INTEGRATING SUSTAINABLE AGRICULTURAL PRODUCTION IN THE DESIGN OF LOW-COST SANITATION TECHNOLOGIES BY USING PLANT NUTRIENTS AND WASTEWATER RECOVERED FROM HUMAN EXCRETA-DERIVED MATERIALS

AO Odindo, W Musazura, S Migeri, JC Hughes and CA Buckley

Guideline for Sustainable Agricultural Use of Human Excreta-Derived Materials

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Guideline for Sustainable Agricultural Use of Human Excreta-Derived Materials

Report to the
Water Research Commission

by

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The publication of this report emanates from a project titled: "*Integrating sustainable agricultural production in the design of low-cost sanitation technologies by using plant nutrients and wastewater recovered from human excreta-derived materials*" (WRC Project No. K5/2777). This project has been an extension of the WRC Project K5/2220, which was titled "*Integrating agriculture in designing on-site, low-cost sanitation technologies in social housing schemes*".

This report forms part of a set of two reports. The other report is *Volume 1: Final Report* (WRC Report No. TT 870/1/21)

EXECUTIVE SUMMARY

Management of human excreta materials from various non-sewered sanitation systems is of environmental concern. The regulatory and legal framework to promote agricultural use of human excreta-derived material (HEDMs) exists in South Africa. However:

i. the framework does not focus on specific processed HEDMs that have undergone certain treatments based on recent scientific developments;
ii. some guidelines were produced for HEDMs emanating from large treatment plants (city-level) and effectively exclude those from onsite sanitation systems; and
iii. there is no guideline that comprehensively addresses the management of HEDMs from various excreta streams.

Therefore, the project aimed to develop a comprehensive consolidated technical guideline on the safe and practical agricultural use of HEDMs and treated wastewater emanating from onsite sanitation technologies in South African rural and urban communities. The guideline provides evidence-based norms and practices for safe and beneficial recycling of human excreta. The target audience for this guideline includes municipal authorities, regulators, town planners and government officials in relevant departments. It can be adopted at a local, regional or national level to influence policy on sustainable sanitation solutions in South Africa.

The guideline is informed by studies conducted in previous WRC projects (K5/2002 and K5/2220), findings of the current project (WRC K5/2777), and various local (South African) and international guidelines. It focuses on the regulatory framework and legal context, planning, implementation, monitoring, evaluation and reporting of HEDMs used in a number of projects. The aspects covered include agronomic practices, health and environmental protection and dealing with social perceptions of the agricultural use of HEDMs.

The guideline is divided into three distinct sections that cover treated wastewater, faecal sludge-derived products and urine-derived products. The treated wastewater emanates from a Decentralised Wastewater Treatment System (DEWATS), which is a modularised technology that treats household wastewater to produce high-quality effluent with potential for agricultural use due to its nutrient composition. The faecal sludge-derived product is thermally processed, dry and sterile Latrine Dehydration Pelletisation (LaDePa) pellets which are made by using faecal sludge from onsite sanitation systems such as Ventilated Improved Pit latrines. The urine-derived products include nitrified urine concentrate (NUC), struvite and stored raw urine. The NUC is defined as a sterile, compact and odourless liquid urine fertiliser made from the nitrification and distillation process. Struvite is a solid urine-based P fertiliser made through an precipitation, filtration and drying processes. Urine can be kept at 20°C for six months; the ammonia is emitted thereby increasing urine pH and deactivation of pathogens. As a result stored urine is a safe product for agricultural use.

The DEWATS effluent is used for crop fertigation, meaning that it supplies water and nutrients. The planning process in the agricultural use of DEWATS effluent involved assessment of site-suitability for irrigation with focus on soil irrigability (physical properties and fertility), environmental risk assessment (depth to water table, distance from nearby domestic boreholes and surface water), and characterisation and assessment of DEWATS effluent for agricultural use fitness (impacts on crop nutrients, salinity, soil physical properties, microbial risks and oxidisable carbon loading). The implementation process involve calculating land area required using water balance and nutrient balance approach, storage requirements in full effluent reuse schemes. The management practices in DEWATS-effluent irrigated land included the basis for selecting crop types, cropping systems and suitable irrigation equipment. The approaches to manage soil quality (physical and chemical properties), crop quality and crop yield optimisation were given. The DEWATS effluent does not meet standards for unrestricted agricultural use, hence the human health risks management options were provided based on the Sanitation Safety Planning tool. The nutrients (N and P) are of environmental concern when DEWATS effluent is used for irrigation, therefore the guideline provided methods and tools for integrated environmental pollution management. The physical properties (odourfree and colourless appearance), agricultural benefits (source of water and nutrients) and environmental health benefits (minimal pollution through discharge of wastewater into water bodies) make DEWATS effluent socially acceptable. However, high microbial loads limit its acceptability, hence with proper health education and promotion, its use will be socially acceptable.

The LaDePa pellets are important soil amendments and at the same time contain nutrients. The characterisation and classification of LaDePa pellets showed that they belong to microbial class A, stability class 1 and pollutant class A. Therefore, they can be used safely for unrestricted agricultural production. The general considerations for using LaDePa pellets in agriculture was given to site selection, management practices (crop management, application rates and frequency, timing and other required field operations). No health risks are expected to farmers and families, and consumers of products produced by using LaDePa pellets. The pollution of borehole and groundwater may occur especially when the LaDePa pellets are applied continuously at high application rates exceeding agronomic requirements, therefore recommended management practices were given. LaDePa is socially acceptable if they are well marketed.

The last section of guideline focused on three urine streams: NUC, struvite and stored urine. The urine products are used just like other inorganic fertilisers, whereby NUC and stored urine are sources of macro and micronutrients while struvite is a source of P. The guideline provides recommendations for site selection, implementation (raw urine storage technical requirements and crop management practices, human health risks assessment and environmental pollution control). Different urine products have unique characteristics; NUC is concentrated, hence needs to be diluted prior to application, stored urine is bulky and ready for application and struvite is powdery. Therefore, the guideline provides technical requirements to ensure that the respective urine products is efficiently applied to crops. Most urine products were assumed effectively treated therefore pose no health risks. The pollution of groundwater and surface water resources in urine-derived products is similar to conventional fertilisers. Stored urine is the least socially acceptable product due to its smell. However, proper marketing and farmer training increases social acceptability.

The monitoring, evaluation and reporting requirements for each HEDM were given to ensure that their use is not negatively impacting human health, crop productivity, the environment and social perceptions. For each HEDM, decisions to continue or discontinue are based on evaluation outcomes from relevant authorities.

However, it is important to note that recommendations provided in this current guideline are socio-economically site-specific. Thus the constraints and opportunities related to the use of HEDMs are likely to vary nationally. As such this is a living document which is likely to be updated or changed as new information become available.

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ABR	Anaerobic Baffled Reactor
AF	Anaerobic Filter
BOD	Biological Oxygen Demand
BSFL	Black Soldier Fly Larvae
CFU	Coliform forming units
COD	Chemical Oxygen Demand
DALRRD	Department of Agriculture, Land Reform and Rural Development
DEA	Department of Environmental Affairs
DEWATS	Decentralised wastewater treatment system
DOH	Department of Health
DSS	Decision Support System
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
ESP	Exchangeable Sodium Percentage
HEDM	Human Excreta-Derived Material
HFCW	Horizontal Flow Constructed Wetland
LaDePa	Latrine Dehydration Pasteurisation
MAR	Maximum Application Rate
MAT	Maximum Available Threshold
MPL	Maximum Permissible Level
NUC	Nitrified Urine Concentrate
NWA	National Water Act
PGF	Planted Gravel Filter
PPE	Personal Protective Equipment
ROD	Record of Decision
SANAS	South African National Accreditation System
SARA	Sludge Application Rate Advisor
SAWQG	South African Water Quality Guideline
SSP	Sanitation Safety Planning
TIL	Total Investigative Level
TMT	Total Maximum Threshold
UDDT	Urine Diverting Dehydrated Toilet
VFCW	Vertical Flow Constructed Wetland
VIP	Ventilated Improved Pit latrine
WFD	Wetting Front Detector
WHO	World Health Organisation

GLOSSARY OF TERMS

100-year flood line
The flood event with a 1% probability of being equalled or exceeded in any given year.

Aquifer
An underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials, which can be used to provide drinking water after installation of a well or borehole.

Biosolid
Organic matter from faecal sludge that can be used for agriculture.

Co-composting
The controlled aerobic degradation of organic materials, using more than one feedstock (usually faecal sludge and other organic material).

Composite sample
A series of individual samples that are collected and then combined into a single sample.

Duckweed
An aquatic flowering plant which floats in water and is used in stabilisation ponds to remove nutrients and harvested as biomass for different purposes such as soil conditioning and aquaculture.

Exchangeable sodium percentage
It is the amount of adsorbed sodium on the soil colloids expressed in per cent of the cation exchange capacity.

Human excreta-derived materials
Fertilisers emanating from urine and/or faecal sludge and includes treated domestic wastewater.

Hydroponics
A method of growing crops without soil by using mineral nutrient solutions in an aqueous solvent.

Infiltration rate
The speed at which water on the surface enters the soil.

LaDePa pellets
A biosolid made from thermal treatment of faecal sludge using infrared technology that is sterile and odour free.

Micropollutants
Inorganic and organic substances that can negatively affect the environment even at very low concentrations.

Off-site land application of sludge
The beneficial use of sludge outside the boundaries of the WWTP or sludge collection area in onsite sanitation systems.

On-site land application of sludge
The beneficial use of sludge within the boundaries of the wastewater treatment plant (WWTP) or sludge collection area in onsite sanitation systems.

Percolation
The movement of water through porous media.

Piezometer
An instrument for measuring the pressure of a liquid or gas that is placed in boreholes to monitor the pressure or depth of groundwater.

Sanitation Safety Planning
A step-by-step risk-based approach to assist in the implementation of local level risk assessment and management for the sanitation service chain (containment, transportation, treatment and end-use).

Sludge Application Rate Advisor (SARA)
A simple database model developed to help sludge producers and users classify their sludge according to the guidelines for the utilisation and disposal of wastewater sludge: Volume 1. This can be used to estimate sludge application rates and the least economic sludge transportation distance.

Soil irrigability
The suitability of soils to irrigation-based on quantitative limits of soil characteristics pertinent to irrigation.

South African Water Quality Guideline
The South African risk-based, site-specific, irrigation water quality guideline developed as a Decision Support System in irrigation using treated wastewater to conform with requirements of the Department of Water and Sanitation (DWS), South African General Authorisation of the National Water Act (Act 36 of 1998).

Stored urine
The urine that has been collected, stored for a certain period and pathogen are deactivated as the pH rises due to ammonium emissions.

Struvite
A crystalline phosphate mineral fertiliser ($NH_4MgPO_4 \cdot 6H_2O$) made from precipitation of urine with Mg salt and used as a source of P for crop production.

Struvite effluent
The urine left after precipitation and filtration of struvite.

Surface runoff
The flow of water occurring on the ground surface when excess water can no longer infiltrate the soil, and that carries pollutants into surface water bodies.

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INTRODUCTION

1.1 General background

Several waterborne and dry technologies provide onsite sanitation in areas where municipal connections to centralised treatment plants may be hindered by terrain, accessibility and population dynamics such as uncontrolled urbanisation, which makes municipal planning processes difficult (Foxon et al., 2004, Crous et al., 2013). Examples of onsite sanitation technologies include the Decentralised Wastewater Treatment System (DEWATS), Ventilated Improved Pit latrines (VIPs) and Urine Diversion Toilets (UDTs). The management of human excreta-derived materials (HEDMs) emanating from onsite sanitation systems is a challenge. Treated wastewater (DEWATS), faecal sludge (VIPs), and urine and faecal matter (UDTs) are of human and environmental health concern if improperly managed. The disposal of treated wastewater into surface water or groundwater may cause pollution and death of aquatic life. The leachates emanating from faecal sludge contained in unemptied VIPs and urine discharged in soakaways (Gounden et al., 2006) may contaminate groundwater resources. In cases where the faecal sludge is removed, this should be disposed of in a landfill designed to accept hazardous waste, incinerated or composted (Still et al., 2015). However, there are concerns that faecal sludge accumulating in landfills emit greenhouse gases (Still et al., 2015) which contribute to climate change.

1.2 Justification and scope

Currently, South African legislation enforces safe treatment of human excreta emanating from waterborne and dry sanitation systems, followed by safe discharge into the environment, provided certain standards are met (Department of Water and Sanitation, 2016). On the other hand, several policies, for example, the National Environmental Management Act (NEMA) No. 59 of 2008 encourages minimal discharge of waste into the environment through recycling (Department of Environmental Affairs, 2009).

There are various technologies to valorise human excreta materials from onsite sanitation systems. The Valorisation of Urine Nutrients (VUNA) project run by the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) and eThekwini Water and Sanitation (EWS), worked on identifying methods to valorise urine into low-cost, portable, socially and economically acceptable products, namely struvite and nitrified urine concentrate (Etter et al., 2015). The EWS in collaboration with Particle Separation Systems Technologies (Pty) developed the Latrine Dehydration Pasteurisation (LaDePa) faecal sludge process to produce pellets for agricultural use (Mirara et al., 2018).

Treatment, valorisation and agricultural use of human excreta products, whereby soil serves as a sink for water, nutrients and organic matter emanating from sanitation systems, has socio-economic benefits. These include reduced costs required for stringent treatment before discharge into the environment, low energy consumption and emissions of greenhouse gases during inorganic fertiliser production, recycling of finite agricultural resources such as phosphorus (P) and reduced agricultural input costs for low-income farmers who are unable to afford the high costs of commercial, inorganic fertilisers.

The World Water Development launched in Durban, South Africa on 22 March 2017 recommends improved and sustainable human excreta management to focus on reducing pollution and recovering beneficial products to generate social, environmental and economic benefits (United Nations World Water Assessment Programme, 2017). Although the benefits of human excreta use in agriculture are acknowledged, the risks associated with the practice should be monitored. It is, therefore, critical to consider ways of minimising environmental and human health impacts due to the use of HEDMs while maximising potential crop yield benefits as well as stimulating social acceptance by several actors along the food value chain in communities utilising the resulting food products.

Guidelines to promote safe and sustainable agricultural use of human excreta materials are available. Published sewage sludge guidelines for utilisation and disposal of wastewater sludge focus on management options, and the requirements for agricultural use, for off-site and onsite disposal, for beneficial use and for thermal management practices and commercial products (Snyman et al., 2006). Recent developments have focused on site-specific and user-friendly tools such as the Sludge Application Rate Advisor (SARA) to aid decision-making processes on the utilisation of sludge by estimating application rates and economic viability (Tesfamariam et al., 2015, Tesfamariam et al., 2020, Tesfamariam et al., 2018). The South African Water Quality Guideline (SAWQG) is a decision support system that provides a site-specific and risk-based approach for the safe and productive agricultural use of treated wastewater that has been developed following recent scientific development to conform with the Department of Health (2018) National Water Act (DuPlessis et al., 2017). There is no local specific guideline on the agricultural use of urine and its products except for an updated EcoSanRes guideline (Richert et al., 2010, Schönning and Stenström, 2004, Johnnsson and Vinerras, 2004).

1.3 Aim

- To develop a comprehensive, consolidated technical guideline on the safe and practical agricultural use of HEDMs and treated wastewater emanating from onsite sanitation technologies in South African rural and urban communities.

The need for a robust South African practical guideline on the agricultural use of HEDMs is justified by certain issues:

- All the existing guidelines are generic and do not focus on specific processed HEDMs from onsite sanitation systems including DEWATS effluent, LaDePa pellets, NUC and struvite.
- The current sludge utilisation guidelines were developed based on wastewater sludge emanating from centralised treatment plants (usually connected to urban areas) and do not consider sludges

from onsite sanitation systems such as VIPs and UDTs in informal settlements and rural areas, which have been collected, transported and treated differently.

- The same applies to DEWATS wastewater which has undergone a treatment route different from conventional centralised systems, thereby exhibiting different quality in terms of biological and physicochemical composition, meaning that its agricultural use should follow unique management practices.
- The existing urine guidelines are established by Schönning and Stenström (2004) later by Richert et al. (2010) are old and there have been some recent developments in science in terms of urine collection, transportation, treatment/valorisation and reuse methods that require consideration. To date, there is no practical guideline applicable to South African context.
- The quality of processed HEDMs requires specific planning, execution and monitoring programmes to manage health, environmental, agronomic impacts and social perceptions.
- Current guidelines are scattered and not user-friendly for easy management of various streams of human excreta (wastewater, urine and faecal sludge). Therefore, one comprehensive document focusing on all human excreta streams, applicable to South African conditions, is needed.

