayed in Figure 2.5. The energy consumed during evaporation for the different samples was plotted in Figure 2.6. Each curve represents the average of the triplicate measurements.

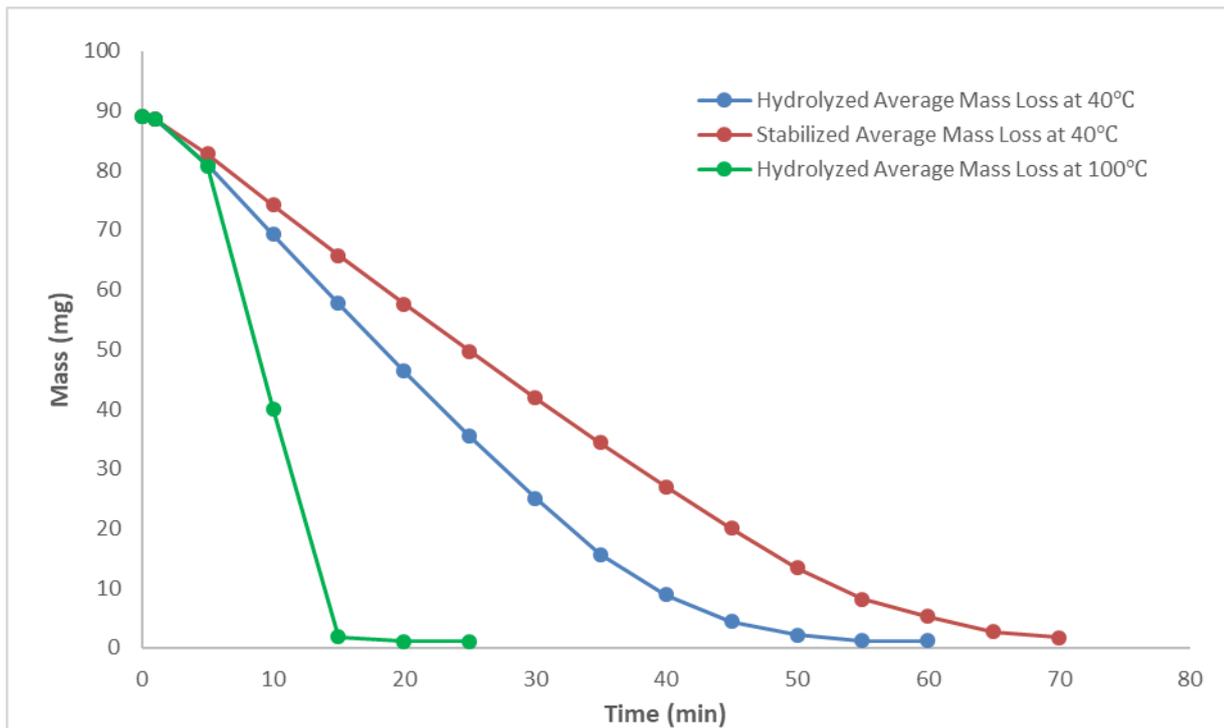


Figure 2.5. Mass of urine samples during evaporation at different temperatures

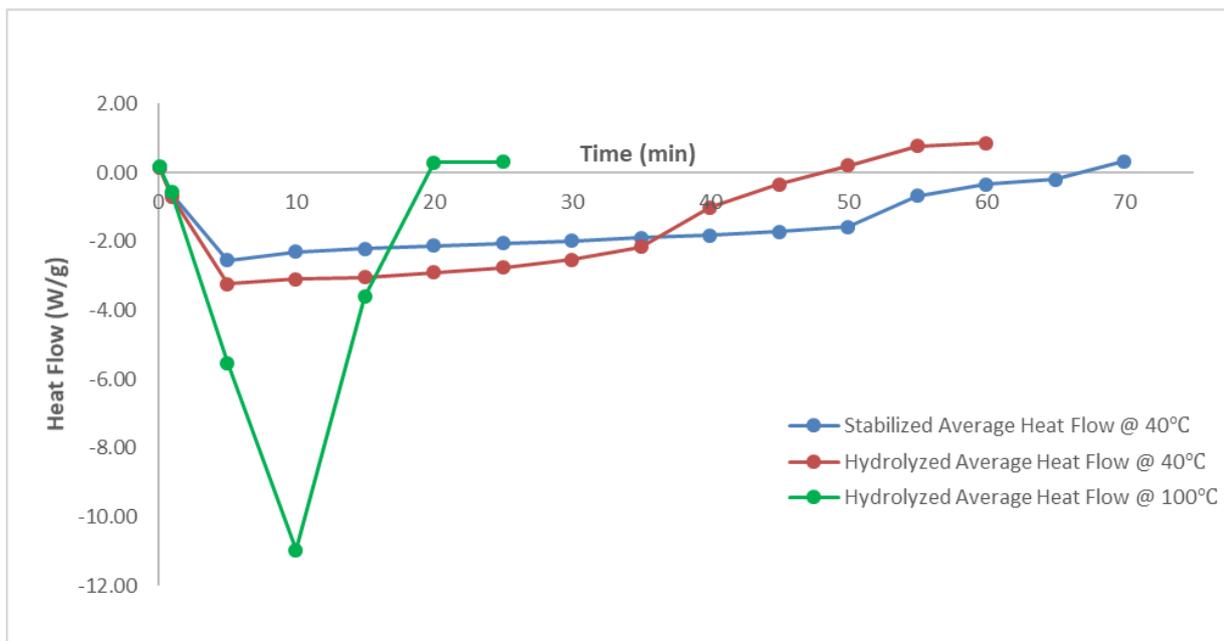


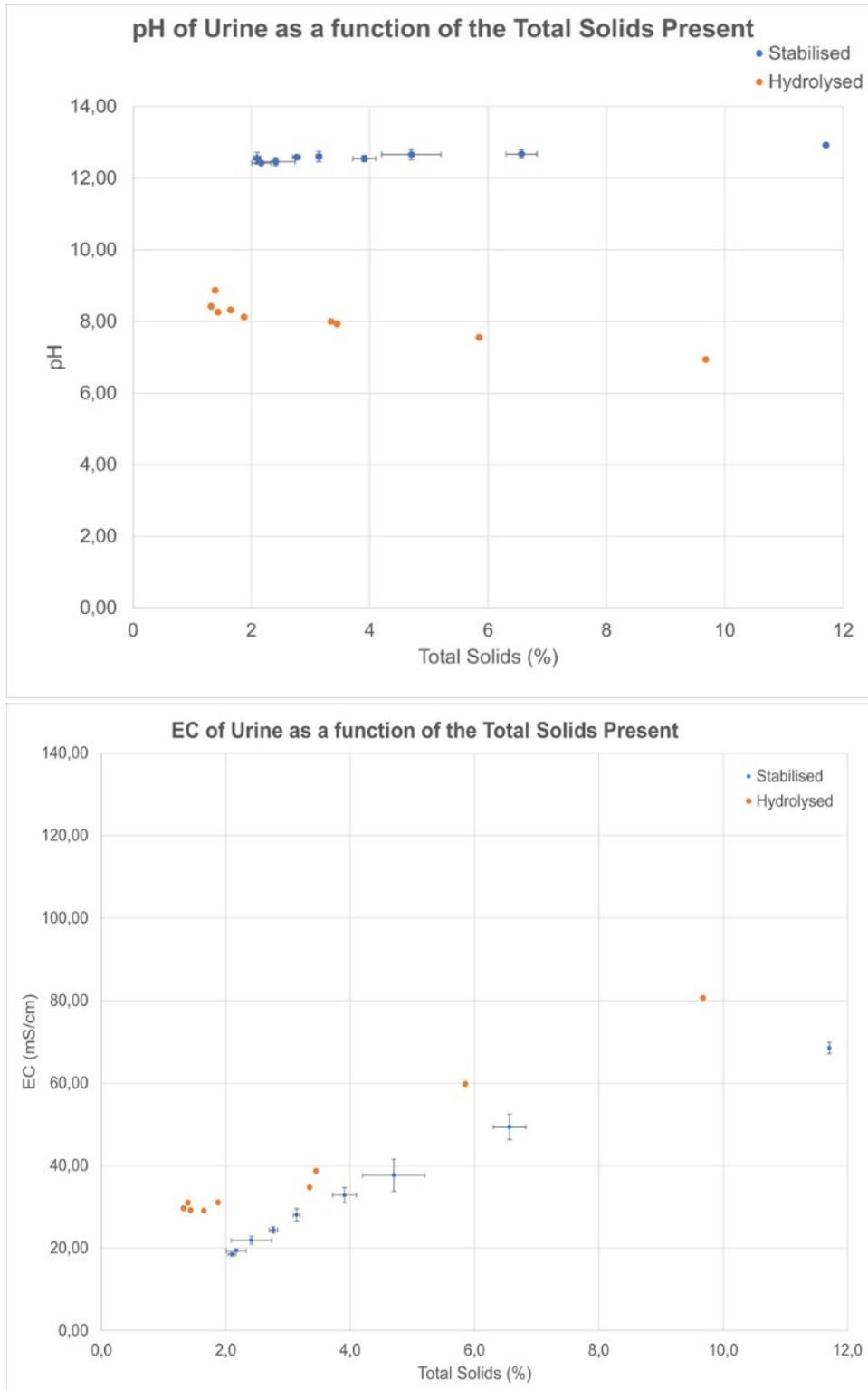
Figure 2.6. Energy consumption during the evaporation of the urine samples at different temperatures

As expected, evaporation occurred much faster at 100°C compared to 40°C (Figure 2.5). Evaporation at 100°C led to a higher energy consumption peak but during a shorter time (Figure 2.6). This could be due to a higher evaporation rate. Comparing the evaporation of the different urine samples at 40°C, it can be observed that the hydrolysed urine was evaporated slightly faster than the stabilised urine (Figure 2.5), but the energy consumption was close between the two cases (Figure 2.6).

A finer analysis of the evaporation kinetics will be undertaken and the specific energy consumption will be determined for urine evaporation at the different experimental cases.

2.4.3 Evolution of the thermophysical properties of urine during evaporation

The investigation involved monitoring the evaporation process of the urine samples at varying TS levels. Figure 2.7 illustrates the significant observations made regarding several key physiochemical properties throughout this process. The evaporation tests led to a striking reduction in water content up to approximately 93% from the tenfold increase in solids concentration from the initial 1%w TS to around 12%w TS.