1.4 Specific objectives

- To provide a technical guide for best agricultural practice of using HEDMs and DEWATS effluent in South Africa. To guide management practices that minimise environmental and human health risks in agricultural lands amended with HEDMs and DEWATS effluent.
- To develop on-farm agricultural practices for the safe and environmentally sustainable use of DEWATS effluent and HEDMs for rural and urban crop production via a farmers training guide.

1.5 Application and limitations

The guideline can be used at the local, regional or national level to influence policy and hence the primary target audiences are:

- **Municipal authorities** – to implement housing development programs that link sanitation to sustainable housing development,
- **Policymakers** – the document provides evidence-based information to influence policy on the legal agricultural use of HEDMs

Furthermore, the guideline may indirectly benefit the following individuals in different ways:

- **Extension workers** – to train farmers on the safe and appropriate use of HEDMs for agriculture,
- **Academic institutions** – for academic research on safe and sustainable reuse of HEDMs in agriculture.

1.6 Limitations

The guideline does not cover full details on sanitation systems, wastewater or human excreta treatment and disposal processes. It is limited to agricultural use of various HEDMs emanating from onsite sanitation systems, different human excreta streams and treatment processes, namely:

1. Domestic wastewater
    - DEWATS effluent
2. Faecal sludge derived materials
    - LaDePa pellets
3. Urine derived materials
    - Stored raw urine and struvite effluent
    - NUC
    - Struvite

1.7 Approach to guideline development

A summarised approach towards the development of this guideline is shown in Figure. The guideline was developed from various studies on the sustainable onsite sanitation systems linked to agriculture, which included field, laboratory, tunnel studies, desktop reviews and focus group discussions conducted under Water Research Commission (WRC) projects K5/2002, K5/2220 and the current K5/2777. Some information was also collected from work done external to the University of KwaZulu-Natal.

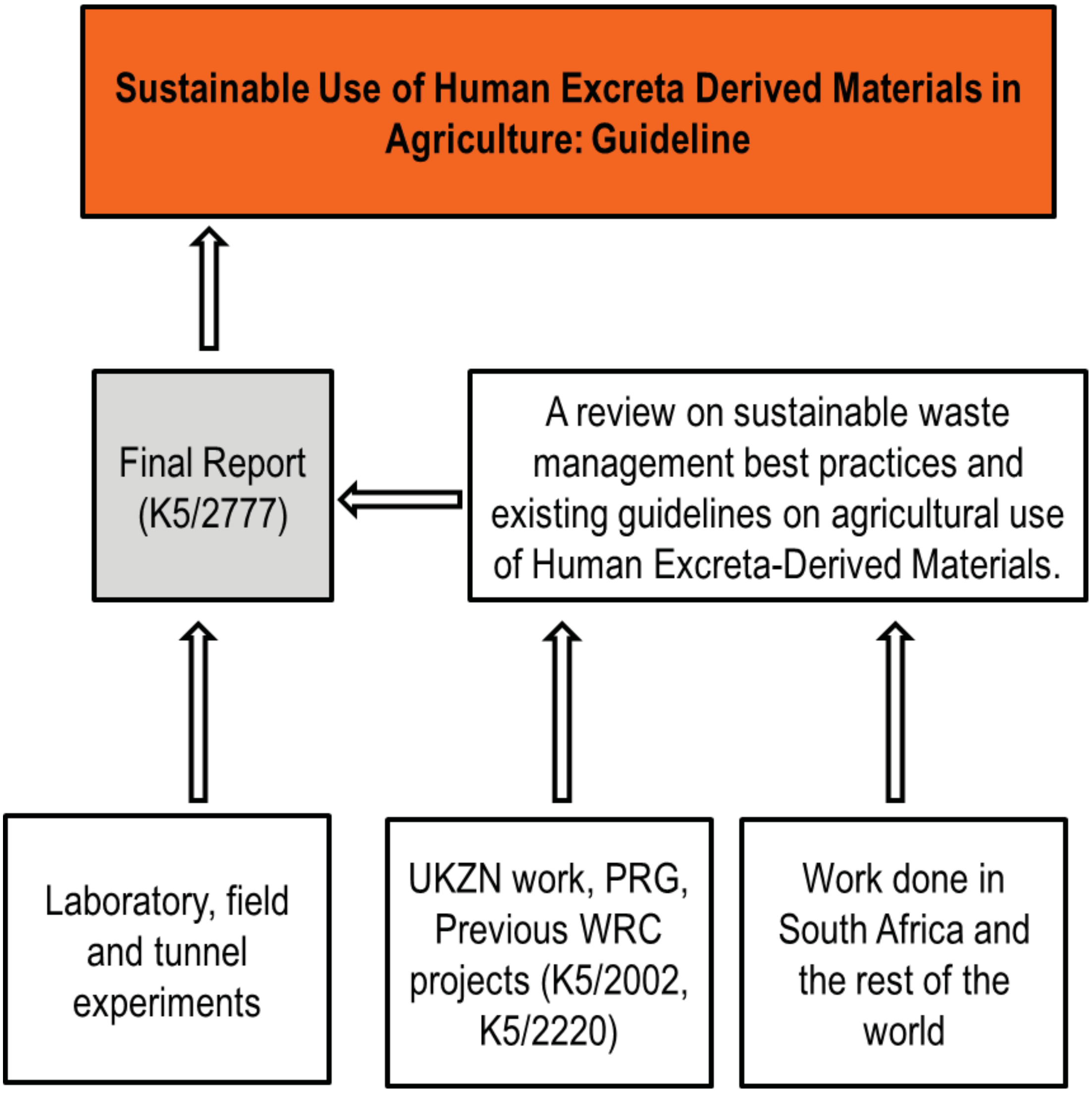

Figure 1.1: A summary of the approach towards the development of the guideline on safe and sustainable agricultural use of human excreta-derived materials and wastewater.

2 THE USE OF DEWATS EFFLUENT FOR CROP PRODUCTION

2.1 Background

The DEWATS is a modular waterborne technology that comprises of the settler, anaerobic baffled reactor (ABR), anaerobic filter (AF) and planted gravel filters (PGFs) that include the vertical flow constructed wetland (VFCW) and the horizontal flow constructed wetland (HFCW) (Figure). The DEWATS treats different types of wastewater, including blackwater, by anaerobically degrading organic compounds into inorganic compounds, producing an effluent rich in nitrogen (N), P and potassium (K) (Gutterer et al., 2009).

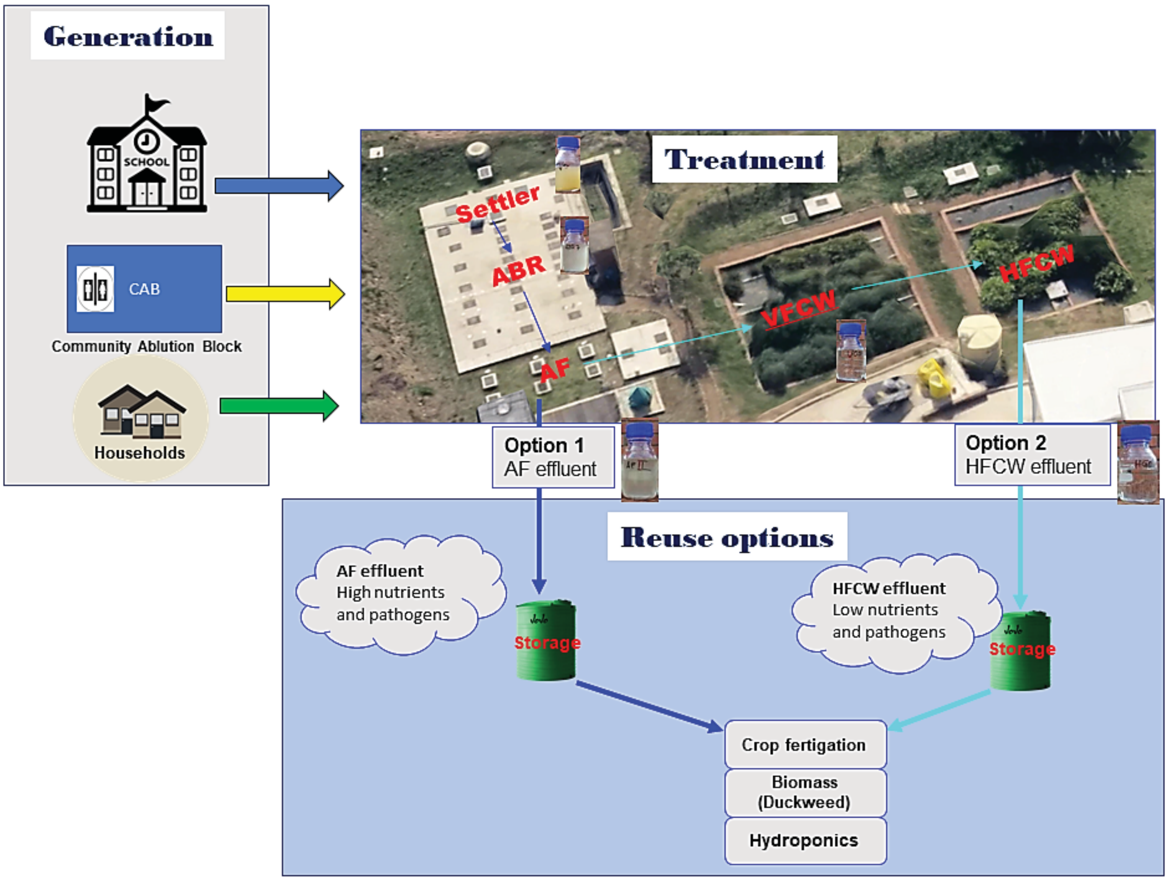

Figure 2.1: A schematic diagram showing domestic wastewater generations streams (school, community ablution blocks or households), connection to the Decentralised Wastewater Treatment and potential reuse of various treatment effluents (after the anaerobic filter (AF) and from the horizontal flow constructed wetland (HFCW)).

The treatment process involves sludge settling and scum removal in the settler. The wastewater then moves in an up and down manner within baffles of the ABR where anaerobic digestion degrades complex organic compounds thereby reducing the chemical and biological oxygen demand (COD and BOD). During the treatment process, P increases after the ABR treatment due to microbial processes releasing intracellular phosphates from the substrates and minimal reduction of pathogens have been reported (Singh et al., 2009, Foxon et al., 2004). The wastewater undergoes further treatment by the AF where activated sludge completes the anaerobic digestion. The effluent produced after the AF is high in microbial load and ammonium N as a result of the anaerobic digestion.

In hybridised wastewater treatment systems, the AF effluent can be further treated with PGFs. The AF effluent enters the VFCW where aerobic conditions promote nitrification. Nutrients are removed from the wastewater by plant uptake and some denitrification. The pathogen are attached to the gravel particles and subsequently deactivated due to various factors such as physicochemical aggregation, oxidation, biological predation, high hydraulic retention times (Shingare et al., 2017) and temperature (Reed et al., 1995). The phosphorus removal efficiency decreases with time, being very low in wetlands that are >9 years old due to reduced P sorption capacity by the media and this occurs faster when plant biomass is not harvested (Vymazal, 2004). The wastewater is further treated by flow through the HFCW. The HFCW effluent differs from the AF effluent in terms of microbial load, physical appearance and chemical properties.

The general physicochemical and biological properties of DEWATS effluents based on monitoring studies at Newlands Mashu, Durban are given in Table. The effluent produced from different stages of treatment (AF and PGFs) complies with most standard requirements for irrigation water quality as stipulated by the SAWQG (Department of Water and Sanitation (formerly DWAF), 1996) and FAO guidelines (Food and Agriculture Organisation, 1992) but do not meet the minimum standards for unrestricted use with regards to microbial concentrations.

The physicochemical and biological properties of DEWATS effluents show their potential for agricultural use as irrigation water. Therefore, this section aims to provide a practical guide on the safe agricultural use of treated wastewater (DEWATS effluent from AF and HFCW) concerning good agronomic practices, human health and environmental risk management, and social perceptions.

Table 2.1: The general chemical, biological and physical properties of the anaerobic filter (AF) and horizontal flow constructed wetland (HFCW) effluents monitored for six years (2013-2019) from the DEWATS pilot plant at Newlands Mashu in comparison with the South African Department of Water and Sanitation (DWS) and Food and Agricultural Organisation (FAO) irrigation quality guidelines for the most severe restriction of crop use

Property	Unit	AF effluent		HFCW effluent		DWS limits	FAO limit
		Mean	Range	Mean	Range		
Total-N		57.3 ± 1.4	51.2-62.5	19 ± 3	0.15-56	-	-
Nitrate-N		2.1 ± 0.5	0-4.1	5.6 ± 4.2	1-26.8	< 30	5-30
Ammonium-N	mg L^{-1}	54.8 ± 1.4	48.1-60.1	16.9 ± 3.9	0.15-56	-	-
Orthophosphate-P		9.3 ± 1.3	4.5-19.5	17.3 ± 4.7	7.4-37.9	-	-
K		14.2 ± 2.3	8.3-19.4				
Chemical oxygen demand	mg O_2 L^{-1}	465 ± 288	81.2-2 500	64.7 ± 7.8	3.1-159	< 5000	-
pH(H_2O)		7.6 ± 0.1	7.3-8	6.7 ± 0.1	6.2-7.3	6-9	6.5-8.5
Electrical Conductivity	mS m^{-1}	8.5 ± 7.2	0.9-95	73.7 ± 2.7	54-99	< 540	70-300
Total suspended solids	mg L^{-1}	91.01 ± 16.7					450-2000
Alkalinity	mg $CaCO_3$ L^{-1}	199 ± 38.7	7-319	23.5		-	92-519
S	mg SO_4^{2-} L^{-1}	61.3 ± 10.8	48-74.4				
Al		0.1	0-0.4	*	*	5-20	< 5
Bo		0.02	0-0.06				
Cd		0	0	*	*	0.01-0.05	< 0.01
Cr		0	0	*	*	0.10-1.0	< 0.1
Fe		0.1	0.08-0.12	*	*	5.0-20.0	< 5
Mg		14.7 ± 9.5	4.2-27.1				
Na	mg L^{-1}	35.3	1.8				
Mo		0.1	0.04-0.11	*	*	0.01-0.05	< 0.01
Pb		0.1	0-0.12	*	*	0.2-2.0	< 5
Zn		0	0	*	*	1.0-5.0	< 2
Escherichia coli	[#]cfu per 100 mL	24 900 ± 11 370	2 600-40 000	5 200 ± 6 800	70-24 200	1 000-50 000	< 50 000
Salmonella	cfu per 100 mL	33 000 ± 845	-	1 650 ± 650	-	1 000-50 000	< 50 000

[#]cfu - coliform forming units; * Not determined; DWS is the Department of Water and Sanitation.

2.2 Regulatory framework and legal context

The DEWATS effluent can be used for crop fertigation to supply both water and nutrients. Therefore, this guideline applies to irrigated areas where continuous effluent production resulting from domestic water consumption allows uninterrupted fertigation.

The agricultural use of DEWATS effluent is regulated by the following Acts and guidelines:

- The National Water Act (Act 36 of 1998) (NWA) (Department of Health, 2018).
- The Environment Conservation Act (Act 73 of 1989) (Department of Environmental Affairs, 1989).
- The National Health Act (Act 61 of 2003) (Department of Health, 2004).
- The National Environmental Management Act (Act 107 of 1998) (Department of Environmental Affairs, 2009).
- The United States Environmental Protection Agency: Guidelines for wastewater use (United States Environmental Protection Agency, 2012).
- The International Organization for Standardization (ISO) guidelines for treated wastewater use for irrigation projects:
    - Part 1: The basis of a reuse project for irrigation (International Organisation for Standardisation, 2020a);
    - Part 2: Development of the project (International Organisation for Standardisation, 2020b);
    - Part 3: Components of a reuse project for irrigation (International Organisation for Standardisation, 2020c); and
    - Part 4: Monitoring (International Organisation for Standardisation, 2016).
- The South African Water Quality Guideline for irrigation water (Volume 4) (Department of Water and Sanitation (formerly DWAF), 1996).
- The South African risk-based, site-specific, irrigation water quality guideline (SAWQG) (DuPlessis et al., 2017).

There are two types of wastewater fertigation schemes and these can either be partial or full (Department of Environment and Conservation, 2004). In a “partial reuse scheme” the user utilises the effluent needed and discharges excess into water bodies while in a “full reuse scheme” all the effluent is used leaving no excess for discharge. This guide, therefore, focuses on a full reuse scheme.

2.3 Planning for reuse

Proper planning is required to achieve a safe, legally and socially acceptable wastewater fertigation project. Aspects that need to be considered include registration, site assessment and demarcation of suitable areas.

- The South African NWA (Act 36 of 1998), requires the user to lawfully occupy the land to be fertigated (Department of Health, 2018). The user should register for fertigation using any treated wastewater with the DWS.

2.3.1 Site selection

2.3.1.1 Climate

Climatic data on rainfall patterns, temperature, relative humidity, wind speed and solar radiation is required for various reasons:

- Provides information for crops that can be grown in a specific area.
- Enables the calculation of crop water requirements based on the water balance.
- Site-specific weather data can be obtained upon request from various organisations such as the South African Weather Service, Agricultural Research Council (ARC) or South African Sugar Research Institute (SASRI) and National Aeronautics and Space Administration (NASA) website (https://power.larc.nasa.gov/data-access-viewer/).

2.3.1.2 Geographical location

The South African NWA requires a geological survey to be done before the fertigation program and the suitable site should:

- Be 50 m above the 100-year flood line;
- Be 100 m from the edge of a water resource; and
- Not overlie an aquifer, the identification of which can be done in consultation with the DWS.

2.3.1.3 Soils

Soil irrigability refers to the suitability of soil for irrigation which is indicated by chemical and physical properties. The South African soil irrigability classification classes are summarised in Appendix 2.1.

2.3.1.4 Soil Texture

- Soil texture can be analysed at any accredited soil analytical laboratory following ISO 17892-4:2016 standard methods for particle size determination.
- Highly irrigable soils (Class 1) should have a clay content of between 10 and 35% and the least irrigable soils (Class 3) have either a high clay content (>35%) or a very low clay content (<10%) (Reinders, 2010).

2.3.1.5 Soil wetness and effective depth

- The classification of soil irrigability can be based on soil wetness and effective depth (Table). Soil wetness is defined as an indication of the rate at which water is removed from the soil by percolation and surface runoff. This is affected by various factors ranging from slope, position, infiltration rates, permeability and redoximorphic features.
- Soil wetness can be determined by qualified personnel (e.g. soil scientist) following ISO 25177:2019 standard methods for field soil description.
- The water saturation depth is determined using the profile morphology whilst the maximum height of signs of hydromorphy is used as the depth limit. Therefore, the soil wetness of classes of 2 and above should be irrigated, paying special attention to drainage (Reinders, 2010).
- Soil effective depth affects root development, soil water reservoir, nutrient uptake and the degree of drainage past the soil.
- The soil effective depth is determined by digging or auguring the soil profile down to the limiting layer, which is a layer of poor hydraulic conductivity and this is harder than the soils above.
- Soils within a class 1 effective depth are irrigable, and class 2 and 3 are conditionally irrigable while classes 4 and 5 are non irrigable.

Table 2.2: Classification of soil irrigability based on soil wetness (Reinders, 2010).

Class	Soil wetness	Soil effective depth
1	Not wet within 1 500 mm	900-1500 mm
2	Wet in some part between 1 000 and 1 500 mm	600-900 mm
3	Wet in some part between 500 and 1 000 mm	300-600 mm
4	Wet in some part between 250 and 500 mm	150-300 mm
5	Wet in some part within 250 mm	0-150 mm

2.3.1.6 Soil fertility

- Important soil properties include organic carbon (C), pH, electrical conductivity (EC), exchangeable sodium percentage (ESP), trace elements and plant nutrients. These should be analysed by an ISO/IEC 17025:2017 accredited soil analytical laboratory according to appropriate standard methods.
- Irrigable soils are characterised by:
    - pH between 5.5 and 7.5 and the EC is <300 mS m^{-1}.
    - If these values are exceeded the SAR and ESP must be determined.

2.3.1.7 Soil suitability maps

- The NWA requires the demarcation of both the location of the irrigation area and the extent of the area or areas under irrigation. These should be presented on a suitable scale map(s), to show information on areas, the dominant soil units (soil types, areas in hectares or percentage), effective soil depth and irrigation potential (Reinders, 2010).

2.3.2 Assessing the DEWATS effluent for reuse fitness

Determining the suitability of a certain treated wastewater for agricultural use is the first recommended step in the planning phase (United States Environmental Protection Agency, 2012). The Decision Support System (DSS), developed by the Water Research Commission and the South African Department of Agriculture, Forestry and Fisheries is a novel approach used to assess the potential agronomic, health and environmental risks associated with irrigation using water of a certain quality (DuPlessis et al., 2017). The DSS (also the SAWQG) makes use of water quality and assesses risks based on specific site information, making it a robust tool that can be applied in different agroecological regions of South Africa. The SAWQG software is obtainable from the NB systems website free of charge via the following link: https://www.nbsystems.co.za/downloads.html (DuPlessis et al., 2017).

The first step involves characterisation of the effluent and the information generated can be included in the SAWQG. Characterisation information required includes macronutrients, trace elements and biological constituents (Figure 2.2). There is no clear information on the minimum number of effluent samples to be characterised, but a minimum of three composite samples may be used.

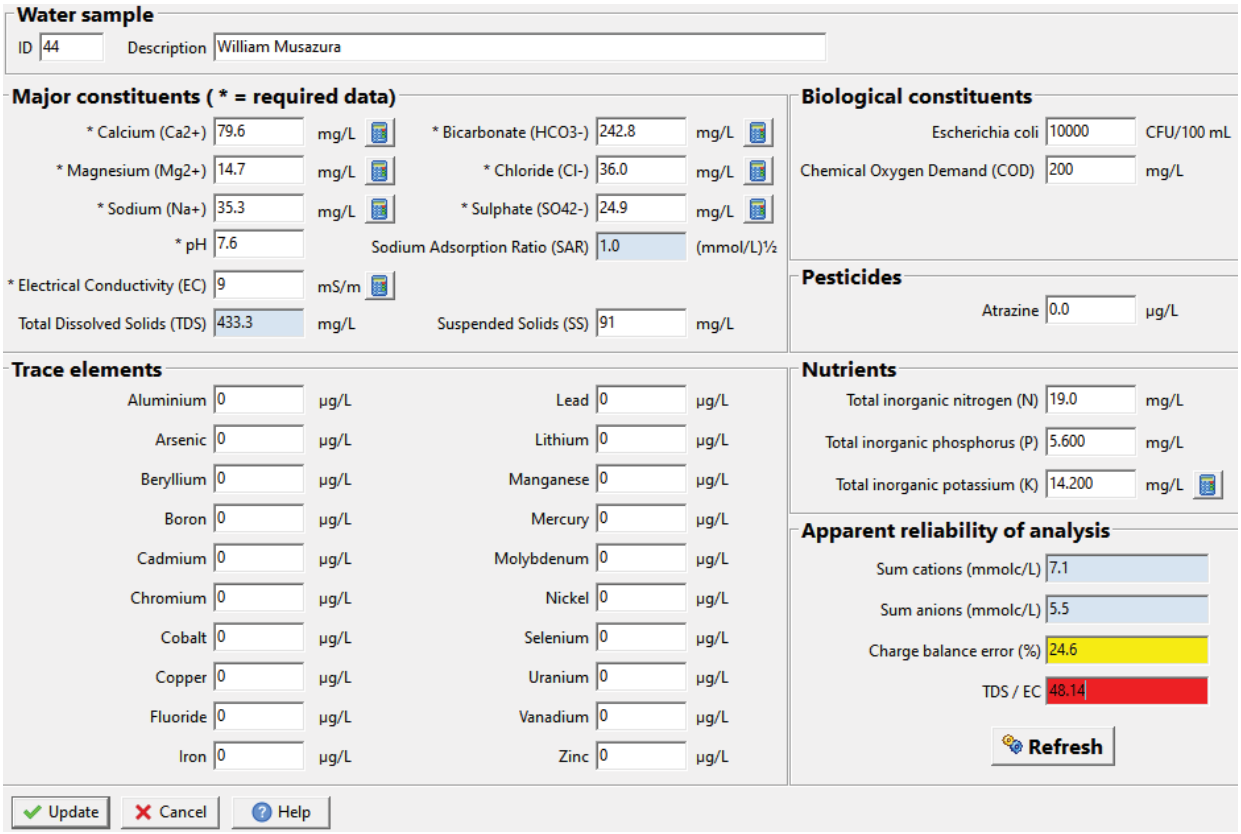

Figure 2.2: An example of the South African Water Quality Guideline tier 1 irrigation water fitness for use based on DEWATS effluent characterisation data.

2.4 Implementation

The NWA requires the wastewater reuse system design to be effectively constructed, maintained and monitored to ensure consistency, effectiveness and safety (Department of Health, 2018). Therefore, precautionary measures to be considered include the prevention of:

- Waterlogging of the soil and pooling of the effluent on the soil surface;
- Vector attraction, odour and secondary pollution;
- Contaminated water entering a water resource;
- Contamination of runoff or stormwater;
- Chemical or physical deterioration of soil on the fertigated site;
- Unauthorised use of wastewater by the public; and
- People exposed to the mist originating from fertigation using treated wastewater;

Also there should be a regular communication between the effluent supplier and the user (United States Environmental Protection Agency, 2012).

2.4.1 Land area calculation

The limiting land area required for each DEWATS plant is calculated based on a water or nutrient balance. The limiting land area is the largest amount of land required to satisfy a specific irrigation scheme, i.e. the crops produced and the cropping system (monocropping, crop rotation or intercrop) should fully utilise all the effluent without extra available for discharge or storage.

- The land area required should be at least double the calculated one and staggering planting dates to overlap harvesting times of several cropping systems can be done to ensure continuous utilisation of effluent in full reuse schemes since some crops require irrigation termination about 30 days before harvesting (Alberta Environment, 2000).
- When the DEWATS effluent is used as a source of irrigation water, the land area can be calculated based on crop water requirements and DEWATS effluent flow rates as shown in Equation 2.1 (Musazura et al. (2018).

$$\text{Land area } (m^2) = \frac{\text{Annual effluent produced } (m^3)}{\text{Crop water requirements (mm)}} \qquad \text{Equation 2.1}$$

Where: the annual effluent produced is determined from average actual effluent flow rates from the DEWATS system. Flow rates are likely to vary in different areas, being higher in more affluent communities than informal settlements (Crous et al., 2013). The DEWATS at Newlands Mashu has a design flow rate of 50 m^3 per day but the actual flow as reported by Musazura et al. (2018) was 35 m^3 per day.

The crop water requirement refers to the amount of water required for irrigation. This varies with crop growing stage, crop species (crop factor), climate (rainfall, humidity, temperature, and wind speed), and seasonal variations.

- o The SAWQG, which has a database of various crops and 50 years of weather data from various weather stations around South Africa can be used to calculate crop water requirements.
- o The SAWQG also allows the user to decide on which cropping system and combinations to use.

2.4.2 Storage requirements for full reuse

Seasonal variations in rainfall and crop water demand affect effluent utilisation (Figure 2.3). Effluent storage is required to resolve effluent supply/demand imbalances (United States Environmental Protection Agency, 2012). According to Odindo et al. (2016), effluent retention in storage deactivates some pathogens. Therefore, excess effluent should be stored properly as per the designs stipulated by the NWA, which requires the users to register with the DWS if >500 m^3 of effluent is to be stored for reuse. The storage can be designed according to standards specified in the International Organisation for Standardisation (2020c), which consider factors such as:

- o The use of compact lagoons lined with impervious layers such as clay and plastic.
- o Pipelines which carry wastewater should be of sufficient size and they must be strong enough to withstand flow of wastewater for many years without leakage.
- o The storage must be able to accommodate the maximum volume of effluent that is likely to occur at any time and enough reserve volume to cope with possible emergencies.

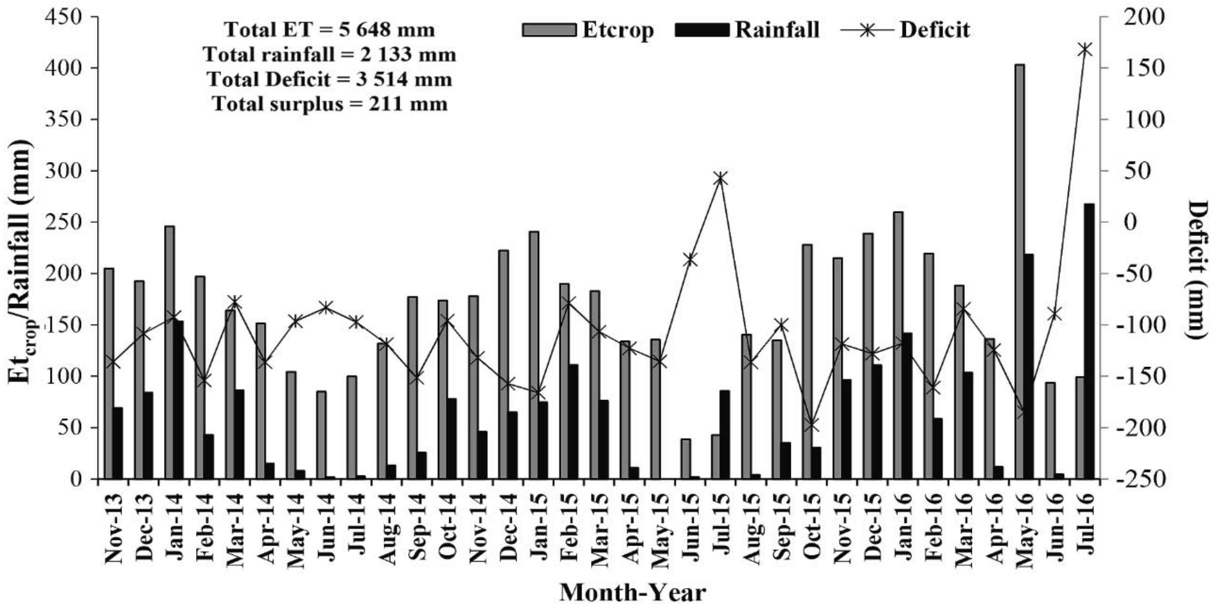

Figure 2.3: Water balance showing crop water requirements (ET), total rainfall, irrigation required (deficit) and surplus effluent (DEWATS flow rate-total deficit) in banana/taro intercrop at Newland Mashu. Adapted from Musazura et al. (2018).

Therefore, according to the United states Environmental Protection Agency (2006), the storage volumes required are determined according to the water balance based on historical climatic data. The storage requirements are calculated as follows:

1. Determine the monthly effluent surplus (M_s):

$$M_s = \text{Av. month effluent flow rates} - \text{Av. month crop water req.} \quad \text{Equation 2.2}$$

Where: M_s is the maximum monthly cumulative storage (mm). The monthly flow rates are the average volumes of effluent produced per certain design of the DEWATS. The average monthly crop water requirements can be computed by the SAWQG software for a specific crop.

2. Determine the storage volume (S_v):

$$V_S = M_s * F_a * 0.001 \quad \text{Equation 2.3}$$

Where: V_S is the storage volume (m^3); M_s is the maximum monthly cumulative storage (mm); Fa is the calculated irrigation field area (m^2).

3. Calculate the area of storage pond (A_s):

$$A_s = \frac{V_s}{d_s} \quad \text{Equation 2.4}$$

Where: A_s is the area of the storage pond (m^2); V_s is the storage volume (m^3) calculated in Equation 2.3 d_s is the pond depth (m).

4. Calculate the net volume of water gained or stored in the storage:

$$\Delta V_s = (Pr - E - S)\ 0.001 * A_s \quad \text{Equation 2.5}$$

Where: ΔV_S is the change in storage (m^3); Pr is the precipitation (mm); E is the evaporation (mm); S is the monthly seepage (mm); A_s is the area of the storage pond (m^2). Assumption: seepage is negligible due to the quality of materials used to construct the storage

5. Determine the total annual change in storage (ΔV_S) from monthly values and total available wastewater volumes from monthly data (Q_m).

6. Calculate adjusted field area to account for annual net gain/loss in storage:

$$A_w = \frac{\sum \Delta V_s + \sum Q_m}{(L_w)(0.001)} \quad \text{Equation 2.6}$$

Where: A_W is the adjusted field area (m^2); ΔV_S is the change is the net gain/loss in storage (m^3); Q_m is the annually available wastewater (m^3) and L_w is the design annual loading rate (mm).