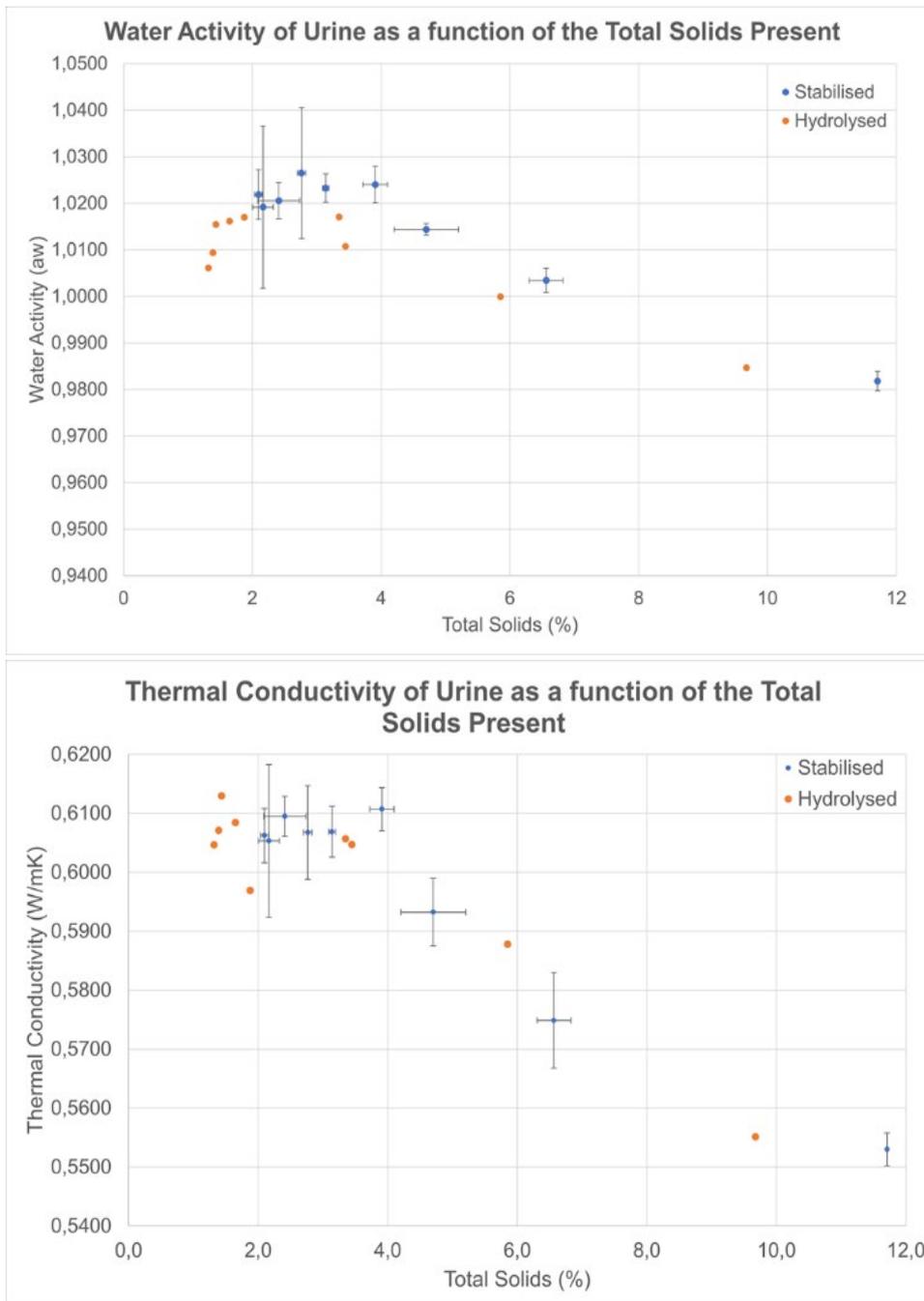


Figure 2.7. pH, electrical conductivity, water activity and thermal conductivity of the stabilised and hydrolysed urine after evaporation to different total solids up to 11%

Regarding pH, stabilised urine exhibited a consistent pH level hovering around 12 throughout the evaporation process. In contrast, hydrolysed urine experienced a considerable shift in pH, dropping from 9 to 7. This change is attributed to the volatilization of ammonia gas, leading to a subsequent reduction in ammonium ions, an alkaline compound, consequently impacting the pH of the solution.

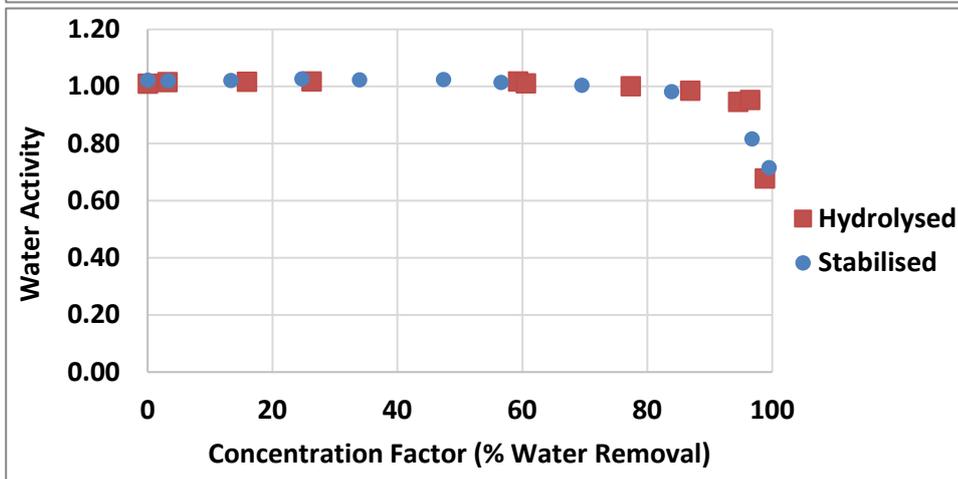
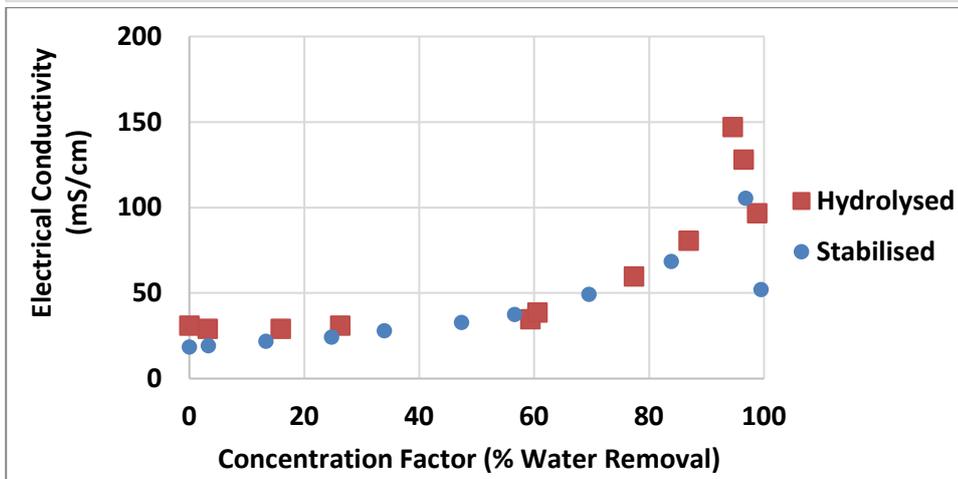
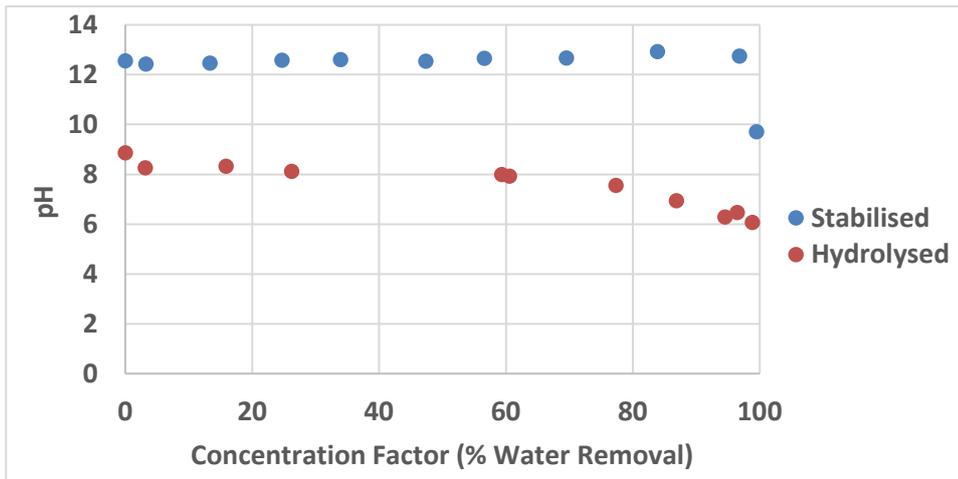
Electrical Conductivity (EC) demonstrated a consistent increase in both stabilised and hydrolysed urine samples during evaporation. This increase of EC was a direct result of the rising solids content, particularly the increase in ions within the solution. Interestingly, the EC of hydrolysed urine was notably higher than that of stabilised urine, primarily due to the presence of nitrogen in the form of ammonium ions, as previously discussed in section 3.2.3.

Water activity remained relatively stable around 1 for both urine samples until reaching 6% TS, after which it exhibited a decline. This trend suggests a significant binding of water from the urine with solutes present in the

solution, leading to a subsequent decrease in vapor pressure by approximately 2%. Notably, the type of urine did not seem to significantly influence this property.

Thermal conductivity initially mirrored water's value at 0.6 W/m/K and remained constant during evaporation until reaching 4% TS. However, beyond this threshold, a slight decrease in thermal conductivity to 0.55 W/m/K, approximately 10%, was observed. Like water activity, the type of urine did not demonstrate a noticeable impact on this property.

Figure 2.8 illustrates the progression of urine physicochemical properties during evaporation across a broader total solid range in comparison to Figure 2.7. In these graphs, urine evaporation achieved a remarkable 98% reduction in moisture, resulting in a final total solids content of approximately 60%. This significant volume reduction is well-suited for the urine evaporation process. It is important to note that even at 60% total solids, the urine remains in a liquid state.



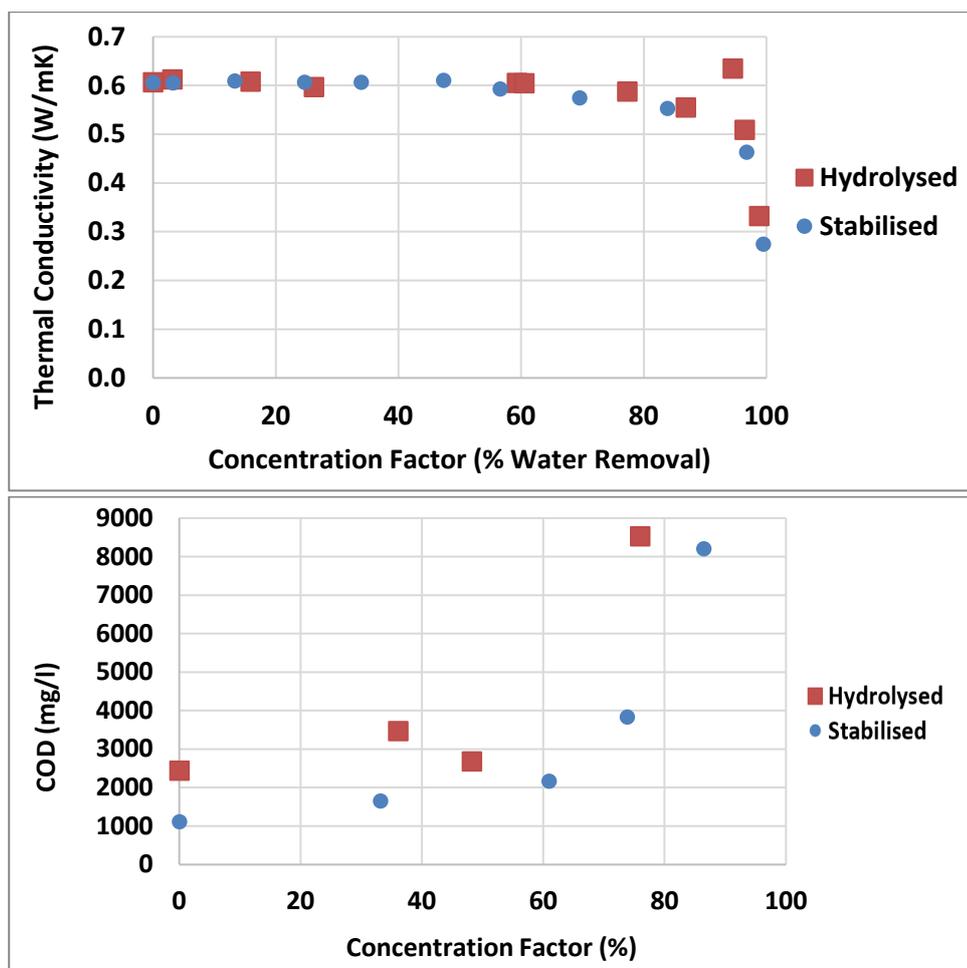


Figure 2.8. pH, electrical conductivity, water activity, thermal conductivity and COD of the stabilised and hydrolysed urine during evaporation until achieving a concentration factor of 99% (corresponding to 60% total solids)

As it can be seen in Figure 2.8, the pH of hydrolysed urine exhibited a gradual decrease from 9 to 6, while stabilised urine maintained relative pH stability around 13, with a decline after reaching a concentration factor of 97% (equivalent to 33% TS). The observed decrease in the pH of hydrolysed urine may be attributed to ammonia volatilization, as previously pointed out. The pH stability of stabilised urine across the process demonstrate the efficacy of lime addition to avoid ammonia loss and consequently to retain the nitrogen.