7. **The monthly volume of applied wastewater is calculated using the design monthly hydraulic loading rate and adjusted field area:**

$$V_w = (L_w)(A_w) * 0.001 \qquad \text{Equation 2.7}$$

Where: V_w is the monthly volume of applied wastewater (m^3); L_w is the design annual loading rate (mm); A_w is the adjusted field area (m^2).

8. **The monthly net change in storage is calculated and used to calculate the cumulative storage at the end of each month:**

$$\Delta V_s = \Delta V_{s\ (net\ gain/storage)} + Q_m - V_w \qquad \text{Equation 2.8}$$

Where: ΔV_s is the net change in storage (m^3); $\Delta V_{s\ (net\ gain/storage)}$ is the net storage gain/loss (m^3); Q_m is the sum of available wastewater (m^3); V_w is the monthly applied wastewater (m^3).

- The final storage then be determined as the highest cumulative storage (m^3).

Wastewater production is a continuous process. Some farmers irrigate when the crop demand is high, they might choose low water and nutrient consuming crops and sometimes weather variations might affect the quantities of effluent used in any particular year. As result wastewater may accumulate and overflow from storage facilities, exposing other non-effluent users to risks and polluting the environment. It is therefore recommended to consider alternative utilisation options:

- Irrigation at rates above crop water requirements.
- Use of crops with high nutrient and water requirements.
- Increasing crop densities especially for forage plants that are harvested frequently.
- Diversifying effluent uses to include other activities (Figure 2.4):
    - Hydroponic production of vegetable crops.
    - Production of nursery ornamental plants.
    - Production of duckweed for biomass harvest.

2.4.3 Deciding on the cropping systems

The decision on the cropping system, crop and irrigation type requires a multidisciplinary and inclusive approach with community members or users. Choice of crops and irrigation system should be selected as discussed in Section 2.4.3.1.

2.4.3.1 Crop selection

The decision on the choice of crops to irrigate is a complex process which requires a multiple decision approach that considers various factors such as:

- **Climatic requirements** – different crops have different rainfall and temperature requirements.
- **Crop use** – some crops are grown for income generation and food security in most South African communities.
- **Health issues** – crops that are consumed raw or unprocessed such as lettuce pose higher health risks to the consumer. Some crops such as maize and dry bean are much less likely to be contaminated since they are covered in husks or peels and are produced away from the ground where effluent is applied, especially when surface and drip irrigation methods are being used.
- **Environmental control** – forage crops such as grazing sorghum can be grown at high densities (triple normal density) to maximise nutrient removal through frequent biomass harvesting. Grasses, e.g. sod grass, bermudagrass and vetiver grass have deep and dense root systems so can be used to remove excess nutrients from the effluent irrigated soils.
- **Economic issues** – horticultural crops such as tomato, Swiss chard, chillies and peppers have higher returns per unit area and can be grown viably on limited land areas. High value crops such as tomatoes may be grown using hydroponics (Figure 2.4).
- **Effluent management** – effluent is continually produced and crop water requirements vary seasonally and spatially. Therefore, to fully utilise the effluent without investing in storage high water and nutrient consuming crops may be grown (Musazura et al., 2018).

A: Tomatoes grown in hydroponics using DEWATS effluent
B: Duckweed produced for biomass using DEWATS effluent after AF treatment
C: Banana and taro intercrop fertigated with HFCW effluent

Figure 2.4: Alternative ways of managing excess effluent volumes through (A) hydroponically production, (B) duckweed production and (C) production of high water-consuming crops (banana and taro).

2.4.3.2 Irrigation system management

The irrigation system may be selected based on capital establishment, health and safety implications, choice of crops to be grown and available expertise to manage the system. A summary of factors to influence the choice are given in Table 2.3.

- The information on recommendations for pumping stations, filtration, water network systems, irrigation equipment, and physical and chemical treatment is contained in the International Organisation for Standardisation (2020c),
- Irrigation system corrosion can be managed by:
  - Using water with <100 mg L^{-1} (Cl), <70 mg L^{-1} (Na) and <1.5 mg L^{-1} (Fe and Mn) (World Health Organisation, 2006). The DEWATS effluents meet these standards and hence can be used without risk of corroding the irrigation system.
- Clogging of irrigation systems is not a risk when using DEWATS effluent since it is low in suspended solids. When drip irrigation is to be used, general maintenance activities such as acidification and installation of a backwash system is recommended.

Table 2.3: Factors that affect the choice of irrigation method using DEWATS effluent

Irrigation method	Factors	Management option using wastewater
Border (flood irrigation)	○ Low cost ○ No levelling required. ○ May be used to fertigate rice by alternating wetting and drying (Busari et al., 2019). ○ Some bottom leaves might be in contact but no effect on yield ○ Less likelihood of salts to accumulate in the root zone since the wastewater moves vertically ○ Plants may experience water stress between irrigation intervals ○ Fair to medium ability to handle wastewater	○ Strong protection for field workers, crop handlers and consumers needed. ○ Good irrigation management practices and drainage produce good yields ○ Alternate wetting and drying may be used for crops such as rice (Busari et al., 2019).
Furrow irrigation	○ Low cost ○ Need levelling ○ No foliar damage – plants grown on the ridge ○ Salts accumulating on the ridge may damage the plants ○ Plants may experience water stress between irrigation intervals ○ Fair to medium ability to handle wastewater	○ Protection for field workers and sometimes crop handlers and consumers ○ Good irrigation management practices and drainage produce good yields
Sprinkler irrigation	○ Medium water use efficiency ○ No levelling needed ○ Severe foliar damage may affect yields ○ Less likelihood of salts to accumulate in the root zone since wastewater moves vertically ○ Impossible to maintain high soil water potential throughout the growing season ○ Poor to low ability to handle wastewater – foliar damage reduces yields	○ *Category B crops, e.g. fruit trees should not be grown
Subsurface and trickle irrigation	○ High cost to establish ○ High water use efficiency ○ No foliar damage – higher yields ○ Salt movement is radial following the direction of water movement – salt wedges are formed around the drippers ○ Possible to maintain high soil water potential throughout the growing season – minimal root zone salinity effects ○ Excellent to good ability to handle wastewater – less yield reduction in almost all crops	○ Filtration needed to prevent clogging of emitters

* Industrial crops that can be processed or are not consumed, e.g. cotton, fibre, canning crops (Food and Agriculture Organisation, 1992).

2.4.4 Soil quality management

The use of treated wastewater has direct and indirect beneficial and detrimental effects on soil quality. The SAWQG assesses the potential of wastewater fertigation on soil quality. It can be used as a tool in the management of root zone salinity, soil permeability, oxidisable carbon loading (Appendix 2.2) and trace elements (Appendix 2.4) in soil fertigated with DEWATS effluent.

Soil root zone salinity refers to the concentrations of salts (EC) in the soil resulting from irrigation using water of a certain quality. Soil salinity affects plant growth and can reduce yields.

- Soil salinity in DEWATS effluent irrigated soils is not a challenge.

Soil permeability is the rate at which water passes through the soil and is a result of surface infiltrability (water entry to the surface) and hydraulic conductivity (water movement within the soil). However, this is not a problem when DEWATS effluent is used.

High chemical oxygen demand (COD) in fertigation water loads organic carbon in the soil, increasing the C: N ratio and immobilisation of N by microorganisms.

- The DEWATS effluent has low COD of 465 mg L^{-1} for AF effluent and 64.7 mg L^{-1} for the HFCW effluent, and simulations done using the SAWQG found that even in hot and arid climates, where irrigation requirements are high the C loading was within acceptable limits.

2.4.5 Crop management practices

The SAWQG is used to assess the potential effects of fertigating crops with DEWATS effluent on the effects of root zone salinity to plants, nutrient management and human health risks resulting from microbial contamination (Appendix 2.3).

2.4.6 Effects on plants

The DEWATS effluent have no effects on plant specific ion toxicity.

2.4.7 Nutrients

DEWATS effluent contains macronutrients such as nitrogen (N), phosphorus (P) and potassium (K). These nutrients can be applied to plants through fertigation using DEWATS effluent. The advantage of fertigation with DEWATS effluent is that:

- The nutrients are supplied throughout the growing season and are usually readily available for plant uptake, thereby reducing fertiliser requirements.
- The uptake of nutrients by plants minimises environmental pollution risk.

The challenges are that plants have different nutrient requirements at different stages of growth and the effluents do not contain plant nutrients in optimum ratios. Also the wastewater is applied based on crop water requirements. As a result plant nutrients may be over or underapplied in a manner that might affect crop quality or cause environmental pollution. It is very important to balance crop water and nutrient requirements.

2.4.7.1 Assessing the extent of nutrient imbalances

- The nutrients that can potentially be applied via fertigation using DEWATS effluent can be calculated using the SAWQG based on average crop water requirements estimated from climatic data.
- The fertigation programme is more manageable when the nutrients are undersupplied than oversupplied. Therefore, the SAWQG recommends that supplementary nutrients should contribute <50% of nutrients that can be removed by the crop and the most ideal target is for the effluent to supply 0-10% of the total nutrients required by the crop (Appendix 2.3).
- An example in Table 2.4 shows that fertigation of sorghum with DEWATS effluent needs special management for N, P and K, while the management of K is not problematic for Swiss chard and maize.

Table 2.4: Nitrogen (N), phosphorus (P) and potassium (K) requirements in comparison to the amount provided through fertigation using DEWATS anaerobic filter effluent taking an example of a scenario simulated using the decision support system for a site in Upington, South Africa (arid zone) in a clay soil under sorghum/Swiss chard rotation and maize/Swiss chard rotation

Crop	N (kg ha^{-1})		P (kg ha^{-1})		K (kg ha^{-1})	
	*Required	Fertigation	*Required	Fertigation	*Required	Fertigation
Swiss chard	168-224	328	24-34	39	0-140	59.2
Sorghum	54	459	13	74	45	114
Maize	200	524	39	85	195	130

N.B. Red boxes represent where nutrients supplied by effluent are severely in excess amounts for optimum crop nutrient management, yellow boxes shows were nutrients supplied by the effluent are tolerable for optimum crop nutrient management, the blue boxes show where the nutrients applied by the effluent are very ideal for optimum crop management. *Source: Fertilizer Society of South Africa (2007).

2.4.7.2 Managing nutrient imbalances

Nutrient management should be based on residual soil fertility and so the local fertiliser advisory services provider should be consulted to provide fertiliser recommendations based on soil analysis.

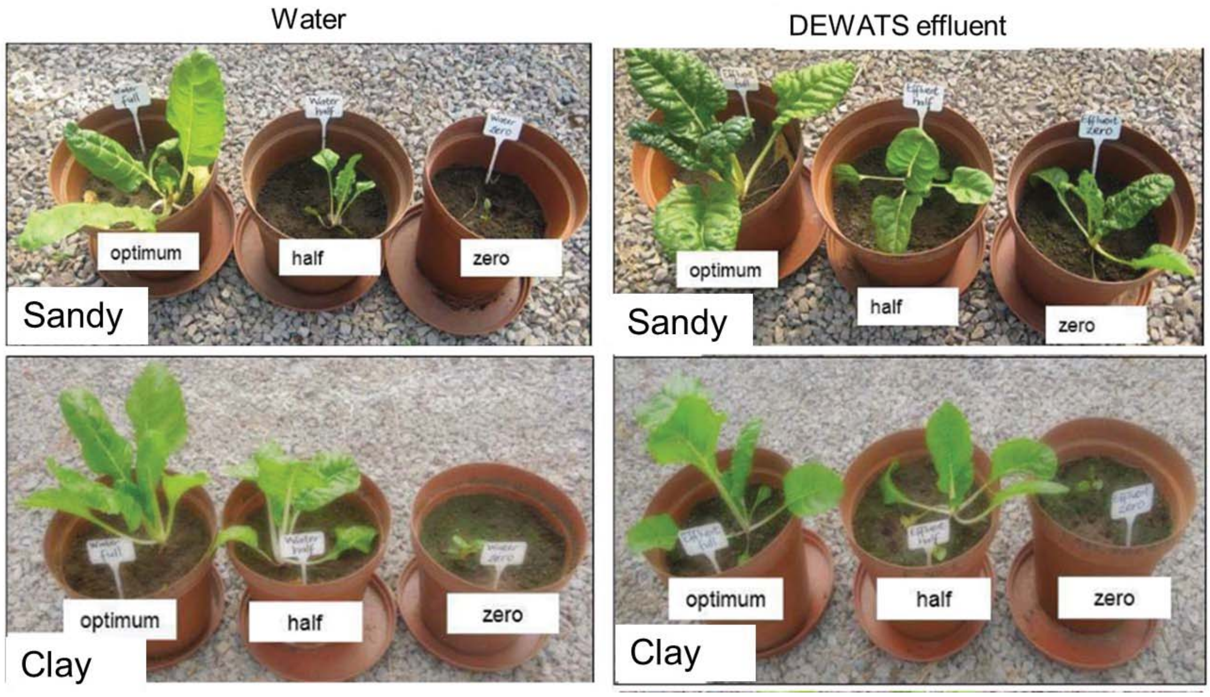

Figure 2.5: The effects of AF effluent (DEWATS effluent) on different soils (sand and clay) at different recommended fertiliser application rates based on soil analysis results. Adapted from Odindo et al. (2016).

Different nutrient management options are provided below:

- The rule of thumb is nutrient application should be based on the N requirement for specific crops and this can be obtained from:
  - Fertilizer Society of South Africa (2007) handbook.
  - Plant tissue analysis results by soil fertility advisory services provider.
- Effluent may be applied as a fertiliser source based on crop N requirements and the crop water may be supplemented with freshwater,
- Blending the effluent with freshwater may be done to satisfy crop N requirements per unit area. Some of the issues of consideration when blending are:
  - In full reuse schemes, the land area should match with blended volumes.
  - The amount of freshwater required for blending can be calculated as shown in Example 1 below, meaning that land area must be multiplied by the blending dilution factor.
- When applying based on N requirements sometimes P is supplied in excess while K may be underapplied. Therefore:
  - Management programmes to minimise the accumulation of P in the soil and potential losses to the environment via run-off and subsequent pollution of surface water resources can be implemented through the production of crops such as turfgrass sod (Tesfamariam et al., 2009).
  - Supplementary K fertilisers can be applied to meet crop requirements.

- The application should be done to fully utilise the volumes of effluent produced.
  - Higher planting densities, for example, increasing the planting densities of crops that are frequently harvested such as forage sorghum and ryegrass thrice.
  - The irrigated site should be larger allowing space for more crops during the wet season.
- The HFCW is low in N (19 mg L^{-1}) compared to the AF effluent (57.3 mg L^{-1}). Therefore, the HFCW effluent can be used to obviate the need for blending with freshwater.

Example 1

Maize crop nutrient requirements to attain 12 tonnes ha^{-1} yield[1] (MCR) = 200 kg ha^{-1} (N), 39 kg ha^{-1} (P) and 195 kg ha^{-1} (K) – based on the South African nutrient requirements for specific yield target (obtained from consultation with local fertiliser advisory service providers).

Soil residual nutrients (RN) = 50 kg ha^{-1} (N), 20 kg ha^{-1} (P) and 100 kg ha^{-1} (K) – obtained from soil analysis results and recommendations provided by the local fertiliser advisory service providers.

Nutrients potentially applied through fertigation (FT) see Table 2.4 = 524 kg ha^{-1} (N), 85 kg ha^{-1} (P) and 130 kg ha^{-1} (K) – calculated from the SAWQG algorithms.

Nutrient uptake efficiency of the irrigation system (IE) – depends on the irrigation system and these can be obtained from Reinders et al. (2005).

*Amounts required to be supplied through fertigation (AP) = MCR – (RN * IE) Food and Agriculture Organisation (2003).*

Effluent dilution factor =

Dilution factor required to meet N = 3.5 meaning 1 part of effluent needs 2.5 parts of freshwater

2.4.8 Health risks management

Health and safety should be prioritised from the collection of treated effluent, transportation to the field, irrigation methods and hygienic practices during harvesting and post-harvest handling.

The Sanitation Safety Plans (SSPs) developed by the World Health Organisation (2016) can be used for safe agricultural use of DEWATS effluent. The SSP is a site-specific tool which makes use of the WHO multi-barrier approach and has been used to guide on managing health risks associated with fertigation using DEWATS effluent along the value chain (Figure 2.).

[1] The yield target of 12 tonnes ha^{-1} applies to commercial farmers and small holder farmers attains a yield target of approximately 1 tonne ha^{-1}

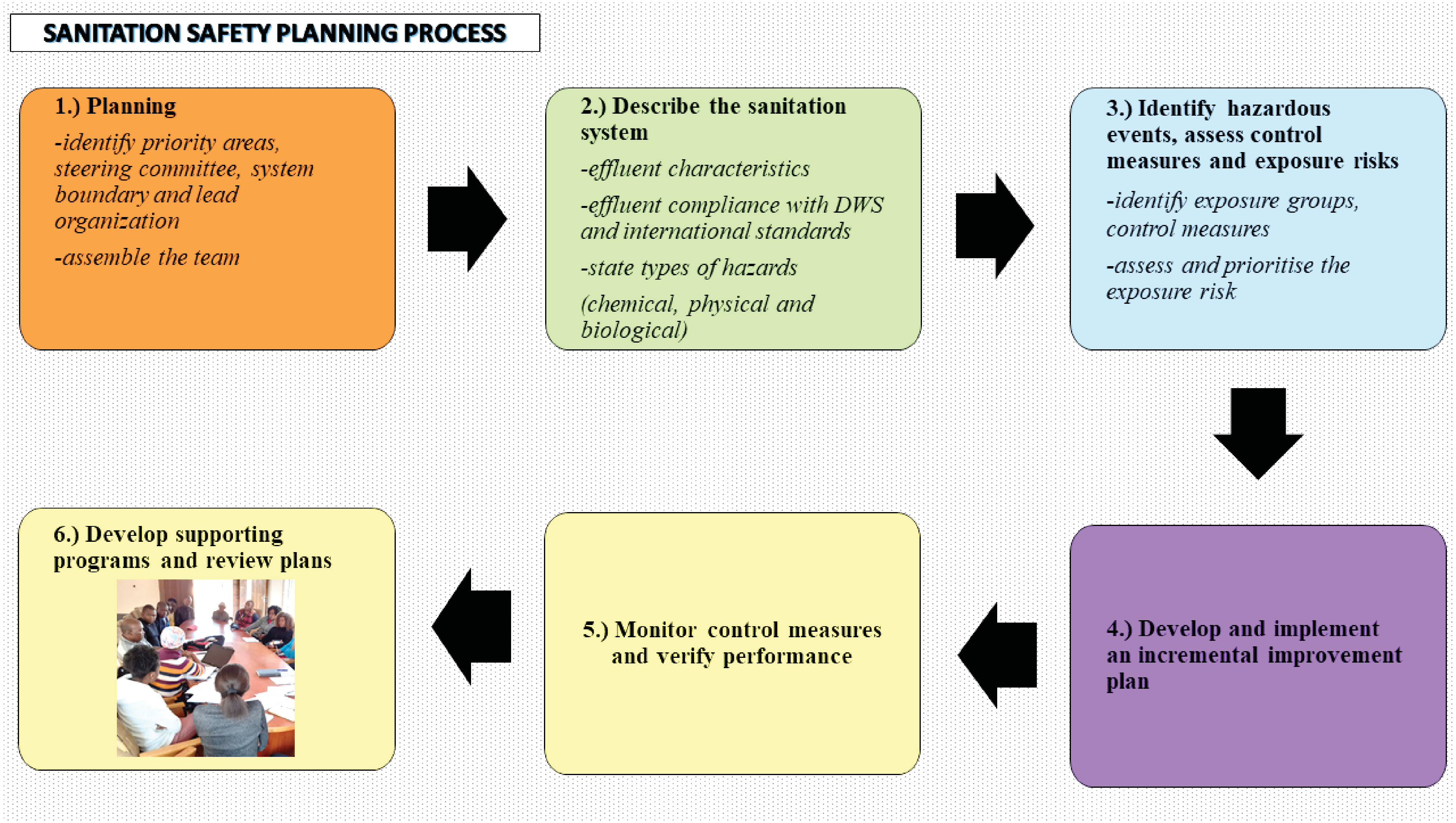

Figure 2.6: A step by step Sanitation Safety Planning process for safe agricultural use of DEWATS effluent.

The generic risk-based approach for the safe use of DEWATS effluent in crop production is summarised in Table 2.5. The major risk imposed by the use of DEWATS effluent is microbial contamination along the whole chain. The DEWATS effluent does not comply with minimum standards for unrestricted agricultural use since the bacterial loads are >1 000 cfu per 100 mL even after passing through the HFCW (Table). As a result, workers along the value chain are at risk of accidental ingestion, dermal contact and consumption of food irrigated with DEWATS effluent.

The first group of people who are at risk are workers maintaining the DEWATS plant (W3) and their families. Some of them do not wear personal protective equipment (PPE) or follow hygienic practices such that they expose their families to microbial risks after work, especially during food handling at home.

During crop production, farmers (F2) are exposed to microbial risks depending on the irrigation methods used. If the effluent is conveyed manually to the field through the use of containers, farmers will be exposed to accidental spillages. The problem is exacerbated if farmers are working under unfavourable conditions such that they may be uncomfortable wearing PPE. In well-established irrigation systems, microbial risks are high during maintenance, spraying if a sprinkler is used and sometimes contact with soil fertigated with effluent. Effluent drift from sprinkler irrigation might affect people some distance from the farm and even contaminate crops in nearby farms, especially when fertigation is done on windy days. The same group is exposed to risks when consuming contaminated crops such as tomatoes. Some farmworkers taste the farm produce thereby extending the ingestion risks to farm level.

The consumers are the most affected people in the value chain. They are at risk of dermal exposure after handling contaminated produce and gastric diseases through ingestion. The risk of infection to consumers consuming vegetable crops fertigated with DEWATS effluent has been found to exceed the tolerable risk level for consumption (Odindo et al., 2016).

Health risks management in DEWATS effluent fertigated fields should be done according to recommendations given by Odindo et al. (2016):

- The site manager/supervisor should monitor the health and safety of employees ensuring that they abide with occupational health protocols.
- Some farm activities should be done when weather conditions are conducive to the workers' comfort. For example, restricting operations such as fieldwork too early in the morning and indoor activities to the hotter times of day.
- The WHO recommends the use of micro-irrigation (drip, subsurface and trickle) and surface irrigation because:
    - They administer the effluent directly on to plant roots, minimising human exposure,

    - The effluent does not have direct contact with the edible parts of crop during irrigation as done by sprinkler irrigation systems.
- Effluent can be stored in storage ponds before use and the longer the storage time the more pathogens are deactivated.
- Tertiary treatment in PGFs significantly reduces pathogen loads but the effluent is still not fit for unrestricted use, therefore, risk minimisation can be done through crop selection for example:
    - Food crops and forage crops that can be processed or cooked (potato, silage maize, Swiss chard, sorghum and madumbe),
    - Crops with edible parts produced away from the ground (fruit crops),
    - Crops with edible parts covered in husks or pods (maize, sorghum or dry bean).
- Pre- and post-harvest hygienic practices should always be practised, for example avoiding fruits or edible plant parts that have accidentally fallen on the ground. Contamination may be minimised in various ways:
    - Delaying harvesting operations for at least 72 hours after the last fertigation event so that surface pathogens can die off.
    - Some fruits or vegetables may be sanitised before consumption by washing with salty water, chlorine based disinfectants, vinegar or running water to remove surface pathogens.
    - Therefore, to successfully ensure that the consumer risk is minimised people along the value chain must be trained on good hygienic practices. Farmers also need training on good agricultural practices to minimise contamination at the farm level.

The occurrence, persistence, and transfer of micropollutants in DEWATS effluent is a subject of concern. The International Organisation for Standardisation (2020a) guideline does not consider the chemicals of emerging concern (pharmaceuticals and personal care product residuals) as hindrances to irrigation using treated wastewater since there is no evidence of their adverse effects on human health.

Table 2.5: Human health risks assessment and management in DEWATS effluent fertigation programmes based on the Sanitation Safety Planning approach

Sanitation step	Hazard identification				Existing control	Risk assessment **L:** Likelihood **S:** Severity **R:** Risk level Allowing for existing control				Comments
	Hazard event	Hazard	Exposure route	Exposure groups*		L	S	Score	R#	
Treatment	Exposure to raw sewage during descumming and desludging	Microbial	Dermal or accidental ingestion	W3	PPE, vaccination	2	2	4	LR	Accidental contact with PPE and unwillingness to wear a face mask
	Foul smell	Malodour	Inhalation	W3	Face mask	2	2	4	LR	Unwillingness to wear face mask
Irrigation of crops with DEWATS effluent	Exposure to pathogens	Microbial	Dermal and accidental ingestion	F2	PPE, use of micro irrigation systems and surface irrigation	2	2	4	LR	There is a higher risk if AF effluent is used due to its microbial load.
Consumption of crops irrigated with DEWATS effluent	Pathogens	Microbial	Ingestion and dermal	C2	Hygienic practises during pre and post-harvest handling. Safe irrigation management methods established by WHO	2	6	8	V	Lack of knowledge of handling harvested produce
	Micropollutants	Pharmaceuticals and personal care products	Ingestion	C2	None					No evidence of their adverse effects on human health

* W3: Workers who operate and maintain the DEWATS plant, F2: Farmers who use DEWATS effluent for irrigating crops, C2: Consumption of crops fertigated with DEWATS effluent by F2 farmers;

V: very high; LR: low risk

2.4.9 Environmental pollution management

Irrigation using DEWATS effluent may discharge nutrients and pathogens into the groundwater and surface-water resources causing pollution. The summarised environmental risks and management options are reported in Table 2.6.

Table 2.6: Summarised environmental risks associated with fertigation using DEWATS effluent (AF and HFCW effluent) and subsequent management practices

Environmental risk	Remarks	Causes	Management options
Groundwater pollution	○ Nitrate pollution (> 10 mg L^{-1})	Nitrate leaching ○ High rainfall and irrigation regimes ○ Soil type (coarse-textured soils) ○ High soil nitrates	○ Irrigation scheduling (room for rainfall, leaching requirement) ○ Soil nutrient management ○ Consider irrigable soils (well-drained) (Section 2.3)
Surface water pollution	○ Eutrophication (algal bloom) ○ Death of aquatic life	Nitrogen and phosphorus loading ○ Surface runoff ○ Soil erosion ○ Lateral underground water flows into rivers	○ Same as above ○ Conservation tillage practices

Irrigation using DEWATS effluent increases soil N which undergoes various transformations in the presence of soil microorganisms to produce nitrate that may leach through the soil profile to groundwater. Nitrate leaching is higher in coarse-textured soils and through cracks in clayey soils. The process is hastened by overirrigation, high soil N content that exceeds crop requirements and high rainfall. Studies done using DEWATS effluent reported low N leaching in clay soils (Musazura et al., 2019a, Musazura et al., 2015, Musazura et al., 2019b).

Phosphorus may be retained in the soil when adsorbed by minerals such as iron and aluminium oxides in acidic soils or precipitated with Ca in alkaline soils. The soil phosphorus is lost into nearby rivers through surface runoff and soil erosion since it adsorbed onto the soil surface, causing non-point pollution evidenced by excessive algal blooms (eutrophication) and subsequent death of aquatic life. Surface runoff is exacerbated by poorly drained and shallow soils, high rainfall, excess irrigation and steep sloping sites.

There are several methods to manage environmental pollution from irrigation using DEWATS effluent:

- Nutrient losses from agricultural fields are minimised by implementing good nutrient management practices such as application based on crop nutrient requirements as detailed in Section 3.4.7.
- Irrigation scheduling strategies such as allowing room for rain minimise nutrient leaching in well-drained soils and surface runoff from less permeable soils.

- Site selection should consider irrigability (Section 3.3), for example, well-drained, deep soils allow deep root development and increase the efficiency of crop nutrient uptake.
- Some interventions to minimise soil erosion include:
    - Planting trees around the field and implementation of conservation tillage practices, which can be done in consultation with the local extension officer/advisor,
    - In case of groundwater rising due to continuous fertigation, the NWA requires the implementation of measures to collect contaminated stormwater or runoff coming from the fertigated area and this should be retained for disposal in general accordance with Section 3 of the Department of Health (2018) NWA.
    - Subsurface drainage and subsequent recycling of drained wastewater may be considered (Musazura et al., 2019a).

2.4.10 Perceptions and attitudes

Perceptions and attitudes towards the use of DEWATS effluent as a resource are important issues. Studies have shown that social perceptions towards handling fertilisers and food produced from HEDMs are driven by several factors such as the physical appearance of the HEDM, its economic benefits, impacts on yield and its health safety in terms of handling and consumption (Simha and Ganesapillai, 2017, Müller et al., 2017, Wilde et al., 2019, Odindo et al., 2016). Therefore, these have been used as the basis for guidance on managing social perceptions in the agricultural use of DEWATS effluent (Table 2.7).

Table 2.7: A summary of factors driving social perceptions in the use of DEWATS effluents in agriculture and corresponding management options

Factor	Remarks	Approaches/tools
Physical properties	○ The AF and HFCW effluents are clear and odourless.	○ Marketing the DEWATS through site visits.
Socio-economic benefits	○ Fertiliser value ○ Reduced environmental costs ○ Reduced health costs from water pollution ○ Potential for alternative crop production techniques (e.g. hydroponics)	○ Interactive implementation of reuse project involving farmers, experts and stakeholders. ○ Acknowledgement of the benefits of using DEWATS effluent as fertigation water during workshops.
Impacts on crop yield	○ Increased crop yields and quality ○ Contribution to food security	○ Farmer training workshops on best agricultural practices. ○ Establishment of community demonstration fields. ○ Site visits to areas using treated wastewater.
Health safety	○ The AF and HFCW effluents have high microbial loads that prohibit unrestricted use in agriculture ○ Retention in storage might reduce microbial load	○ Training farmers on safe agricultural practices for handling the effluent. ○ Public health education and promotion.

Physical properties such as malodours and turbidity may increase resistance towards handling DEWATS effluent. However, the DEWATS treatment processes remove solids and the resulting effluent is clear and odourless. As the effluent undergoes further treatments in the PGFs the resulting effluent becomes clearer (Figure 2.7).

Photographs of samples taken through the Newlands Mashu DEWATS process. Abbreviations: ABR, anaerobic baffled reactor; AF, anaerobic filter; VGF, vertical flow wetland; HGF, horizontal flow wetland.
Photos by Bjoem Pietruschka (2014).

Figure 2.7: Samples of the DEWATS effluent taken at different stages through the DEWATS process at Newlands Mashu, Durban. Adapted from Pietruschka et al. (2014).

Strategies to encourage farmers to use DEWATS effluents can include:

- Organising visits to treatment plants as part of training programmes.
- Training farmers on good agricultural practices using treated wastewater.
- People should be acquainted with the benefits of using DEWATS effluent for agriculture (Figure 2.8) and the content can be included in training curricula, workshops and field visits.
- Inclusive planning process between small scale farmers, experts and stakeholders in activities such as drafting viable business plans may enlighten farmers on how best to optimise profits from wastewater reuse projects.
- Demonstration plots in community agroecological centres should be established.
- Organised field visits to scientific research areas working on wastewater fertigation will allow farmers to interact with scientists.

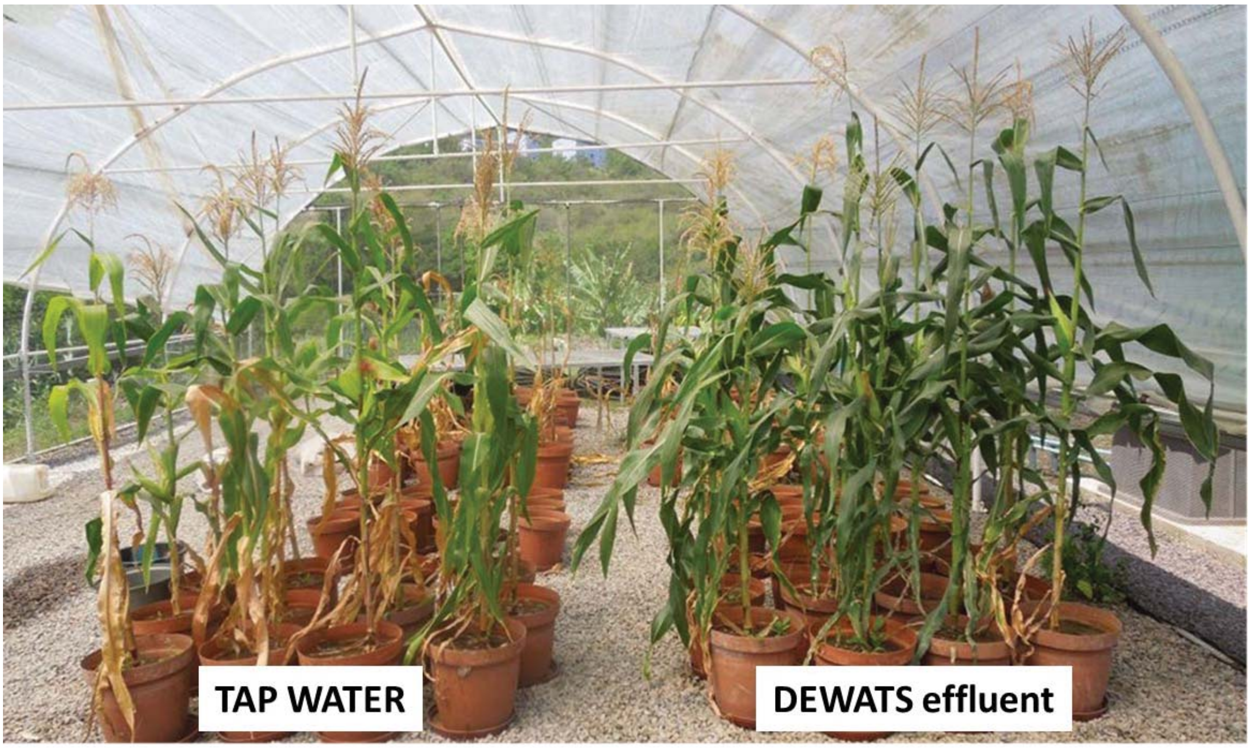

Figure 2.8: The effect of AF effluent fertigation on maize in a clay loam soil, in comparison to the application of tapwater without any fertiliser application.