Figure 2.8 showed that the electrical conductivity increased similarly in both urine samples, displaying a smooth, nearly linear progression (as displayed in Figure 2.7) until reaching a concentration factor of approximately 60% (corresponding to 4% TS). Beyond this point, an exponential increase was observed, indicating a significant concentration of salts in the urine that starts to have an effect on its properties. An apparent drop in electrical conductivity was noted at a concentration factor of 95% (23% TS), but this could be attributed to potential experimental errors arising from the low amounts of liquid available for analysis after having evaporated most of the water, since it is difficult to depict a physical explanation of this behaviour.

As shown in Figure 2.8, water activity remained stable at around 1 for both urine samples until reaching a concentration factor of 80% (corresponding to 6% TS). Beyond this threshold, the water activity decreased exponentially (results observed with a higher resolution in Figure 2.7). This trend suggests that urine behaved thermodynamically like pure water until about 87% of water was removed, implying that urine exhibited the same vapor pressure at its surface than that of pure water at the same pressure and temperature conditions. The subsequent decrease in water activity reflected that the influence of salt concentration started to affect urine vapor pressure, presumably leading to a decrease of water volatilisation. However, it can be assumed that the overall energy required for urine evaporation was similar to the energy required for pure water vaporisation, given that water activity was equal to 1 during the major part of the evaporation process.

Preliminary calculations using the TGA-DSC data (Figure 2.4) confirm that the specific heat of urine evaporation was comparable to the latent heat of water vaporization (calculations pending confirmation). Thermal conductivity remained relatively stable until a concentration factor of 60% (i.e., 4% TS), after which an exponential decrease was observed according to the results from Figure 2.7 and Figure 2.8. This trend was consistent for both urine samples. Notably, the inflection point from which thermal conductivity decreased coincided with the point from where the electrical conductivity started to exponentially, demonstrating a relationship between electrical conductivity and thermal conductivity. It can be then deduced that, beyond 60% of urine evaporation (or > 4% TS), the impact of solids became pronounced (particularly the salts), leading to an increase in electrical conductivity and a decrease in thermal conductivity. Nevertheless, there is no discernible effect of the solid concentration on urine volatilization until reaching a higher urine concentration (> 80% concentration factor, or > 4% TS), at which point water activity began to decrease. The COD experienced an exponential increase (Figure 2.8), likely due to the concentration of organic matter after water evaporation. As discussed in section 2.2.3, COD in stabilised urine was lower, potentially because lime had oxidized organic matter. The COD evolution observed during the evaporation indicated no significant degradation or volatilization of the organic matter.

Figure 2.9 illustrates viscosity measurements obtained at various vane rotation rates using a rotational viscometer for raw hydrolysed and stabilised urine (1-2% TS), as well as evaporated samples (2-42% TS).

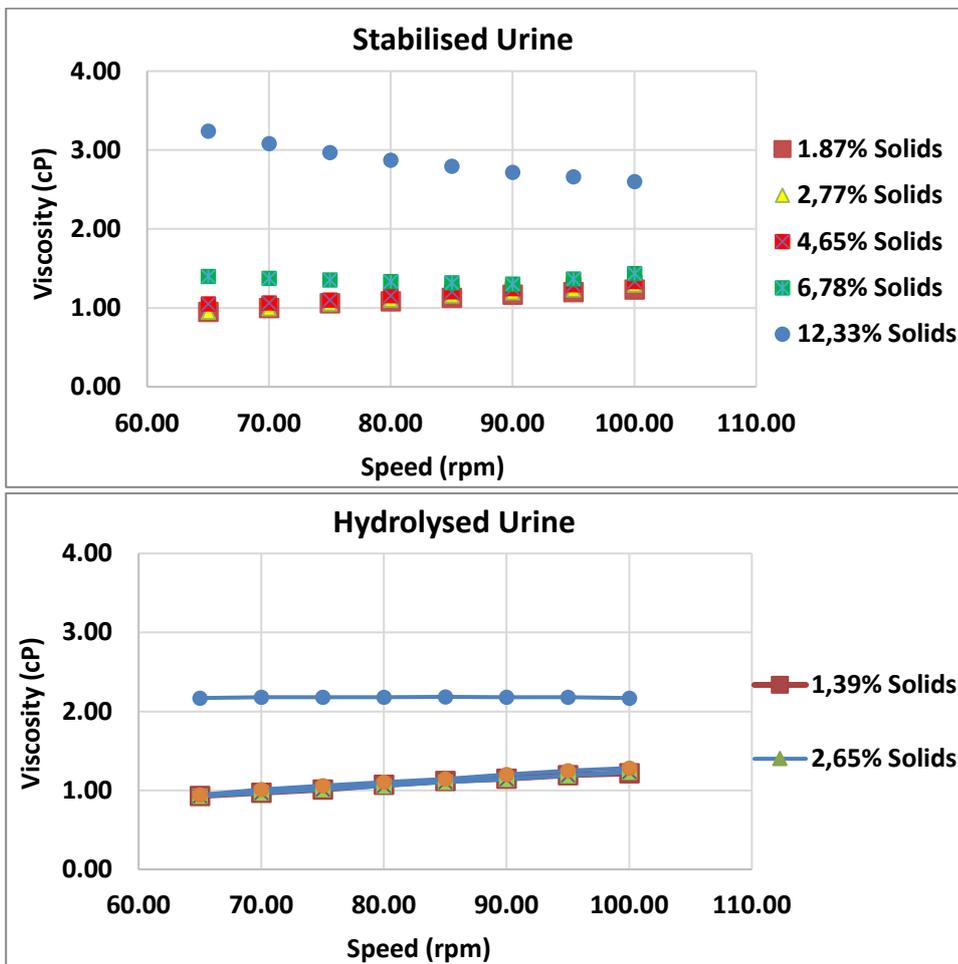


Figure 2.9. Viscosity measurement at different vane rotation rate for urine at different TS

For total solids concentrations lower than 7%, minimal to no difference in viscosity was observed between the raw and evaporated urine samples. Within this range, both raw and hydrolysed urine exhibited similar viscosities, ranging from 1 to 1.5 cP, closely aligning with the typical value of water (~1 cP). It is noteworthy

that viscosities tended to increase at higher vane rotation rates, suggesting a potential non-Newtonian characteristic induced by the suspension in the urine affecting the measurements.

At higher total solid concentrations, viscosity significantly increased. Notably, stabilised urine demonstrated a higher viscosity than hydrolysed urine even with lower total solid (viscosity between 2.5 – 3.5 cP for 12% TS stabilised urine versus a viscosity close to 2 cP for 41% TS hydrolysed urine).

These findings have important implications. The viscosity of urine remained largely unchanged or experienced a slight modification during most part of the evaporation process, at least until removing approximately 80% of the water from the urine. A significant increase in viscosity was observed only until achieving the final stage of evaporation. In this stage, stabilised urine appeared to exhibit higher viscosity than hydrolysed urine. However, this last observation remains inconclusive and necessitates further exploration.

2.5 CONCLUSIONS

The addition of lime into urine increased the pH by alkalinising the solution, decreased the electrical conductivity by avoiding the release of ammonium ions from urea degradation, and decreased the VS and COD probably by oxidising part of the organic matter. Lime addition did not affect the physical properties, such as density, water activity, heat capacity and thermal conductivity. Some properties of the raw urine were similar to that pure water, such as density, thermal conductivity and vapour partial pressure. The lime stabilised samples looked much clearer than the hydrolysed samples, but the TSS content was higher due to the non-dissolved lime that settled at the bottom of the beaker.

The TGA-DSC evaporation tests suggest that urine stabilised with lime evaporated at a slower rate compared to hydrolysed urine, even though the energy consumed seemed quite similar between the two samples. This result could be due to ammonia volatilisation that was accelerated by the hot temperatures during evaporation, but this must be verified with further testing.

The characterisation of urine properties during evaporation may assist in understanding the evaporation behaviour of the hydrolysed and stabilised samples. During the major part of the evaporation process, most of the urine properties remained fairly stable or varied only slightly (e.g., the smooth increase of the electrical conductivity). Urine evaporation beyond 80% water removal caused a drastic electrical conductivity increase and thermal conductivity decrease, while evaporation beyond 80% water removal resulted in a considerable water activity decrease and viscosity increase. These trends were probably result of the increase of the solute concentration, leading to higher ionic strength, subsequently increasing the electrical charge concentration in the solution and the binding of the water molecules with the ions, leading to a more viscous and less volatile liquid medium where heat is transferred less efficiently. Nonetheless, because these changes occur rather at the final stage of the process, evaporation will occur mostly at steady urine conditions. Another important implication from these results is that the energy consumption could be expected to remain constant during most of the evaporation process, with a specific heat of evaporation that could be approximated to the latent heat of water vaporisation (since the water activity was equal to 1 until achieving 80% of concentration).

The evaporation behaviour was similar between the hydrolysed and stabilised urine, with the exception of the pH that decreased for the hydrolysed urine, probably due to ammonia volatilisation, while it remained constant for the stabilised urine thanks to the action of the lime.

To finish, evaporation seemed to not affect the organic material in the urine, which was consequently more concentrated as water was evaporated. The increase of organic matter could be a cause of fouling in the evaporator, so a special attention to this should be taken during the evaporator operation.

3. DEVELOPMENT OF THE URINE EVAPORATOR (WP2)

This Chapter describes the core of the project, consisting in the development and testing of the urine evaporator. In this Chapter, the basic concepts of the urine evaporator, the component, the development process, the testing procedure and results are presented. The urine evaporator was developed and tested by undergraduate mechanical engineering students through their final year project. The work of the students is detailed in the reports that can be consulted in **Supporting Documents C**.

3.1 FUNDAMENTAL CONCEPTS OF THE URINE EVAPORATOR

The underlying concept of the urine evaporator is driven by optimizing mass transfer to enhance the efficiency of water vaporization. This is achieved through the following key mechanisms:

- Increasing surface area generated by breaking the urine into small droplets and creating a thin film on surface the surface of the material within the evaporator.
- Continuous airflow around the urine to avoid the saturation in humidity of the surrounding atmosphere and enhance the migration of water molecules from the urine interfacial surface to the air.
- Elevating the temperature of both urine and air stream serving to amplify water volatility and decrease air relative humidity.
- Recirculation strategy in batch mode, involving the recirculation of urine within the evaporator to attain specific concentration solids levels and water removal.

3.2 OPERATING PRINCIPLE OF THE URINE EVAPORATOR

The urine evaporator is depicted in Figure 3.1 and its process flow diagram can be observed in Figure 3.2. The process initiates with urine being fed into the recirculation tank from the feed reservoir tank. Subsequently, the urine is pumped from this tank into the evaporator, consisting in a heated packed column (illustrated in Figure 3.3). The urine is introduced inside the column as small droplets through a spraying mechanism and flows downwards through the packing material, which is expected to increase the surface area by creating a liquid thin-film. The packing material is placed inside a grid basket that can be removed easily from the column. An air stream is introduced at the bottom of the column (underneath the basket) and expelled at the top to induce a counter-flow contact with the urine for a higher mass transfer. An electrical resistance element is incorporated within the column to expedite the heating process. This mechanism ensures rapid volume heating, accelerating the evaporation of urine. The air stream could be preheated before introduction into the evaporator to reduce the relative humidity, which augment the vapour water holding capacity of the air stream. After traversing the column, urine is collected from the bottom and is sent to a stirrer tank to induce the coagulation of precipitates through intensive mixing for a faster settling. After this stage, urine is returned to the recirculation tank where the coagulated precipitates are expected to settle at the bottom of this tank. The liquid fraction of urine (expected to be above the settling area) is recirculated to the evaporator. The cycle is repeated until concentrating the urine at a given solids concentration, and the concentrated urine is then discharged into an outlet collection tank. The different tanks and piping are set in a metallic frame, ensuring stability and structural integrity.