- Education to enable understanding that treated wastewater can be used safely without any adverse health impacts.
- The Sanitation Safety Planning process should be included in the training curriculum whereby farmers are educated on how DEWATS processes reduce pathogens, and how good agricultural practices and post-harvest handling methods minimise health risks.

2.5 Monitoring and evaluation

Monitoring and evaluation of a wastewater irrigation program is a requirement as mentioned in Section 1 (Subsection 1.9) of the South African General Authorization; NWA of 1998 (Department of Health, 2018). The reasons for monitoring wastewater fertigation projects is to ensure that the health, environmental and crop production benefits are being achieved and find ways for possible interventions where necessary. The International Organisation for Standardisation (2020b) has developed various aspects of monitoring and evaluation and these are summarised in Table.

Table 2.8: Parameters to be monitored in DEWATS effluent irrigation project to ensure that health, environmental and crop productivity are successfully addressed

Effluent quality	Soil health	Crop production	Environment
○ Physicochemical properties ○ Biological properties	○ Nutrient concentrations ○ Microbial activity or organic carbon	○ Crop yields ○ Crop quality - *Micropollutants concentrations ○ Surface pathogens (faecal coliforms and helminths)	○ N and P leaching ○ Surface runoff ○ Groundwater and surface water quality

*There are no micropollutant monitoring techniques to date.

2.5.1 Effluent quality

The South African NWA and some international guidelines such as the Australian Department of Environment and Conservation guideline (Department of Environment and Conservation, 2004) require a monthly quality monitoring of treated wastewater for agricultural use. The general design of DEWATS plants is a treatment capacity of about 50 m^3 per day, therefore as per the South African General Authorization; NWA of 1998, effluent quality parameters of interest for agricultural use are given in Table 2.9.

- The DWS encourages monthly monitoring for EC, pH, COD, faecal coliforms and SAR if the DEWATS capacity is 50 m^3 per day need to be considered (Department of Water and Sanitation, 2013).
- Effluent samples should be collected following procedures in the International Organisation for Standardisation (2016) and characterisation for physicochemical and biological properties carried out according to standard methods in Rice et al. (2017). Analyses should be done at an accredited laboratory as per the SANS 17025:2005 according to the South African National Accreditation System (SANAS). In areas where there is no accredited laboratory nearby, tests should be done at:
  - A laboratory that has proof of intra- and inter-laboratory proficiency whereby quality is assured as prescribed in Standard Methods (International Organisation for Standardisation, 2016).

Table 2.9: The standard limits for irrigation with 50 m^3 of DEWATS effluent on a specific day as per the General Authorisation of the National Water Act (Department of Water and Sanitation, 2013)

Parameter	Unit	Value
Electrical conductivity	$mS\ m^{-1}$	≤ 200
pH		6-9
Chemical oxygen demand	$mg\ L^{-1}$	5 000
Faecal coliforms	per 100 mL	100 000

2.5.2 Soil quality

The use of treated wastewater affects soil physicochemical and biological properties. Different soil quality parameters mentioned in the SAWQG should be monitored in DEWATS effluent fertigated fields (Table) stipulated in the International Organisation for Standardisation (2016).

- The soils should be sampled before planting and every 4-6 weeks thereafter depending on the soil type and the irrigation system and the user should refer to the methods stipulated in the International Organisation for Standardisation (2016).
- The analysis of soil samples should be done in an ISO/IEC 17025:2017 accredited soil analytical laboratory following standard methods for a specific test.

2.5.3 Crop quality

Fertigating crops using DEWATS effluent aims to increase yield without jeopardising crop quality. It is crucial to see if this aim is achieved by monitoring indicators of impaired crop growth and quality. These indicators include specific ion toxicity and leaf scorching.

- Plant tissue nutrients indicate nutrient sufficiency or deficiency in response to a fertiliser application programme, which in this case is fertigation using DEWATS effluent. These can be done by accredited laboratories and academic institutions, following specific standard methods for plant tissue analysis as stated by Kalra (1997).
- Different crops have different sampling intervals and sampling plant parts. The farmer should consult with the fertiliser advisory service provider on when and how to sample plant parts.

2.5.4 Environmental quality

The toolkits for sampling leachate and groundwater water are shown in Figure 2.2.8. Each piezometer should be installed at least 1 m deeper than the groundwater table (International Organisation for Standardisation, 2016).

- The wetting front detectors are funnel-shaped instruments which can be inserted at various depths such as 300 or 500 mm to passively collect leachate from the soil (Stirzaker, 2005).
- The extent to which groundwater quality is impacted can be monitored using piezometers according to the International Organisation for Standardisation (2016):
  - Piezometers should be sampled on a monthly basis during the first year and then twice a year thereafter.
  - Sampling should be done after pumping out water already in the piezometer. The samples collected should be analysed for chemical properties especially nitrate, phosphate and perhaps pathogens according to standard methods (Rice et al., 2017).

•

Figure 2.9: Toolkits for sampling leachates using wetting front detectors (WFD) (A=300 mm and B=500 mm depth) and piezometers (C and D). Adapted from Odindo et al. (2016).

- The irrigation using DEWATS effluent should not deteriorate the borehole drinking water with at least 1 class (see Table 2.10) but the maximum permissible concentration is 20 mg L^{-1} (Herselman and Moodley, 2009).
- If the ground water is deteriorated the farmer should decide based on evaluation of relevant authorities. Some of the measures that might be taken include:
  - Revision of the initial risk assessment such as site factors, availability of boreholes for drinking water, irrigation management practices and other relevant factors that might be contributing to nutrient leaching.
  - If the groundwater is continuously being impacted, especially in high risk areas where people use borehole water for domestic purposes, irrigation on that area should not be continued.

Table 2.10: The South African Water Quality guideline for domestic water NO_3-N.

	Target Water Quality Guideline (Class 0)	Acceptable (Class 1)	Tolerable (Class 2)	Unacceptable (Class 3)
NO_3-N (mg L^{-1})	6	10	20	>20

2.5.5 Record keeping

- Record keeping is part of the requirements as per the NWA. Issues to consider are detailed in the record-keeping section (Part 1) of the NWA (Department of Water and Sanitation, 2013). The user must keep the following information:
    - DEWATS effluent quantity on weekly basis and quality on monthly basis,
    - Soil quality
    - Crop quality
    - Groundwater and surface water quality
- The area where DEWATS effluent is being used for irrigation should be inspected by the relevant authority in terms of Section 125 of the NWA (Department of Water and Sanitation, 2013).

3 THE USE OF FAECAL SLUDGE-DERIVED PRODUCTS

3.1 Background

Faecal sludge contained in VIPs and UDDTs contains nutrients (NPK) and organic carbon. Approximately 0.4 kg N, 0.2 P and 0.4 kg K capita^{-1} year^{-1}are excreted with faecal sludge in South Africa (Johnnsson and Vinerras, 2004). These nutrients end up in the environment through leachates from unemptied VIP toilets, sludge disposed of in landfill and sometimes in the soil when buried onsite. At the same time, farmers in low-income communities are encountering low crop yields due to soil degradation and lack of fertilisers (Moya et al., 2017). Sustainable agricultural practices that promote the recovery of nutrients and organic carbon from faecal sludge are required.

Agricultural use of faecal sludge improves soil physical properties, fertiliser use efficiency and adds nutrients thereby reducing fertiliser requirements. There are challenges in handling fresh faecal sludge for agricultural use. Faecal sludge has a foul smell, contains pathogens and sometimes it is bulky to transport. Safe collection, transportation, treatment or valorisation of faecal sludge before agricultural use is required (Andersson et al., 2016).

Although there are various technologies to process faecal sludge into agricultural products, including deep-row entrenchment, blending with food waste and farming black soldier fly larvae (BSFL) (Mutsakatira et al., 2018) and co-composting this chapter focuses on the thermal treatment of faecal sludge using the Latrine Dehydration and Pasteurisation (LaDePa) process (Septien et al., 2019). Faecal sludge is screened, pasteurised at high temperatures to deactivate pathogens including ascaris while maintaining the N, P and K content and dry pellets are produced (Figure 3.1).

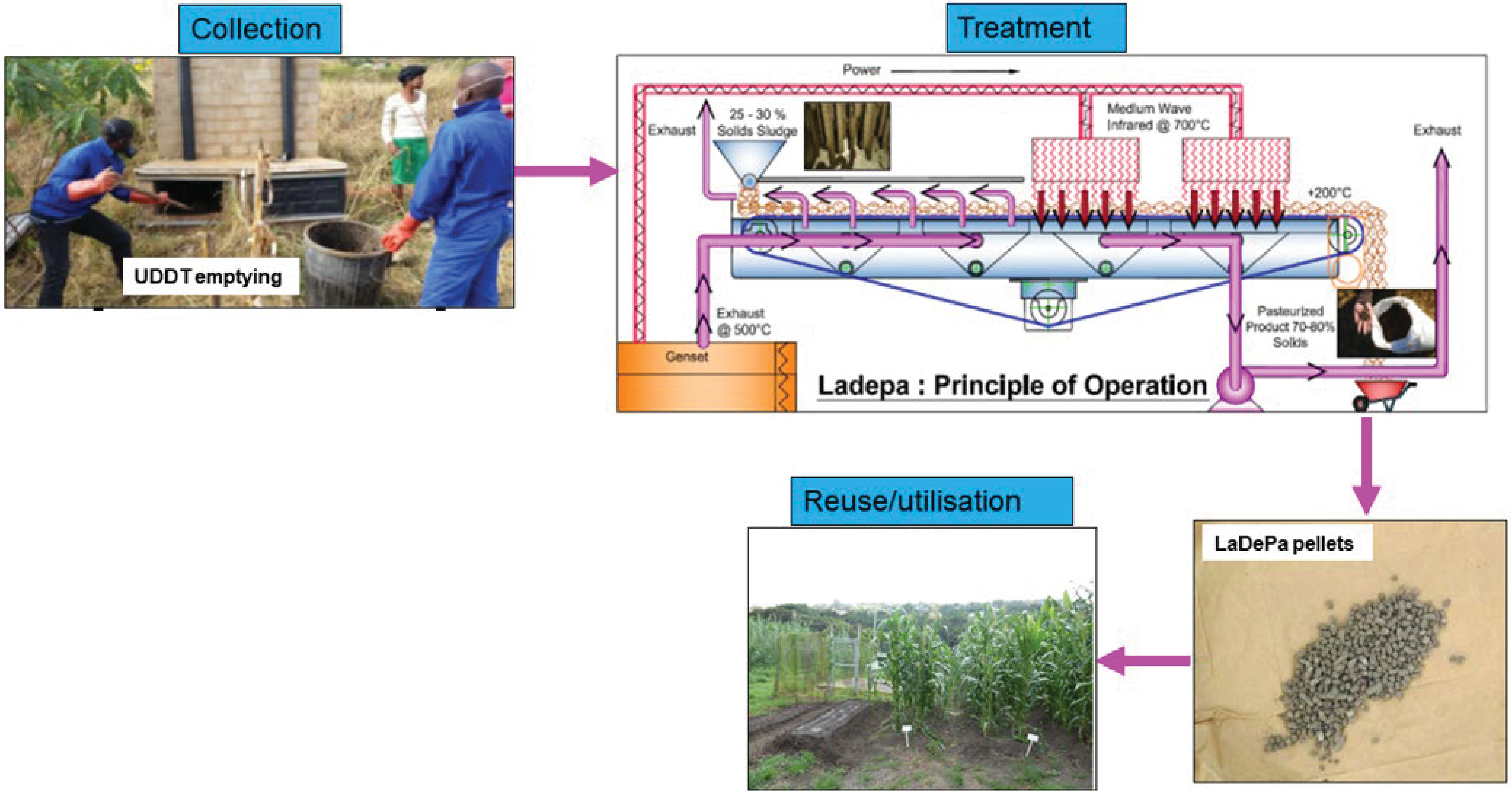

Figure 3.1: Faecal sludge collection, treatment (LaDePa pasteurisation and pelletisation) and utilisation in agriculture. The LaDePa principle of operation diagram was adapted and modified from Mirara et al. (2018).

This Chapter provides a guide on the safe agricultural use of LaDePa pellets with focus on good agronomic practices, human health and environmental risk management, and social perceptions. According to the Fertilisers, Farm Feeds, Agricultural remedies and Stock Act, 1947 (Act no 36 of 1947) the organic fertiliser should meet certain thresholds of pollutants (trace elements), pathogens and stability.

The LaDePa pellets from VIPs are sterile (Table 3.1), the heating process deactivates even helminths, which are persistent in excreta derived materials. The absence of pathogens from LaDePa pellets, qualifies it as a microbial class A organic fertiliser.

Table 3.1: Preliminary classification of LaDePa pellets from onsite sanitation systems (VIP toilets): Microbial class

Property	Mean ± SE	Microbial class		
		A	B	C
Total coliforms (cfu g^{-1})	0	<1 000	1×10^6-1×10^7	>1×10^7
Total viable helminth ova	0	<0.25	<1-4	>4

The second aspect of consideration is the pollutant class. The trace elements in LaDePa pellets are far below the minimum thresholds (Table 3.2) stipulated in the guideline for utilisation and disposal of wastewater sludges Volume 1 (Snyman et al., 2006) as well as required in the Fertilisers, Farm Feeds, Agricultural remedies and Stock Act, 1947 (Act no 36 of 1947) (Department of Agriculture Land Reform and Rural Development, 2017). Therefore, LaDePa pellets belong to the pollutant class A.

Table 3.2: Preliminary classification of LaDePa pellets from onsite sanitation systems (VIP toilets): Pollutant class

#Metal limits for South African Wastewater Sludges (mg kg^{-1})				
Element	**Mean ± SE**	**Pollutant class**		
		a	b	c
As	6.3±1.7	<40	40-75	>75
Cd	nd	<40	40-75	>75
Cr	59±10	<1 200	1 200-3 000	>3 000
Cu	116	<1 500	1 500-4 300	>4 300
Ni	nd	<420	420	>420
Zn	507	<2 800	2 800-7 500	>7 500
##Benchmark metal values (mg kg^{-1})				
B	50.4+8.6	<23	23-72	>72
Co	6.79+0.6			
Mo	nd			

#Elements for classification (Risk-based)

##Elements for benchmarking purposes to identify potential risks (20th percentile for class A, between 20^{th} and 80^{th} percentile for class B and 80^{th} percentile values for class C)

nd - not detected

Very low water content, volatile solids and absence of odour (Table 3.3) due to thermal treatment makes the LaDePa pellets stable. Stability in organic fertilisers is achieved after undergoing at least one of the treatment processes to minimise vector attraction (Snyman et al., 2006). In this case, the reduction of volatile solids by a minimum of 38% is achieved during the LaDePa pellets production. The LaDePa pellets production removes approximately 70% of volatile solids (Buckley, 2013). Therefore, the LaDePa pellets belong to stability class 1, hence they qualify as organic fertiliser under the Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act (Act 36 of 1947) (Department of Agriculture Land Reform and Rural Development, 2017).

Table 3.3: General physicochemical properties of the LaDePa pellets in comparison with the Department of Agriculture Land Reform and Rural Development (2017) regulations on organic fertilisers (Department of Agriculture Land Reform and Rural Development, 2017).