Various sensors are integrated into the system to monitor critical parameters. These include:

- pH and electrical conductivity sensors within the recirculation tank to track the progress of the process and changes in the urine chemistry;
- Relative humidity and temperature sensors at the inlet and outlet air streams to track the amount of evaporated moisture;

- Thermocouples at strategic points within the different tanks and the different sections within the evaporator.

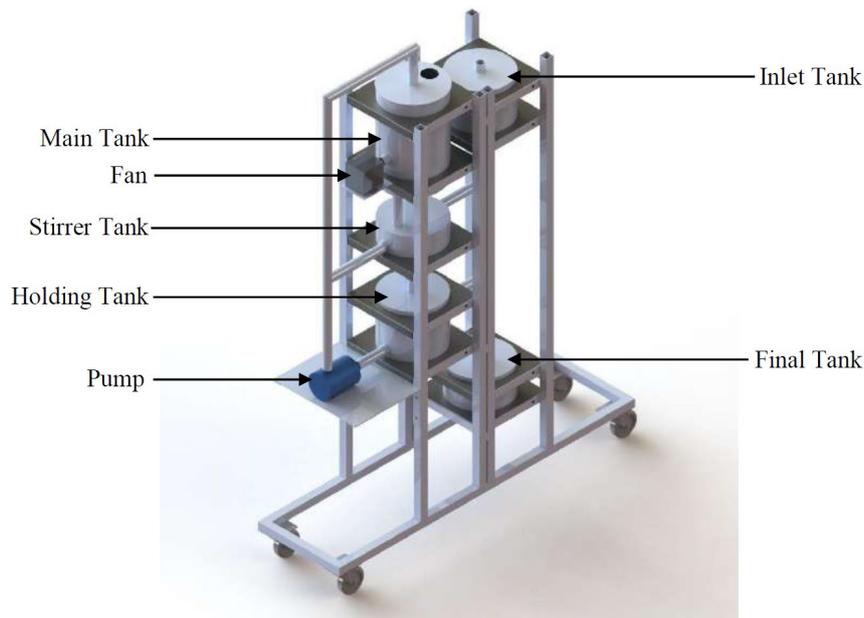


Figure 3.1. Drawing of the urine evaporator

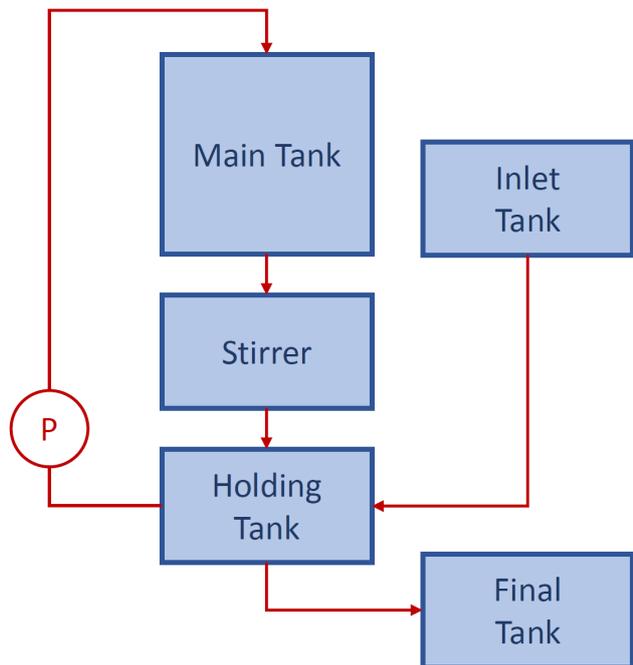


Figure 3.2. Process flow diagram of the urine evaporation system

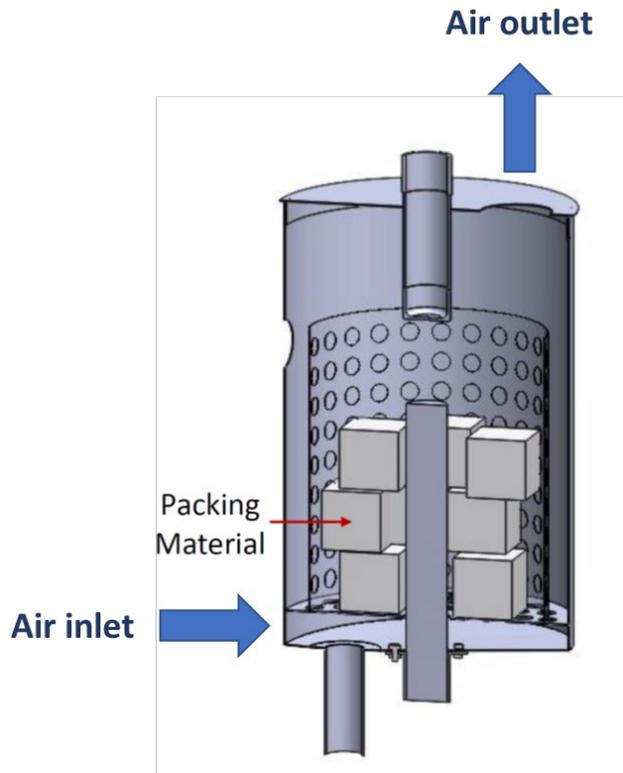


Figure 3.3. Drawing of the packed column

Figure 3.4 depicts a photograph of the urine evaporator with its main components.

Appendix A entails a comprehensive breakdown of the urine evaporator's components, and their functions and specifications. This tabulated data serves as a pivotal reference point, offering intricate details regarding the diverse constituent integral to the functioning of the urine evaporator.

Appendix B exhibits an array of visual representations, capturing the essence of the building of the prototype until getting the entire system. These images meticulously portray the building stages of the urine evaporator, including the building of the frame, installation of the tanks, and the setup of piping, instrumentation and electrical connections. Such visual documentation proves instrumental in providing a detailed overview and facilitates an in-depth analysis of the system's structural intricacies.

Despite the substantial progress made, several crucial tasks remain pending due to time constraints: the setup of thermal insulation into the tanks and pipes, a mechanical stirrer in the stirring tank, and pH / electrical conductivity sensors in the recirculation tank. The incorporation of thermal insulation stands as a priority, essential for fortifying the system's thermal efficiency and ensuring optimal performance during subsequent test cycles. Additionally, the installation of a mechanical stirrer within the stirring tank holds significance to augment the agitation and mixing capabilities, expecting that this will enhance coagulation of the precipitates in large particles that can settle in the recirculation tank. Moreover, the integration of pH and electrical conductivity monitoring mechanisms into the recirculation tank remains important for precise measurement of these key parameters, a crucial aspect for the system's effective functionality and control.

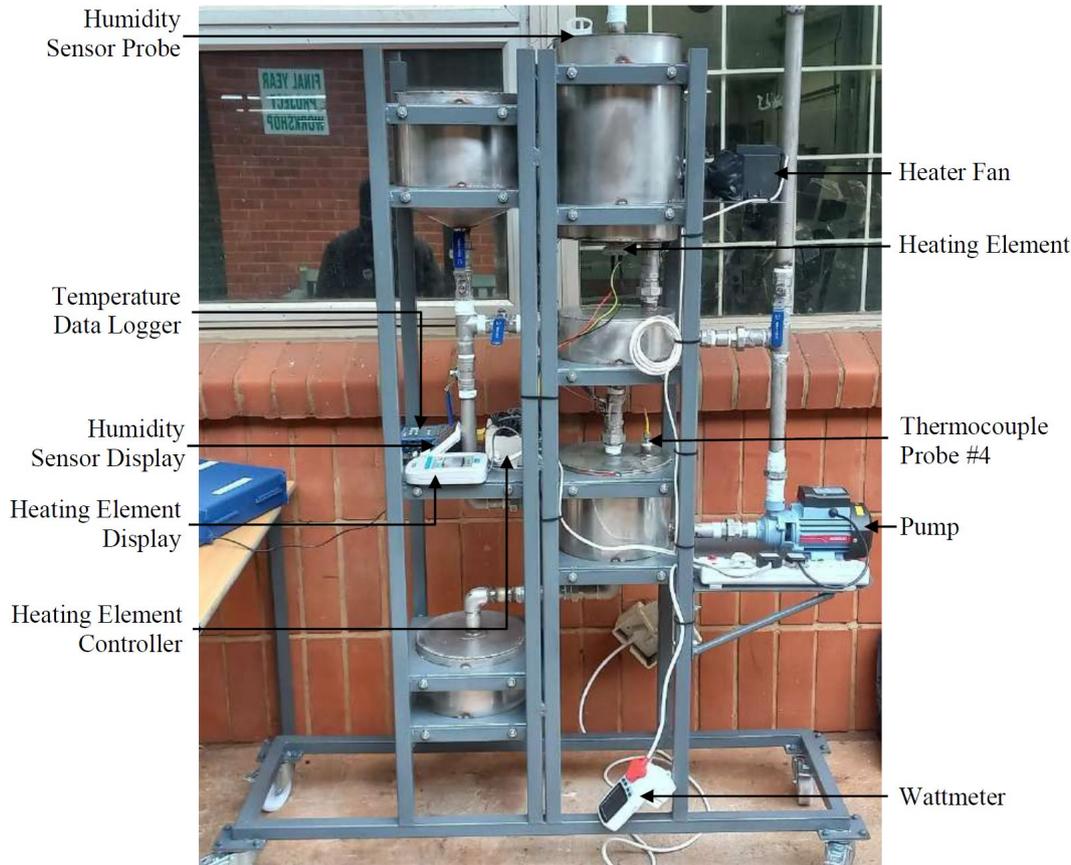


Figure 3.4. Final urine evaporator

3.3 TESTING OF THE EVAPORATOR

3.3.1 Methodology

Throughout the experimental phase, a series of four tests were conducted to comprehensively evaluate the urine evaporator's performance under diverse conditions. The duration of each test was 90 minutes.

These experiments encompassed:

- Varying the packing materials between pebbles and polypropylene pall rigs (as shown in Figure 3.5);
- Adjusting the heating element temperatures to 30°C, 40°C, and 50°C;
- Exploring the impact of individual heating systems focusing solely on the heating of the evaporator column or the air stream;
- Assessing the system's response to different feedstocks such as tap water and salty water (prepared after adding table salt until reaching an electrical conductivity close to urine, i.e. around 22 mS/cm).



Figure 3.5. Pebbles and polypropylene pall rigs used as packing material during the tests of the urine evaporator

Table 3.1 provides a comprehensive summary of the experimental conditions employed in each test.

Table 3.1. Summary of the runs conducted during the urine evaporator testing

Number of the run	Feedstock	Packing material	Temperature evaporator	Air stream heating
1	Water	Pall rigs	40°C	ON
2	Water	Pebbles	40°C	ON
3	Water	Pall rigs	30°C	ON
4	Water	Pall rigs	50°C	ON
5	Water	Pall rigs	40°C	OFF
6	Water	Pall rigs	No heating	ON
7	Salty water	Pall rigs	40°C	ON

Essential parameters were measured meticulously measured and logged, including:

- The temperature within the drying chamber monitored via thermocouples;
- The relative humidity at the outlet measured by a hygrometer;
- The power consumption measured using a wattmeter;
- The final volume of the evaporated water recorded at the experiments' conclusion from the outlet tank.