Property	n	Mean	DALRRD limits
Odour	9	Absent	Absent
Water content (%)	16	15	< 40
Total N (%)	7	3.5	-
Volatile solids (%)	9	17.1	67
Total P (%)	7	8.5	-
Total C (%)	7	38	-
K (%)	7	1	-
Ammonium-N (mg kg^{-1})	9	0	-
Nitrate-N (mg kg^{-1})	9	-	
Orthophosphate (mg kg^{-1})	9	0.05	-
pH	16	6.4	-

3.2 Regulatory framework and legal context

Various South African government departments directly linked to the agricultural use of bio solids include:

- Department of Water and Sanitation (DWS) – it is the leading agency which consults with other departments to issue a licence based on:
  - A positive Record of Decision (ROD) for an Environmental Impact Assessment from the Department of Environmental Affairs (DEA).
  - Positive reports from the Department of Health (DOH) and the Department of Agriculture Land Reform and Rural Development (DALRRD).

The use of faecal sludge products in agriculture is guided by the following acts and guidelines:

- The Environment Conservation Act (Act 73 of 1989) (Department of Environmental Affairs, 1989).
- The National Environmental Management Act (Act 107 of 1998) (Department of Environmental Affairs, 2009).
- The Fertilisers, Farm Feeds, Agricultural Remedies and Stock Remedies Act (Act 36 of 1947) (Department of Agriculture Land Reform and Rural Development, 2017).
- The National Health Act (Act 61 of 2003) (Department of Health, 2004).
- Guidelines for the Utilisation and Disposal of Wastewater Sludge

- Volume 1: Selection of management options (Snyman et al., 2006).
- Volume 2: Requirements for the agricultural use of sludge (Snyman and Herselman, 2006).
- Volume 4: Requirements for the beneficial use of sludge at high application rates (Herselman and Moodley, 2009)
  - Part 4: Restrictions and requirements applicable to a once-off high application rate.
  - Part 5: Restrictions and requirements for continuous high rate sludge application.

The LaDePa pellets have been classified as a microbial class A, pollutant class A and stability class 1 bio solid. Therefore, the following legal procedures should be followed before beneficial use at high application rates exceeding crop nutrient requirements (Herselman and Moodley, 2009):

- **Off-site land application of LaDePa pellets** – Comply with the requirements of Section 20 (5)(b) of the Environment Conservation Act (Act No. 73 of 1989).

- **On-site land application of LaDePa pellets** – A General Authorisation is required in terms of the NWA (Act No. 36 of 1998), if the LaDePa pellets are applied to a maximum load of 150 t per day, and/or when the full capacity of the land area is not exceeded. The authorisation for this may be included as part of the water use licence for the wastewater treatment plant or sludge collection area in on-site sanitation systems.
  - A contract between the LaDePa pellets producer and user for all beneficial use options if this has to be used by a third party.
  - For a once-off high LaDePa pellets application rate – The parties must comply with Volume 4 of the Sludge Guidelines (Part 4).
  - The parties must comply with Volume 4 of the Sludge Guidelines (Part 5).
  - They must have authorisation for such use (Existing Lawful Use, General Authorisation or licence).

3.3 Planning for reuse

3.3.1 Site considerations

- When LaDePa pellets are applied at agronomic rates (Snyman et al., 2006), once-off high application rate and continuous high application rates (Herselman and Moodley, 2009) the following restrictions on buffer zones between the area of application, and groundwater and surface water should be considered:
- Depth to aquifer should be >5 m.
- Distance from surface water or borehole should be >200 m and >400 m when applied continuously at high rates.

- When applied continuously at high rates, extra restrictions include refraining from:
  - Unstable areas such as fault zones, seismic zones and dolomitic or karst areas where sinkholes and subsidence are likely to occur,
  - Areas of groundwater recharge as a result of topography and/or highly permeable soils, to minimise groundwater pollution,
  - Natural habitats with endangered species,
  - Areas directly upwind of a residential area in the prevailing wind direction.
- *In cases where there is proof of the adequate protection of groundwater and surface water, the buffer zone conditions may be relaxed.*

3.3.1.1 Soil and water

For continuous high application rates:

- Soils with clay content <20% should not be considered,
- The likelihood that surface water receptors could be affected and their distance from the site should be identified and recorded.
- Where surface water contamination is possible, water quality sampling is required to determine the baseline values that can be used for monitoring and assessing compliance.
- Aquifer classification should be done according to Table 16 of the Guideline on Disposal and Utilisation of Wastewater Sludge volume 4 (Herselman and Moodley, 2009).
  - Groundwater quality (down and upgradient) provides baseline information on assessing impacts of using LaDePa pellets.
  - The hydraulic gradient should be determined to assess the positioning of piezometers.
  - Where groundwater contamination is expected at existing sites, water samples should be analysed to assess compliance with relevant standards.
  - A qualified person should confirm cases where groundwater impacts are unlikely due to depth to the water table or other circumstances.

3.3.2 Deciding on options for reuse

The LaDePa pellets are used primarily as a source of C and nutrients for plant production and nursery media. Therefore, management options must be considered based on the characterisation of the pellets for their chemical and biological properties.

- Chemical characteristics to be characterised include nutrients such as total Kjeldahl N (TKN), total P and K, and pH as stated in Snyman and Herselman (2006).
- The microbial quality indicators are faecal coliforms and total viable helminth ova.
- The characterisation should be done in any SANAS accredited laboratory according to respective methods mentioned in Table A1 of the guidelines for the utilisation and disposal of wastewater

sludge (Volume 2) and a minimum of three composite samples should be used (Snyman et al., 2006).

The Sludge Application Rate Advisor (SARA) model is a simple database model developed to help sludge producers and users classify their sludge according to the guidelines for the utilisation and disposal of wastewater sludge : Volume 1 (Tesfamariam et al., 2015).

3.4 Implementation

3.4.1 Deiding on the cropping system

- The LaDePa pellets fall within microbial class A and hence there is no restrictions on crop use implying that they may be applied to any crop type without adverse health implications.
- When LaDePa pellets are applied once-off at a high loading rate, beneficial uses include:
  - The use on private lands to rehabilitate degraded soils resulting from nutrient depletion, erosion, acidity, salinity, poor physical properties or low biological activity.
  - Establishment of public spaces such as racecourses, golf courses, parks, road embankments and private lands such as vineyards.
- When LaDePa pellets are to be applied continuously at high application rates the following beneficial uses are applicable:
  - Natural forests and plantations.
  - Medium for plants, flowers and nursery plants.
  - Production of grain crops, fruit trees, and industrial crops (cotton, aromatic plants, biofuels and oilseed).
  - Instant lawn cultivation.

3.4..2 Choice of irrigation system

The LaDePa pellets are solid and hence there is no major restriction on the choice of irrigation system.

- If freshwater is to be used then general irrigation selection factors such as capital establishment, crop type and available expertise to manage the system should be considered.

3.4.3 Crop management practices

3.4.3.1 <u>Requirements for the agricultural use of LaDePa pellets applied at an agronomic rate</u>

Application rates should not exceed plant nutrient requirements and assumes that. N is the most limiting nutrient and calculations are based on the N mineralisation rate or annual N release rate (%) and the N content of the pellets according to Tesfamariam et al. (2020) (Equation 3.1).

$$\text{LaDePa application rate (metric tons ha}^{-1}\text{)} = CNR /(MR * LNC) \qquad \text{Equation 3.1}$$

The CNR is the crop N requirement (metric tons ha^{-1}) obtained from the South African fertiliser handbook (Fertilizer Society of South Africa, 2007). The CNR is the N mineralisation rate of the LaDePa pellets (%), assumed to be 24% (arid zone), 28% (semi-arid), 29% (sub-humid zone), 37% (humid zone), and 42% (super-humid zone) (Ogbazghi et al., 2016). The LNR is the LaDePa pellets N content (%).

- The N, P and K content of the LaDePa pellets must be confirmed before each planting season after analysis of at least four composite sample, collected after bulking at least three subsamples.
- The SARA model can be used to determine LaDePa application rates for various South African agro-ecological regions and crops (Tesfamariam et al., 2015).

3.4.3.2 Requirements for the agricultural use of LaDePa pellets applied once-off at a high application rate

- There are no restrictions on food crops, fodder and forage crops and industrial crops when LaDePa pellets are applied once off at high application rates, exceeding crop nutrient requirements.

3.4.3.3 Application methods

- LaDePa pellets should be applied before planting to allow mineralisation of nutrients so that they become bioavailable during crop growth.

3.4.4 Health risks management

The health risk assessment for using LaDePa pellets has been done following the SSP approach as described in Section 3.4.8 (Table 3.4). The most hazardous part within the LaDePa value chain is the pit emptying and treatment where faecal sludge is handled untreated. However, to the farmers using the LaDePa pellets the risks are very low.

Table 3.4: Human health risk assessment and management of LaDePa pellets based on the Sanitation Safety Planning approach.

Sanitation step	Hazard identification				Existing control	Risk assessment L: Likelihood S: Severity R: Risk level Allowing for existing control				Comments
	Hazard event	Hazard	Exposure route	Exposure groups*		L	S	Score	R#	
Sludge collection	Exposure to untreated faecal sludge	Microbial	Dermal or accidental ingestion	W4	PPE barrier to dermal exposure and vaccination	2	6	8	V	Contamination might occur with accidental contact especially when proper PPE is not worn. Current pit emptying methods are not very risky to human health since machinery is used.
	Foul smell	Malodour	Inhalation	W4	Face masks	3	2	6	L	Wearing of face masks is sometimes not observed during pit emptying.
Treatment	Exposure to untreated faecal sludge	Microbial	Dermal or accidental ingestion	W5	PPE, vaccination, laboratory induction, Follow established protocols	3	1	1	L	The treatment process involves sophisticated machinery, therefore highly skilled people are involved. Therefore, they pay attention to the control measures and general workers will be easily monitored.
	Foul smell	Malodour	Inhalation	W5	Face mask	2	2	4	L	Unwillingness to wear a face mask.
Handling and application	Exposure to pathogens	Microbial	Ingestion and dermal	F4	Hand washing after fertiliser handling, PPE	1	1	1	L	The LaDePa pellets are very sterile and classified under the microbial class A.
Consumption of crops grown with LaDePa pellets	Pathogens	Microbial	Ingestion and dermal	C4	Hygienic practises during harvesting and post-harvest handling.	1	1	1	L	Thermal treatment deactivates pathogens.
	Trace elements	Pharmaceuticals and personal care products	Ingestion	C4	Biosolid characterisation	2	2	4	L	The sludge emanates from domestic onsite sanitation systems hence falls under pollutant class A in the guideline for utilisation and disposal wastewater sludge volume 1 and 2. Potential risks may be accidental sludge contamination with industrial effluent or disposal of heavy metal containing agents in pit latrines.

* W4: workers who collect sludge from pit latrines, W5: workers who treat faecal sludge using the LaDePa machine, F4: farmers applying LaDePa pellets in their fields, C4: consumers ingesting food produced from LaDePa pellets amended fields.

V: Very high risk; L: Low risk

3.4.5 Environmental pollution management

- Nitrate leaching from fields amended with LaDePa pellets at agronomic rates is generally lower compared to inorganic fertilisers. Therefore, P loss through surface runoff and soil erosion may be of environmental concern.
- Minimisation of soil erosion and potential runoff in LaDePa pellets amended soils is necessary by following management practices such as:
    - Surface runoff can be intercepted by constructing cut-off drainage trenches or bund walls down-gradient of the application site.
    - Increasing the buffer zone between the application site and the water body so that run-off will not reach the water body.
    - Planting applicable crops/plants/trees with a high-water that will intercept runoff.
- The LaDepa pellets applied continuously at high application rates may load excess N in the soil which could contaminate groundwater resources. It is advisable to therefore to follow recommendations as given in Section 2.4.9.

3.4.6 Perceptions and attitudes

The four factors driving human perceptions towards the agricultural use of HEDMs (Section 3.4.10) have been adopted for LaDePa pellets (Table 3.5). Approaches to ensure acceptable agricultural use of LaDePa pellets include:

- **Marketing strategies** – correct fertiliser labelling showing product stability as per the Fertilisers, Farm Feeds, Agricultural Remedies and Stock Act, 1947 (Act no 36 of 1947) (Department of Agriculture Land Reform and Rural Development, 2017) enhances consumer acceptability.
- **Stimulate community involvement** – organising communities to come up with a structure for planning, execution and monitoring of the use of LaDePa pellets.
- **Stakeholder interaction** – a feedback mechanism between farmers, experts and stakeholders should be established.
- **Knowledge dissemination** – training farmers on good agricultural practices using LaDePa pellets, by organising field days, community demonstration plots and field visits to research sites.

Table 3.5: A summary of factors driving social perceptions of the agricultural use of LaDePa pellets and corresponding management options

Factor	Remarks	Approaches/tools
Physical properties	○ LaDePa pellets belong to stability class 1 ○ Odourless ○ Dry pellets	○ Production marketing (labelling and packaging)
Socio-economic benefits	○ Fertiliser value (NPK) ○ Reduced environmental costs ○ Reduced health costs from water pollution ○ Soil conditioner	○ Working with users in the planning, execution and monitoring activities ○ Acknowledgement on the benefits of using LaDePa pellets during workshops
Impacts on crop yield	○ Increased crop yields and quality ○ Contribution to food security	○ Farmer training workshops on best agricultural practices ○ Establishment of community demonstration fields ○ Site visits to areas under research using LaDePa pellets
Health and safety	○ LaDePa pellets fall within microbial class A and pollutant class A – no restrictions on human health	○ Acknowledgement of low health risks in the agricultural use of LaDePa pellets during workshops

3.5 Monitoring and evaluation

Monitoring and evaluation is the most important activity to trace the impacts of using LaDePa pellets with regards to human and environmental health.

3.5.1 Agricultural use at an agronomic rate

The agricultural use of LaDePa pellets needs to be monitored as per restriction 6 of the guidelines for the utilisation and disposal of wastewater sludge: Volume 2 (Snyman et al., 2006).

3.5.1.1 <u>Monitoring LaDePa pellets' quality</u>

The LaDePa pellets should be monitored for microbial, physical and chemical characteristics as reported in Table 3.6. Monitoring for microbial characteristics of LaDePa pellets is not necessary because they are thermally deactivated during treatment, assuming that the processes are operating correctly.

Table 3.6: LaDePa pellets sampling and analyses for monitoring purposes as per the wastewater sludge requirement in Snyman et al. (2006)

Parameters to be monitored	Physical and chemical characteristics		
Sampling frequency	**Amount of LaDePa pellets produced (t dry weight)**		**Monitoring frequency**
	<1	<365	Once per year
	1-5	365-1 825	4 times per year
	5-45	1 825-16 500	6 times per year
	>45	>16 500	Monthly
Type of samples	Grab samples to constitute a representative composite		
Number of samples	At least 3 composite samples for each LaDePa pellets stream		
Sampling timing	Before use		
Sampling points	Collect from the discharge side after pelletisation		
Sample size	≥500g dry mass		
Analytical methods	See Appendix 2.1 (Snyman et al., 2006, Snyman and Herselman, 2006)		

3.5.1.2 Monitoring soil quality

- Monitoring the soil quality in fields amended with LaDePa pellets is not necessary since the product belongs to the pollutant class A.

3.5.2 Requirements for continuous high-rate application

3.5.2.1 Monitoring LaDePa pellets

LaDePa pellets applied continuously at high application rates should be monitored for chemical and physical properties as in Section 3.5.1.1 (Snyman and Herselman, 2006).

3.5.2.2 Soil monitoring

- Monitoring the soil quality in fields amended with LaDePa pellets is not necessary since the product belongs to the pollutant class A.

3.5.2.3 Groundwater monitoring

Monitoring the impacts of pollutants on groundwater quality is required to enable possible interventions.

- Monitoring piezometers should be located to intercept groundwater moving away from the application field.

- Piezometers should be located on either side of the application field in the direction of the groundwater flow.
- The groundwater that is most likely to be polluted is monitored first.
- Groundwater levels should be frequently measured to understand changes in water level.
  - Sampling in areas with a water table <5 m should be done quarterly. T
  - Groundwater sampling may be done after 5 years if the water table is >10 m deep and the soil clay content is >35%.
- Summarised sampling and analytical activities for monitoring groundwater quality are shown in Table3.7 3.5.