Utilizing the gathered data, critical metrics such as the evaporation rate, system efficiency, and specific energy consumption (SEC) were calculated. These calculations serve as fundamental indicators for understanding the system's performance and energy utilization efficiency. The evaporation rate refers to the rate of water evaporation per unit time (Equation 4.1). The efficiency evaluates the system's effectiveness in converting energy input into the desired output, i.e. evaporated moisture (Equation 4.2). The specific energy consumption (SEC) determines the amount of energy utilized per unit of water evaporated, aiding in understanding the system's energy efficiency (Equation 4.3).

$$r_{evap} = \frac{V_i - V_f}{t} \quad \text{Equation 4.1}$$

$$\eta = \frac{L_{vap} \cdot r_{evap} \cdot \rho_W}{P} \times \frac{1}{3600} \quad \text{Equation 4.2}$$

$$SEC = \frac{P}{r_{evap}} \times 1000 \quad \text{Equation 4.3}$$

Where:

- r_{evap} : rate of evaporation [l/h]
- V_i and V_f : initial and final volume of the feedstock [l]
- t : time of the test [h]
- η : efficiency [-]
- L_{vap} : latent heat of water vaporisation [2,260 kJ/kg]
- ρ_W : density of water [1 kg/l]
- P : power consumed [kW]
- SEC : specific energy consumption to evaporate 1 m³ of water [kWh/m³]

3.3.2 Results of testing

Table 3.2 shows the performance parameters extracted from the conducted testing.

Table 3.2. Summary of the results from the urine evaporator testing

Number of the run	Evaporation rate (L/h)	Power (kW)	Efficiency	SEC (kWh/m ³)
1	0.383	0.575	42%	1,500
2	0.300	1.020	18%	3,400
3	0.367	0.551	42%	1,500
4	0.427	0.982	27%	2,300
5	0.066	0.515	8%	7,800
6	0.007	0.534	1%	76,300
7	0.260	0.754	22%	2,900

It can be observed that run 1 and 3 led to the highest efficiency and lowest SEC, whereas run 4 resulted in the highest evaporation rate. These results suggest that:

- The propylene pall rigs are a more efficient packing material than pebbles;
- The evaporator heating element and air stream heating must be turned on for more optimal results;
- Operating at low temperature (30 and 40°C) leads to a more efficient evaporation that consumes less energy to evaporate the same amount of water compared to operating at higher temperature (50°C), even though the evaporation rate is higher in the latter case.

Hence, it can be deduced that utilization of pall rigs alongside heating the evaporation chamber at 30 or 40°C and activating the air stream heating yielded to the most optimal results. The SEC exhibited its lowest value at approximately 1,500 kWh/m³. This value is significantly higher than the 2.5 to 4.0 kWh/m³ range typically observed in reverse osmosis (RO) systems for seawater desalination. The thermal efficiency, averaging around 42%, is considered acceptable but holds potential for improvement. Integration of thermal insulation is anticipated to enhance this metric.

Under these conditions (run 1 and 3), it was also observed a higher stability in both temperature control and power consumption compared to the other cases. This disparity is graphically illustrated in Figure 3.6 and Figure 3.7, comparing the temperature and power readings from run 1 (optimal conditions) and run 2.

The evaporation rates with salt water experienced a lower evaporation rate, declining from 0.36 L/h to 0.26 L/h. This shift resulted in an approximate twofold increase in SEC to 2,900 kWh/m³ and a corresponding decrease in efficiency to 30%.

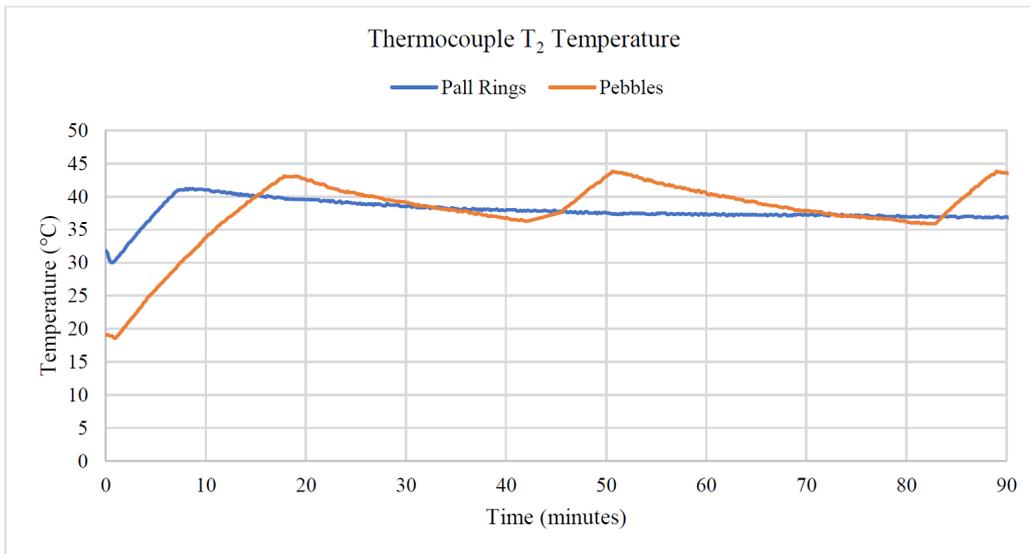


Figure 3.6. Measured temperature in the evaporator by thermocouple T₂ during run 1 and run 2 (with pall rings and pebbles as packing material, respectively)

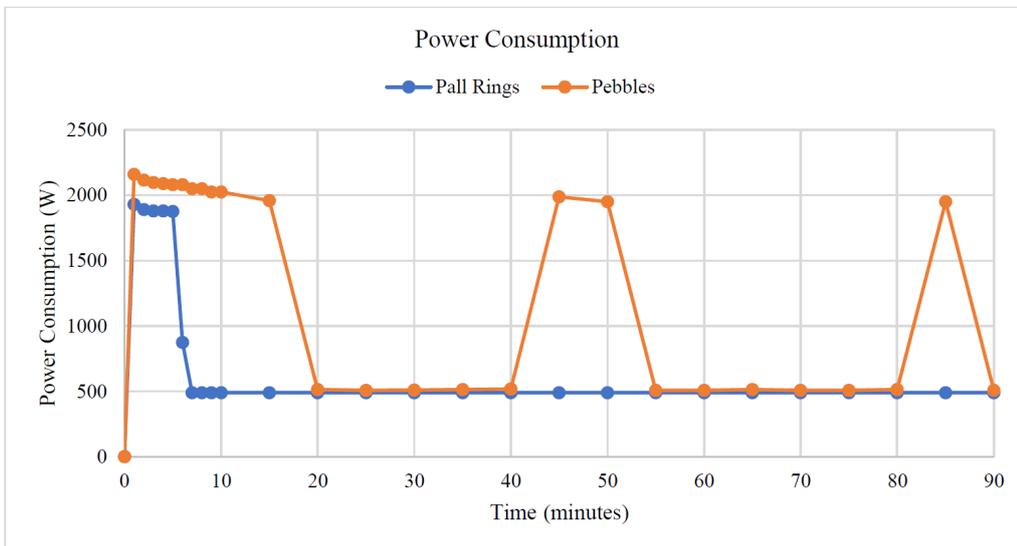


Figure 3.7. Measured power during run 1 and run 2 (with pall rings and pebbles as packing material, respectively)

3.4 TECHNO-ECONOMIC ANALYSIS

Table 3.3 provides an overview of the prototype construction costs, totalling approximately R72k as the capital investment. Considering the calculated SEC for evaporating saltwater at 40°C from the previous section, i.e. 2,900 kW/m³ (or 2.9 kW/L), which closely aligns with our case involving urine, the estimated running cost would stand at 5.2 R/L, based on the standard electricity tariff of R1.8/kWh. Assuming a continuous operation throughout the day (24 hours), the evaporator's daily capacity would be approximately 6 l based on the measured evaporation rate of 0.26 L/h, enough to cater to a household of four individuals, considering an average urine production of 1.5 L per person per day. This results in a daily cost of R30, translating to R900 per month for this household. The running cost of the urine evaporator would be then R225/month/person. Assuming a life expectancy of the urine evaporator of 15 year (similar to a boiler), the capital cost spread in this period would be R400/month. The total cost of the urine evaporator (including the initial investment and operating costs) would represent R1300/month in the household of 4 members, i.e. R325/month/person.

It is evident that both capital and running costs must be reduced for the evaporator to become more commercially competitive. The high capital cost is primarily attributed to the technology being in the prototype stage, with potential for cost reduction post-prototype through the optimization of the design, elimination of unnecessary components and mass production. Running costs can be decreased with the addition of thermal insulation and further optimization of operating conditions. Hence, ongoing research is essential for continued improvement and cost-effectiveness.

Table 3.3. Cost of construction of the evaporator prototype

Present Budget of Group 8 – R670.88 left of R14 000						
	Name of Company	Description	Order No.	Paid For	Amount	Present Balance
1	Macsteel	Mild Steel	A614486	Yes	R1496.40	R12 503.60
2	Cutting Edge Technologies	Bent and Cut Plates	A614493	Yes	R1287.50	R11 216.10
3	Mantech	Pump	A620260	Yes	R1868.75	R9347.35
4	Eurosteel	Pipe and Fittings	A614490	Yes	R3910.00	R5437.35
5	Stay Wheels and Ladders	Castors	A625972	Yes	R483.00	R4954.35
6	RS Components	Heater fan	A614988	Yes	R3747.57	R1206.78
7	Cutting Edge Technologies	Bent and Cut Plates	A614493	Yes	R388.60	R818.18
8	Cutting Edge Technologies	Bent and Cut Plates	A614493	Yes	R147.30	R670.88
WASH Department Funds – R 57 704						
	Name of Company	Description	Order No.	Paid For	Amount	Total
1	Lenzo Engineering	Tanks	-	Yes	R16 790	R16 790
2	Eurosteel	Fittings	A630478	Yes	R3522.45	R20 312.45
3	Evolution Trend	Fan Heater	-	Yes	R499	R20 811.45
4	Techno Spa	Nozzles	-	Yes	R598	R21 409.45
5		Nuts and Bolts			R	R21 409.45
6	East Coast Instruments CC	Sensors	A630119	Yes	R31 316	R52 725.45
7	Mica Durban North	Switched Multiplug	-	Yes	R314.99	R53 040.44
8	Pallchem	Packing Material	-	Yes	R3137.06	R56 177.50
9	SA Fasteners	Paint	-	Yes	R1075	R57 252.50
10		Welding Rods			R	R57 252.50
11	Nature Enterprise (PTY) LTD	Hand Mixer	-	Yes	R167	R57 419.50
12	Omega	Insulation	-	Yes	R295	R57 714.50
13	Northside Electrical	Wiring	-	Yes	R72.96	R57 787.46
14	Builders	Wiring	-	Yes	R84	R57 871.46
15	Eurosteel	Barrel Nipples	-	Yes	R287.50	R58 158.96
16	Natal Stainless Steel	Fittings	-	Yes	R621	R58 779.96
17	Mica Durban North	Wiring	-	Yes	R114.98	R58 894.94
Total – R 72 224.06						

Figure 3.8 displays the total urine evaporation cost per individual per month as a function of the reduction of the capital and running costs based on the case explored above. It can be noted that a reduction of cost of 30%, which is viable, would lead to evaporation cost of around R230/month/person. If the costs are reduced up to 50%, which would be an ambitious target, urine evaporation will cost approximately R160/month/person. In order to achieve an evaporation cost of less than R100/month/person, which would be ideal, the urine evaporation cost should be drastically decreased by more than 70%, requiring a serious optimization of the evaporator design, manufacturing process and operating conditions, which seems difficult to achieve

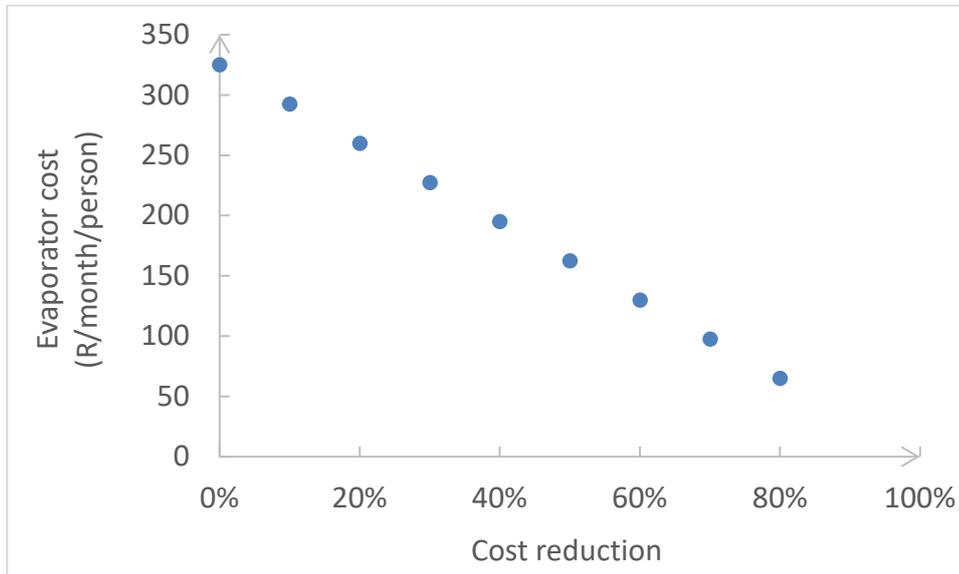


Figure 3.8. Total cost of the evaporator (encompassing capital and operating costs) as a function of the cost reduction

3.5 INTEGRATION TO SOLAR THERMAL ENERGY

An approach to cost reduction involves integrating solar thermal energy into the urine evaporator system. In the current version of the evaporator, thermal energy is sourced from electric resistance, but a more sustainable alternative would be utilizing hot water from a solar thermal collector to heat the urine evaporation tank (as illustrated in Figure 3.9). At the household level, either a conventional flat plate collector or an evacuated tube collector can be employed for water heating. In decentralized urine treatment plant, a solar concentration system could be used for the urine evaporator heating. Notably, the Solar Thermal Energy Research Group at the University of Stellenbosch has designed a low-cost concentrative solar parabolic trough system (Figure 3.10) that requires no tracking, showcasing potential applicability in urine evaporation processes.

In a practical scenario, considering the example from the previous section of a household of 4 members, transitioning to solar energy could yield to savings up to R900/month, assuming that most of the electric energy is used to heat the evaporator. With a median average solar irradiance of 5.5 kWh/m² per day in South Africa (deduced from the average annual range of 4.5 to 6.5 kWh/m²), a solar collector surface of approximately 3 m² would suffice to evaporate 6 l of urine daily. This requirement could be fulfilled by a standard 4'x8' flat plate collector. If the household invests around R15,000 in a solar collector, the evaporator capital cost would increase to R87,000. Over a 15-year period (corresponding to the assumed life expectancy of the evaporator), this translates to an expense of R120/month/person, which represents less than half the cost without solar collection, i.e. R325/month/person as calculated in the previous section. This analysis underscores the substantial potential for integrating the urine evaporator with solar energy, significantly reducing overall costs.

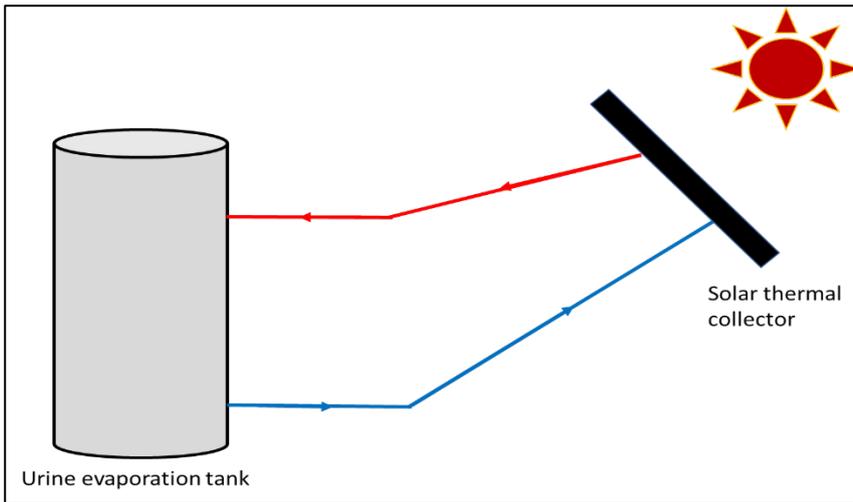


Figure 3.9. Illustration of an example of the evaporator heating through solar thermal energy collection



Figure 3.10. Photographs of the low-cost solar concentration parabolic through system developed by the Solar Thermal Energy Research Group, at the University of Stellenbosch

3.6 CONCLUSION

The optimal operating conditions involved the utilization of pall rings, coupled with air and evaporation vessel heating at lower temperatures (around 30 - 40°C). However, there is the need to explore higher temperatures in the range of 80-100°C to verify if this trend is still valid. It is expected that the installation of thermal insulation will significantly improve the efficiency of the urine evaporator during the next round of tests.

A techno-economic analysis suggests that the urine evaporator requires refinement and optimization to achieve cost reduction to make it commercially competitive. The initial capital cost is relatively high, which is typical for a prototype at an early stage of development, and it holds the potential to be significantly reduced through design improvement and optimization at advanced technology readiness levels, and mass production at the commercialisation stage. Currently, the evaporator running costs to evaporate urine is roughly estimated at about R225 per month per person. This figure could be decreased through the incorporation of thermal insulation and optimization of the operating conditions.

It has been demonstrated that utilizing solar thermal energy to heat the urine evaporator results in a significant decrease in the overall spending. Despite the higher initial investment, substantial long-term savings are realized, amounting to less than half of the expenditure without the integration of solar thermal energy into the evaporator system. This underscores the financial associated with such integration over an extended period.

Currently, the SEC of the developed technology remains comparatively high when juxtaposed with RO systems. Nevertheless, the urine evaporator exhibits enhanced capabilities in reaching higher TS than RO. The evaporation process offers an additional benefit in terms of increased robustness. This is particularly important due to the diverse organic compounds and salts found in urine, presenting a significant fouling potential. Without a protective pre-treatment, this fouling could severely impact the performance of RO membranes.

The perspective for higher TS concentration makes the combination of membrane filtration (such as RO) and evaporation an interesting prospect, promising lower energy consumption to reach a higher TS.

4. OUTCOMES AND WAY FORWARD

This section presenting outcomes from project in terms of scientific and technology outputs, capacity building, knowledge dissemination and awards. Also comparing the objectives achieved against the initial targets and describing the work that could not be undertaken. Finally, project giving the strategy of the way forward at the short and long the for the continuation of this project.

4.1 OUTCOMES

4.1.1 Scientific production

This project yielded a valuable dataset pertaining to urine evaporation, which stands as a unique contribution in the existing literature. The dataset encompasses the characterisation of evaporation kinetics, the heat consumed during the process, and the evolution of urine physiochemical properties throughout the evaporation stage. Two distinct case studies were undertaken: one involving hydrolysed urine and the other incorporating lime (calcium hydroxide) addition to stabilize urine by preventing urea hydrolysis.

The obtained dataset facilitates a comprehensive understanding and characterisation of the urine evaporation process. The data is particularly relevant and beneficial for scientists, sanitation practitioners, and technology developers, as it enables the design, improvement, optimization, and operation of urine treatment technologies focused on achieving volume reduction and solute concentration.

The key findings and implications were as follow:

- (i) The urine physiochemical properties (thermal conductivity, water activity, viscosity, and electrical conductivity) exhibited relative stability with constant values or smooth variations during the majority of the evaporation process. Notable variations in properties occurred only after achieving 60% to 80% urine evaporation (leading to a solid concentration of 4 to 6%). This suggests that evaporation predominantly occurred under steady-state conditions for the major part of the process. Only in the final stages, the solutes concentration significantly influenced urine properties, which would subsequently influence the overall process.
- (ii) The heat consumed during urine evaporation was similar than the latent heat of vaporization of pure water for the majority of the process, accompanied by a similar vapor pressure. However, after evaporating 80% of the urine and achieving a 4% TS, vapor pressure decreased, and consequently the energy demand would increase to evaporate the remaining urine.
- (iii) Evaporation properties of stabilised and hydrolysed urine were found to be similar, with the only exception being the pH evolution. Hydrolysed urine exhibited pH decrease during evaporation due to ammonia volatilization, leading to neutralization. In contrast, stabilised urine maintained a stable alkaline pH, showcasing the efficacy of lime pre-treatment for nitrogen recovery. Ammonia volatilization in hydrolysed urine resulted inapparent faster evaporation kinetics compared to stabilised urine.
- (iv) The liquid state of urine was maintained even after achieving high levels of evaporation (up to 98%). This characteristic is advantageous for the developed evaporator, which was not designed to desiccate urine to a solid state.
- (v) Evaporation did not degrade organic matter. However, it was observed that lime-treatment could have led to the degradation of a part of urine organic fraction.

In conclusion, this comprehensive dataset provides crucial insights into the dynamics of urine evaporation, offering valuable information for the advancement of urine treatment technologies and associated control

strategies. The findings contribute significantly to the existing body of knowledge in the field and have practical implications for both researchers and practitioners.

4.1.2 Technology development

Undergraduate students in Mechanical Engineering successfully designed and constructed a urine evaporator as part of their final year project. The urine evaporator consists in a heated packed column where urine flows from the top to the bottom. The urine is introduced inside the column as small droplets through a spraying mechanism and flows downwards through the packing material, which is expected to increase the surface area by creating a urine thin-film. An air stream is introduced at the bottom of the column and expelled at the top to induce a counter-flow contact with the urine for a higher mass transfer. After traversing the column, urine is returned to the recirculation tank where the liquid fraction of urine is recirculated to the evaporator. The cycle is repeated until concentrating the urine at a given solids concentration, and the concentrated urine is then discharged into an outlet collection tank. Various sensors are integrated into the system to monitor critical parameters (temperature, relative humidity, pH, electrical conductivity).

The evaporator underwent testing using tap water, wherein the effect of the filling material within the evaporation column, the evaporation temperature, and the ventilation pre-heating were explored. Subsequent trials involved using salt water with sodium chloride at a concentration such that the electrical conductivity is similar to raw urine. After testing, the key performance indicators, including the specific energy consumption (SEC), efficiency, and evaporation rate, were measured, followed by a comprehensive techno-economic analysis.

The key findings and implications were as follow:

- (i) The urine evaporator demonstrated functioned as intended, validating the envisioned proof-of-concept.
- (ii) The optimal conditions for the urine evaporator were identified: ventilation pre-heating activated, maintaining a temperature range of 30-40°C, and utilizing pall rings as filling material in the evaporation column.
- (iii) Despite successful functioning, there is room for improvement and optimization in the evaporator design and operation. Notably, energy consumption was found to be comparatively high when compared to reverse osmosis (RO). The challenge lies in reducing both capital and running costs to enhance the commercial viability of the urine evaporator.
- (iv) Preliminary estimates indicate an energy consumption of 3 kWh/l, translating to an estimated running cost of R225/month/person. This underscores the need for further efficiency improvements.
- (v) An encouraging finding was the positive impact of integrating a solar thermal energy collection system into the evaporator. Despite a higher initial investment, the long-term cost was found to be less than half of the expenses incurred when running the evaporator using electricity from the grid.

In summary, the successful construction and validation of the urine evaporator represent a significant achievement in the project. The identified optimal conditions provide a foundation for future enhancements. However, addressing energy consumption and cost challenges is crucial for transforming the device into a commercially viable solution. The potential integration of solar thermal energy presents a promising avenue for reducing long-term operational costs. Efforts in refining the design and operation will continue to the overall success and viability of the urine evaporator as an innovative solution in urine treatment.

4.1.3 Technology uptake

Preliminary discussions took place with EnviroSan regarding the potential integration of the urine evaporator into the re-engineered toilets backend. Conversations also occurred with Teddy Gounden, the former Executive Manager at eThekweni Water & Sanitation, exploring the possibility of establishing a urine centre at the Newlands-Mashu sanitation research facility. The envisioned centre would allow the evaporator to be relocated for testing and optimization. Furthermore, it could be connected to other urine-related projects, e.g. the continuation of the VUNA project if it happens.

4.1.4 Capacity building

The project involved the following students:

- 3 BSc mechanical engineering students in the development of the urine evaporator (WP2);
- 2 BSc chemical engineering students from UKZN Chemical Engineering to test the urine evaporator (WP1);
- 1 MSc student involved in the characterisation of urine evaporation at the laboratory (WP1) and assisting the BSc students in the development of the urine evaporator (WP2);
- 1 process engineering student from the INSA of Toulouse (engineering school at France) who conducted an internship at the WASH R&D Centre for a few months and assisted the MSc student in her experimental work (WP1).

Table 4.1 presents the details of the students involved in the last reporting period.

Table 4.1. Details of the students involved in the project

Name	Gender	Age	Race	Nationality	Degree in course
Brent Yelland	Male	21	White	South Africa	BScEng
Nikhil Pillay	Male	23	Indian	South Africa	BScEng
Talente Mthembu	Male	23	Black	South Africa	BScEng
Shrivar Devraj	Male	-	Indian	South Africa	BScEng
Taskeen Arbee	Female	-	Indian	South Africa	BScEng
Kirthi Rampersad	Female	24	Indian	South Africa	MScEng
Alexis Coppejans	Male	21	White	France	MScEng

4.1.5 Knowledge dissemination

The results from the urine evaporation characterisation work at the laboratory were presented in a few conferences:

- One flash presentation at the UKZN Postgraduate Research & Innovation Symposium (PRIS), held virtually during the 8th and 9th of December in 2022.
- One poster at the 1st International Water Association (IWA) – Non-Sewage Sanitation (NSS) Conference, held in Johannesburg, South Africa, during the 15th to 18th October 2023.
- One oral presentation at the 7th Young Water Professional (YWP) – Water Institute of Southern Africa (WISA), which took place in Stellenbosch, South Africa, from the 8th to the 10th of November 2023.

The urine evaporator was showcased at the UKZN Mechanical Engineering Open Day 2023. In this event, the students presented their final-year project to an open audience (UKZN students and staff, family members, industries representatives, etc...). The photographs from this event with the team of this project are showed in Appendix C.

An abstract was submitted to the WISA 2024 Biennial Conference & Exhibition that will take place from the 27th to 29th May 2024, in Durban, South Africa.

Note that all the conference material can be found in the **Supporting Documents D**. The material from the WISA 2024 will be uploaded after this event will happen.

4.1.6 Awards

Two awards related to this project were received:

- Second best design during the UKZN Mechanical Engineering Open Day 2023;
- Second best oral presentation during the 7th WISA-YWP Conference (by the MSc student).

The certificates of the awards are attached in Appendix D and Appendix E.

4.2 WAY FORWARD

4.2.1 Short-term

Over the next few months, the MSc student is tasked with finalizing the analysis of the following data: TGA-DSC, density, TSS, heat capacity, and kinetics in the Moisture Analyser. Supplementary experiments will be conducted to measure the nitrogen content in the hydrolysed urine samples evaporated at various TS content to verify the presumed nitrogen loss through ammonia volatilization during evaporation.

Currently, two chemical engineering vacation work students are conducting tests with the urine evaporator. They are repeating previous evaporation tests with tap water at different temperatures and conducting new tests after adding insulation material to the tanks and pipes. These new tests involve the evaporation of tap water and salted water (with a sodium chloride content yielding to an initial electrical conductivity similar than urine) at various evaporation temperatures (40, 50, 60, and 75°C, which is the maximum temperature that can be attained). Subsequent tests are planned at 40°C with stabilised and hydrolysed urine, and at 75°C with only hydrolysed urine (as the urea from stabilised urine can be thermally hydrolysed above 40°C). These last tests will be carried out by an intern, but the data will be analysed by the MSc student and included in her dissertation.

The outcomes of this pending work will be integrated into both the MSc dissertation and the vacation work report, which will be uploaded in **Supporting Documents E** once finalized.

4.2.2 Medium term

In 2024, a new Mechanical Engineering final year project is slated to commence, focusing on the development and construction of a second version of the evaporator. This iteration aims to incorporate improvements based on lessons learned from the current project. The envisioned features for the new evaporator include:

- A box-shaped evaporator design that will receive urine from the feeding tank.
- Internal recirculation of the urine in the evaporator box by suctioning it from the bottom and spraying it from the top.
- Implementation of water level sensors to halt urine recirculation pumps once the urine reaches a low level in the bottom of the box, allowing for its drying until becoming a solid (acknowledging the limitation of achieving solid state in the current evaporator).

- Integration of a ventilation system to remove the evaporated water and internal circulation fans to induce turbulence, thereby enhancing the evaporation process thanks to a faster mass transfer.
- Air pre-heating before introduction into the evaporator to reduce relative humidity, which enhances the evaporation driving force.
- Heat recovery from the exhaust air to pre-heat urine in the feeding tank and condense the evaporated moisture for reuse water recovery.

This student project is scheduled to run from March to October 2024. A repository containing documents from this project will be uploaded in **Supporting Documents F** as they are ready.

During this phase, increased communication with EnviroSan and other toilet developers, such as SLU – Sanitation 360 and VUT – BAAS, is anticipated to promote the adoption of the urine evaporator technology. Additionally, efforts will continue to explore the establishment of a urine centre at the Newlands-Mashu facility.

4.2.3 Long-term

In 2024 or 2025, the exploration of opportunities for a project proposal to extend the current initiative will be undertaken. The foundation for this continuation will be built upon the data acquired in the laboratory and the development of the two versions of the urine evaporator. The new project will aim to delve into the integration of solar thermal energy into the technology and the combination with a membrane process. The intended applications include the incorporation of this technology in re-engineered toilets with urine diversion and decentralized urine treatment plants.

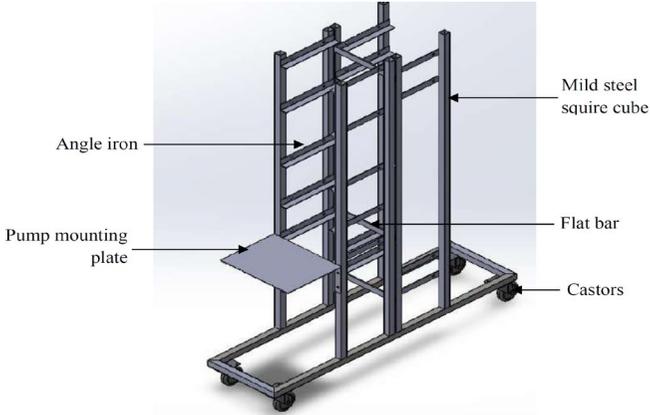
In Durban, it has been envisaged to separate urine and black water in decentralized wastewater treatment system (DEWATS) to circumvent the reliance on wetlands for nutrient removal. However, this practice poses the problem of generating significant quantities of urine with limited disposal solutions. The envisaged future project would offer a viable and sustainable solution for urine treatment within DEWATS post-urine separation.

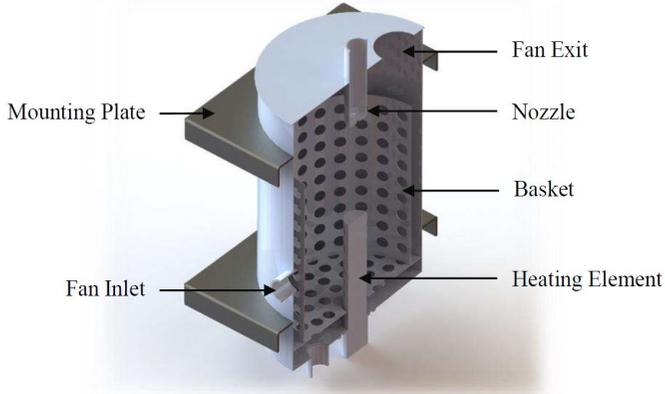
Potential funding sources for this future project include the WRC, Royal Academy of Engineering and European funding programs. Collaboration could be done with partners such as University of Cape Town, University of Stellenbosch, VUNA, EAWAG, SLU - Sanitation 360, and Surrey University (with whom the WASH R&D Centre is initiating a collaboration on urine forward osmosis).

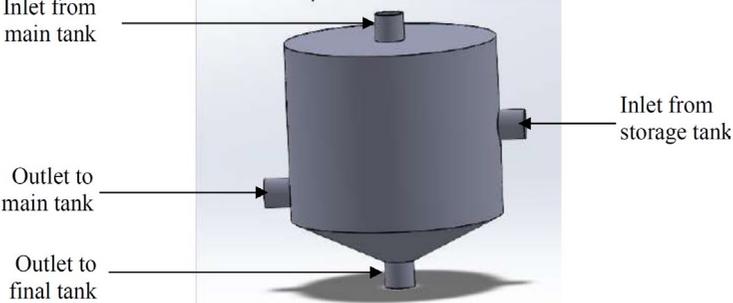
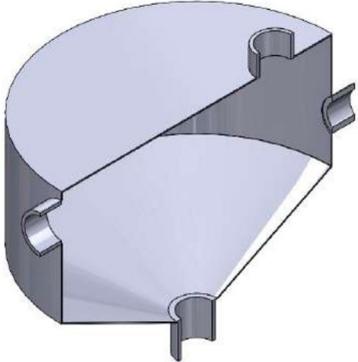
5. APPENDIX

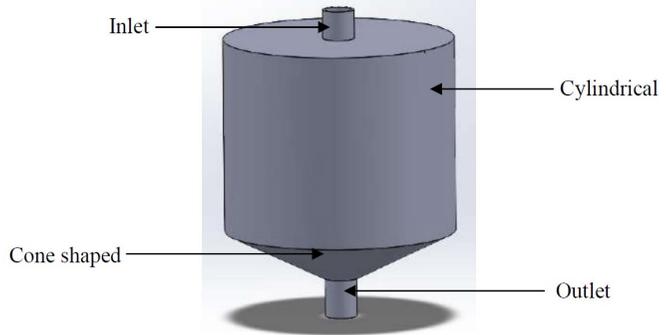
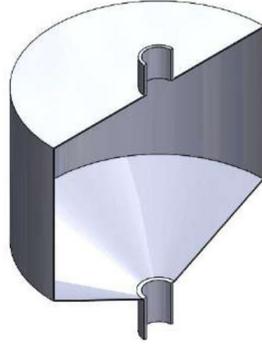
5.1 APPENDIX A: SUB-COMPONENTS FROM THE URINE EVAPORATOR

Table 5.1. Sub-components from the urine evaporator with their function and specifications

Sub-components		Function	Specifications	Image
Support	Frame	To keep the integrity of the system and provide mechanical support to the tanks from the evaporator	Material: mild steel	
	Wheels	To facilitate moving the urine evaporator setup	Housing type: swivel with total brake Dimensions: 100 mm (wheel diameter) x 128 mm (height)	
Evaporator	Vessel	To house the urine evaporation process	Material: 316 Stainless Steel Dimensions: 200 mm (diameter) x 240 mm (height)	
	Packing material	To spread urine as a thin film to increase	Possible to test different types of packing material	

		the mass transfer and enhance the contact with the air stream		
Basket	To contain the packing material	Basket made in a fine mesh Possible to place it and remove it from the vessel		
Heating element	To provide heat into the urine evaporator vessel for the process	Type of element: geyserswise stainless steel heating element Dimensions: 24 mm (diameter) x 200 mm (height) Power: 1400 W		
Spraying mechanism	To introduce urine into the evaporator as small droplets	Type of mechanism: nozzle Possible to change of spraying mechanism to modify the droplets size		
Heather fan	To introduce an airstream into the evaporator that can be heated	Model: Stego heater fan Type of heater: enclosure heater fan Dimensions: 100 mm x 100 mm Power: 250W Regulator to control the heating intensity		

Recirculation loop	Recirculation tank (or holding tank)	To send the liquid fraction of urine to the evaporator To recover the concentrated urine and precipitates from the bottom	Material: 316 Stainless Steel Dimensions: 242 mm (diameter) x 252 mm (height)	
	Pump	To move the urine from the recirculation tank to the top of the evaporator column	Model: <i>Seakoo</i> QB60L Power: 370 W Maximum flowrate: 30 L/min Maximum head: 30 m Suction lift: 8 m Voltage: 220 V Frequency: 50 Hz	
Stirring system	Stirring tank	To house an area of intensive mixing to induce the coagulation of the precipitates for an enhanced settling in the recirculation tank	Material: 316 Stainless Steel Dimensions: 242 mm (diameter) x 150 mm (height)	

	Mechanical stirrer	To induce mixing inside the stirrer tank	Model: "Super Hand Mixer 7 Speed Hand Blender" (electrical appliance used for cooking) Power: 180 W	
Inlet and outlet reservoirs	Inlet tank	To feed urine into the evaporation loop	Material: 316 Stainless Steel Dimensions: 242 mm (diameter) x 252 mm (height)	
	Outlet tank (or final tank)	To collect the evaporated urine at the end of the evaporation cycle	Material: 316 Stainless Steel Dimensions: 242 mm (diameter) x 202 mm (height)	

Sensors	Electrical conductivity	To monitor the urine evaporation progress, identify the precipitation of solutes and detect changes in the chemistry of the solution in the recirculation tank	<p>Model: <i>M1410K</i> Range: 0 -200 mS Accuracy: 1.0% (0.00- 100.0 mS) and 1.5% (100.00- 200.0 mS) Temperature range: 0 - 80°C</p>	
	pH	To detect changes in the chemistry of the solution in the recirculation tank	<p>Model: <i>M1310K</i> Range: 0.00 – 14.00 pH Accuracy: 0.02 Temperature range: 0 - 60°C</p>	
	Hygrometer	To measure the gain of humidity of the air stream at the exhaust of the air stream	<p>Temperature range: -50°C to 70°C Accuracy: +-1°C and +-5% RH Humidity level: 10% - 99% RH</p>	

	Thermocouples	To measure the temperature in the evaporator and the different tanks	Type : k-type Dimensions: 6 mm (diameter) x 150 mm (length)	-
Other	Piping	To connect the tanks between them	Material: stainless steel Diameter: 33.40 mm (outside) / 27.86 mm (inner)	-
	Fittings	To connect the pipes among them and to the tanks	Barrel nipples, unions, tee pieces, sockets, elbows	-
	Valve	To allow urine circulation between tanks	1-piece ball valve in a DN 25 size	
	Thermal insulation	To avoid heat losses to the environment from the pipes and tanks heated during the process	Material: Aluminum laminated SABS material (universal geyser blanket kit)	

5.2 APPENDIX B: BUILDING OF THE DIFFERENT PARTS FROM THE URINE EVAPORATOR



Figure 5.1. Building of the frame of the urine evaporator

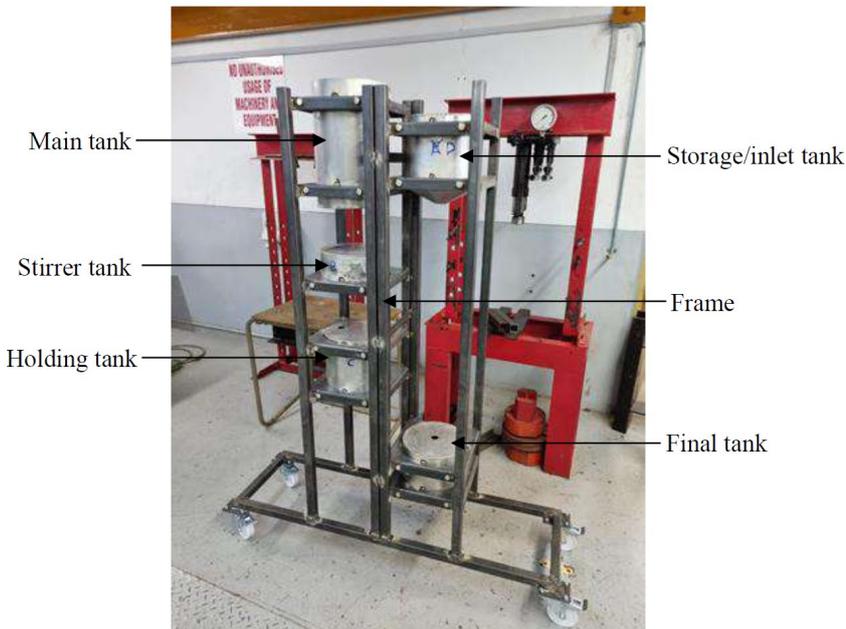


Figure 5.2. Installation of the tanks into the frame

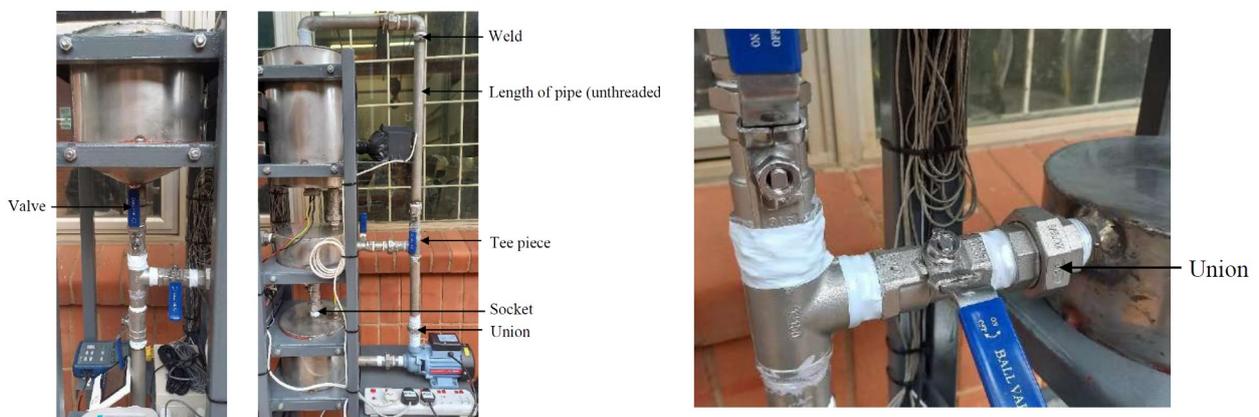


Figure 5.3. Installation of the pipes, valves and pump



Figure 5.4. Installation of the sensors

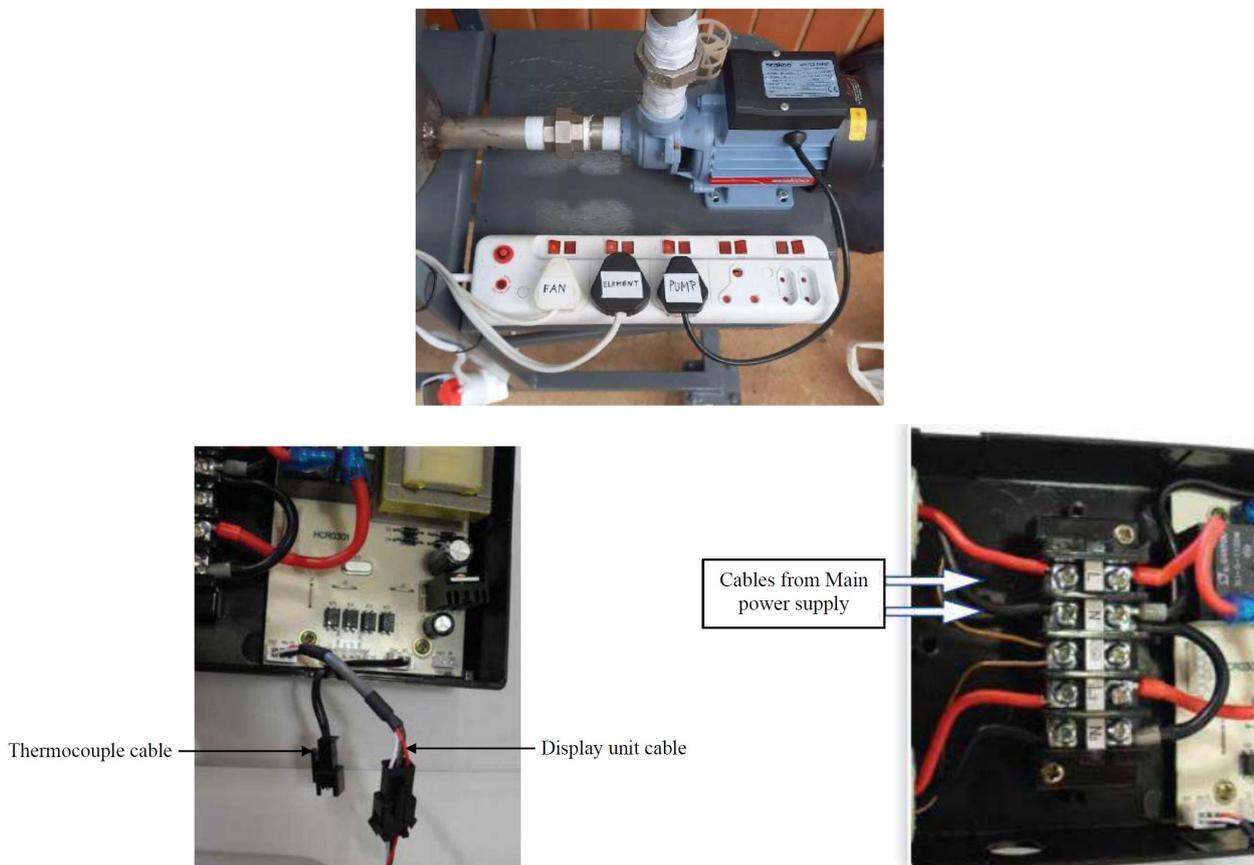


Figure 5.5. Installation of the electrical connections

5.3 APPENDIX C: PHOTOS FROM THE MECHANICAL ENGINEERING EXHIBITION DAY





5.4 APPENDIX D: AWARD CERTIFICATE FOR THE URINE EVAPORATOR AS SECOND-BEST DESIGN DURING THE MECHANICAL ENGINEERING EXHIBITION DAY



5.5 APPENDIX E: AWARD CERTIFICATE FOR THE BEST RUNNER PRESENTATION DURING THE WISA- YWP CONFERENCE



SUPPORTING DOCUMENTS

[Supporting Documents A: previous Deliverable reports from this project](#)

[Supporting Documents B: progress reports from MSc student detailing the work undertaken under WP1 \(characterisation of urine evaporation at the laboratory\)](#)

[Supporting Documents C: reports from the mechanical engineering student group that developed the urine evaporator](#)

[Supporting Documents D: material from the conferences](#)

[Supporting Documents E: dissertation from the MSc student and report from the vacancy work students](#)

[Supporting Documents F: reports from the mechanical engineering students developing the second version of the urine evaporator in 2024](#)