Table3.7: Groundwater sampling and analysis in fields being continuously amended with LaDePa pellets at high loading rates (Herselman and Moodley, 2009)

Parameters to be monitored and frequency	Chemical properties – pH, EC, PO_4-P, NH_4-N, NO_3-N, COD
Sampling frequency	Biennially or quarterly. *This could be relaxed if:* *-the distance to the borehole is >1 km.* *-the user can provide adequate proof that the borehole water will be protected.* *-results for 5 years indicate insignificant impact.*
Sampling equipment	Glass bottles
Sampling techniques	Appendix 3 of Volume 4 (Herselman and Moodley, 2009)
Sample preservation	○ pH, EC, PO_4-P – refrigeration required ○ NH_4-N, NO_3-N, COD – add H_2SO_4 to pH<2
Number of samples	○ At least 2 from each piezometer • 1 for pH, EC, PO_4-P • 1 for NH_4-N, NO_3-N, COD
Sample size	○ At least 100 mL per each sample
Analytical methods	Appendix 1 of Volume 4 (Herselman and Moodley, 2009)

3.5.2.4 Monitoring surface water

Runoff water from amended fields may contaminate surface water resources. The sampling and analytical procedures for surface water should be done according to Table 3.8.

- Runoff should be collected daily and analysed. This need not be done if it is recycled into the treatment system.

Table 3.8: Surface water sampling and analysis in fields being continuously amended with LaDePa pellets at high loading rates (Herselman and Moodley, 2009)

Parameters to be monitored and frequency	Chemical properties – pH, EC, PO_4-P, NH_4-N, NO_3-N, COD
Sampling frequency	Monthly from streams above and below the application site (20-50 m downstream). *This could be relaxed if:* *-the distance to the surface water is >1 km.* *-the user can provide adequate proof that the surface water will be protected.* *-results for 5 years indicate insignificant impact.*
Sampling equipment	Plastic bottles with caps and no liner are required. Glass bottles are used when organic constituents are tested.
Sampling techniques	Appendix 3 of Volume 4 (Herselman and Moodley, 2009).
Sample preservation	○ pH, EC, PO_4-P – refrigeration required ○ NH_4-N, NO_3-N, COD – add H_2SO_4 to pH<2
Number of samples	○ At least 2 from each piezometer • 1 for pH, EC, PO_4-P • 1 for NH_4-N, NO_3-N, COD
Sample size	At least 100 mL per each sample
Analytical methods	Appendix 1 of Volume 4 (Herselman and Moodley, 2009)

As a result of continuously high LaDePa pellets loading rates, monitoring programs should provide a basis for a site remediation plan (Herselman and Moodley, 2009). This should be done if:

- Application of LaDePa pellets deteriorates the groundwater and surface water quality,

3.5.3 Record keeping

After permits are granted, the use of LaDePa pellets becomes self-regulating. The following records should be kept:

- Sludge characterisation and classification
  - Microbial class
  - Pollutant class
  - Stability class
- The original and certified copies of the agreement between LaDePa pellets producer and user, if applicable
- Initial site record
  - Proof that the pellets are not applied in sensitive areas,
  - Groundwater data
    - Aquifer classification
    - Hydraulic gradient
    - Groundwater quality (both up gradient and down gradient)
  - Surface water quality data
  - Soil physical and chemical properties
- Records of LaDePa pellets application
  - Location of the site (include coordinates)
  - Application rate (tons ha^{-1})
  - Dates of application
  - Crops applied
- Monitoring data
  - Soil quality
  - LaDePa pellets quality
  - Groundwater and surface water quality

4 THE USE OF URINE-DERIVED PRODUCTS

4.1 Background

Urine-diverting toilets (UDTs) provide onsite sanitation in off-grid areas and many municipalities have been considering them as a potential reliable technology. The UDT has two vaults to separate the urine and faecal matter (Tilley, 2014). The urine can be allowed to soakaway while faeces are stabilised with ash (Etter et al., 2015). Urine contains the highest concentrations of N, P and K excreted from the human body. In South Africa, about 3 kg N, 0.3 kg P and 1.1 kg K capita^{-1} year^{-1} are excreted via urine (Johnnsson and Vinerras, 2004). Therefore, valuable agricultural resources are being lost when discharged into soakaways. Urine can be directly used as a fertiliser and the WHO encourages a storage time of 6-36 weeks before use for pathogens to die off (Schönning and Stenström, 2004). Some of the challenges in using urine are logistics due to its bulkiness, foul smell that makes it socially unacceptable for use by farmers and the presence of micropollutants (Richert et al., 2010). As a result, there have been several technologies to stabilise, concentrate and precipitate certain nutrients from urine (Figure 4.1).

Nitrified urine concentrate (NUC) is produced from the nitrification process, which stabilises the urine followed by distillation to reduce the water content. The NUC is a compact, sterile, pharmaceutical-free and odourless product that has high concentrations of nutrients. Struvite is a phosphorus fertiliser made by precipitating urine by the addition of excess magnesium (Mg) followed by filtration and dehydration to deactivate pathogens, in a process that recovers 90% of the P and 5% of the N from the initial urine (Figure 4.1). The struvite production process produces an effluent that also contains nutrients of agricultural importance and this can be used, especially on fields located near the processing area.

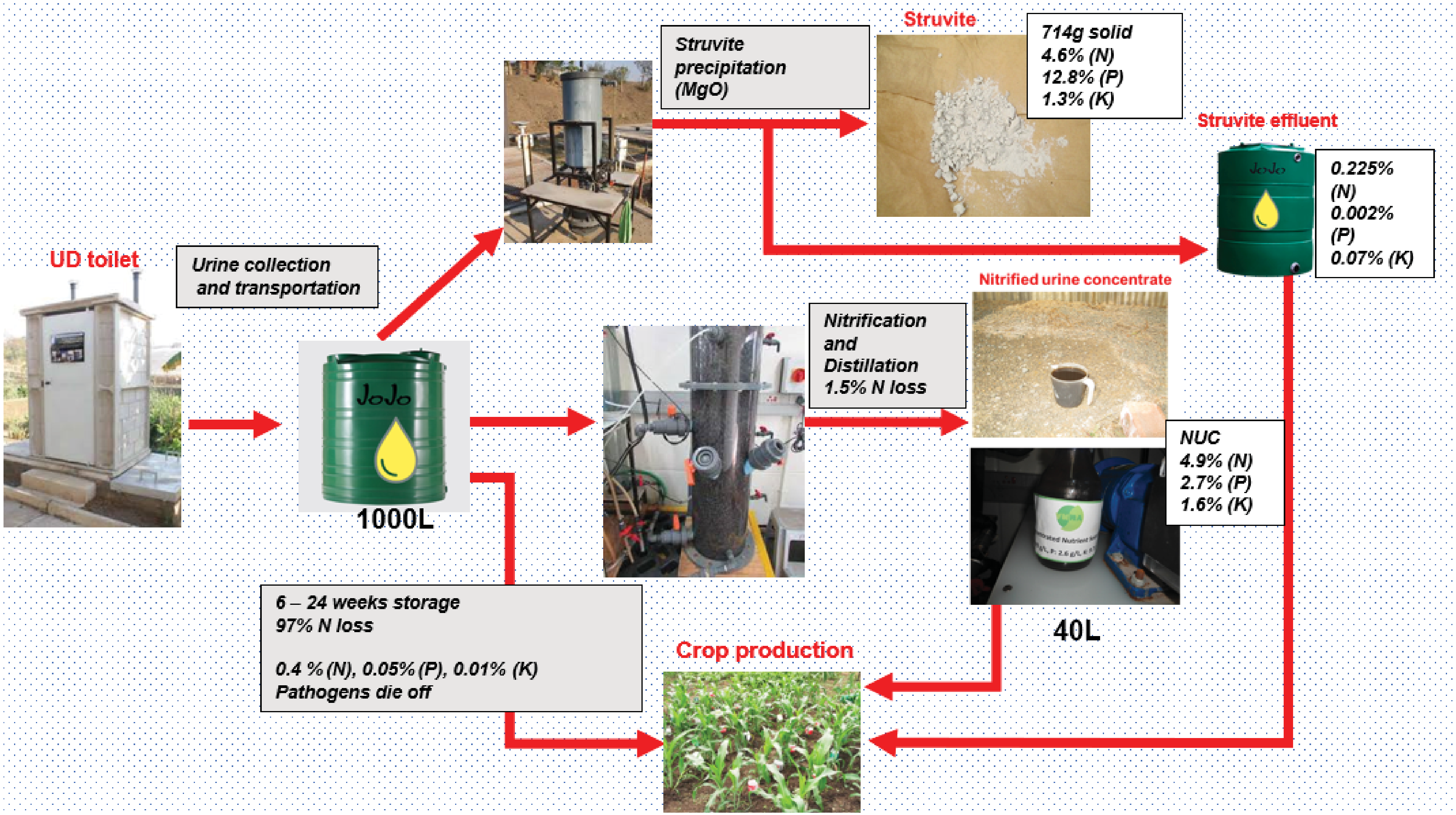

Figure 4.1: A schematic diagram on urine collection, processing into various products (NUC, struvite and struvite effluent) and subsequent use for agriculture (Etter et al., 2015).

The general characteristics of urine products that can be used for agriculture are presented in Table 4.1. This guideline provides a guide on the safe agricultural use of urine-derived products (raw urine, struvite and NUC), focusing on good agronomic practices, human health and environmental risk management, and social perceptions, within the South African context. In this guideline struvite effluent was not considered, however, NUC was rather considered as a source of all nutrients that can be found in struvite effluent except for P.

Table 4.1: The physicochemical and biological properties of stored urine, struvite and nitrified urine concentrate (NUC) in comparison to Department of Agriculture Land Reform and Rural Development (2017) standards for a microbial class A and pollutant class A fertiliser.

Property	Struvite	NUC	Stored Urine	DALRRD limits
Odour	Absent	Absent	Present	Absent
Total-N (%)	4.6	4.9	0.4	-
Nitrate-N (%)	-	2.3	-	-
Ammonium-N (%)	-	2.2	0.4	-
Orthophosphate-P (%)	12.8	2.7	0.05	-
K (%)	1.3	1.6	0.01	-
Ca (%)	2.3	0.025	0.001	-
Mg (%)	7.8	0.002	0.06	-
Na (%)	-	2.0	0.2	-
Cd (ppm)	-	0	-	<40
Cr (ppm)	-	0.1	-	<1 200
Ni (ppm)	-	1.1	-	<420
Pb (ppm)	-	0.05	-	<300
Zn (ppm)	-	5	-	<2 800
Viri	*	#	*	-
Bacteria	*	#	*	<1 000 cfu g^{-1} dry mass
Helminths	*	#	*	One viable ova $4g^{-1}$ dry mass
Pharmaceuticals	-	< 0.02	-	n/a

*Partial pathogen inactivation/possible under certain conditions

Complete pathogen inactivation

cfu refers to coliform forming units

4.2 Regulatory framework and legal context

Urine and its derived products are intended to improve and maintain plant and soil productivity and therefore by definition they are fertilisers according to the South African Fertilizers, Farm Feeds Stock Remedies Act, 1947 (Act No. 36 of 1947) (Department of Agriculture Land Reform and Rural Development, 2017). The existing fertiliser legislation in South Africa does not specifically exclude the use of urine fertilisers for crop production. However, human urine is not classified as normal fertiliser because of its potentially harmful substances and is usually managed through sanitation systems. The

Department of Water and Sanitation (DWS), Department of Environmental Affairs and Tourism (DEAT), Department of Health (DoH) and Department of Agriculture (DoA) have a regulatory role in the authorisation of urine agricultural use.

Agricultural use of urine products is governed by various legislation applying to faecal sludge as discussed in Section 4.2. However, to protect human and environmental health, maintain good agricultural practices and encourage social acceptance, several local and international guidelines have been adopted in the development of this guideline, i.e.

- The Water Research Commission Guidelines for the Utilisation and Disposal of Wastewater Sludge Volume 2: Requirements for the agricultural use of sludge – although the guideline focuses on sludge, it has been used as a baseline for the beneficial use of HEDMs in crop production, where applicable (Snyman et al., 2006).
- Valorisation of Urine Nutrients (VUNA): Promoting Sanitation & Nutrient Recovery through Urine Separation (Etter et al., 2015).
- EcoSanRes guidelines
    - Guidelines on the use of urine and faeces for crop production (Johnnsson and Vinerras, 2004),
    - Guidelines on the Safe Use of Urine and Faeces in Ecological Sanitation Systems (Schönning and Stenström, 2004),
    - Practical Guidance on the Use of Urine in Crop Production (Richert et al., 2010).
- World Health Organisation Sanitation Safety Planning: Manual for Safe Use and Disposal of Wastewater Greywater and Excreta (World Health Organisation, 2016).

4.3 Planning for reuse

4.3.1 Site selection

The characterisation of the site with special reference to climate, geography, soil chemical and physical properties is required as discussed in Section 2.3.1.3.

4.3.2 Deciding on options for use

The user should decide on which urine stream is intended for use. Raw urine can be applied at a large scale (community) or household level. If the urine is to be used on a large scale, several logistical issues should be considered as mentioned by Etter et al. (2015):

- Establishment of the urine collection system to the central point/farm,
    - Ensure household involvement and support in urine collection schemes.
    - Employment of local collectors who know the area and are fluent in the local language to allow fast and efficient collection.
- Technical and social issues to decide if the area is suitable for urine collection

- Number and density of UDTs in the area has to be sufficiently high (approximately 100 households per collection).
- Good cellphone reception and low risk of civil unrest.
- A 20 L tank size per household can be used and this should be labelled in local language "urine".
- Collection truck should be between 500 and 1 000 L capacity.
- Urine collection team should consist of at least 1driver, 2 collectors and 1 local facilitator.

4.4 Implementation

4.4.1 Urine storage before use

Collected urine needs to be stored if it is to be used raw. The urine can be stored in plastic containers in the undiluted form to ensure effective pathogen deactivation at high pH (Andersson et al., 2016). To achieve best pathogen deactivation, the WHO recommends storage of urine at 20°C for at least 6 months if it is to be used for crops consumed by people who did not produce it (Schönning and Stenström, 2004). The storage time can be as short as 1 month if the farmers use their urine at the household level for edible crops. The storage tank should be designed following specifications by Tilley (2014) in Section S1 where the following aspects need to be considered:

- Storage should be done in plastic or fibreglass containers, not metal containers because they are easily corroded.
- During storage organic materials and minerals (from magnesium or calcium) forms a blanket of sludge at the bottom due to high pH. Therefore, the storage container should have adequate opening to remove the sludge, which can be used as a P source.
- The containers should not be ventilated to minimise ammonium emissions.
- Pipes should have a steep slope (>1%), no sharp angles, and large diameters (up to 110 mm for underground pipes) and should be short and accessible in case of blockages.
- Urine should be filled from the bottom of the tank to minimise N losses and odours.

Urine products such as NUC and struvite can be stored in other storage facilities just like conventional fertilisers. According to VUNA (2020), there are no restrictions on the storage of NUC as long it is tightly packaged.

4.4.2 Crop choice

Crop selection should be done based on criteria discussed in Sections 3.4.3.1 and Table 4.2. There are three streams of urine products; struvite, NUC and raw urine. The NUC is the most sterile and stable urine-derived product that is equivalent to a microbial class A, pollutant class A and stability class 1 fertiliser as per the guideline for utilisation and disposal of wastewater sludge guideline volumes 1 and 2 (Snyman and Herselman, 2006, Snyman et al., 2006). Aurin™ made by EAWAG, Dübendorf, Switzerland is a commercially available NUC fertiliser that has been officially licenced as a safe fertiliser for all crops including vegetables by the Swiss Federal Office for Agriculture since 2018 (VUNA, 2020). Its agricultural use has minimal restrictions on crops and can be applied even to those consumed raw.

Urine is generally free from trace elements because these are rarely consumed and excreted by humans (Johnnsson and Vinerras, 2004). As a result, the agricultural use of urine and its products including struvite should preclude the impacts of trace elements on environmental pollution. Therefore, the major focus is given to microbial impacts. The struvite production process deactivates pathogens but according to Etter et al. (2015), the deactivation process may be partial or complete depending on conditions and the same applies to stored urine Since struvite and stored urine may encounter partial pathogen deactivation, crop selection may be based on Swedish guidelines for urine use (Schönning and Stenström, 2004) see Table 4.2.

Table 4.2: The types of crops that can be amended with various urine products (nitrified urine concentrate, struvite and raw urine stored at various temperatures and time) based on Schönning and Stenström (2004).

Product	Processing method	Recommended crops
Nitrified urine concentrate	Nitrified and distilled urine	○ No restriction on crops. Can be applied to crops eaten raw
Struvite fertiliser	Precipitated and dehydrated	○ May be applied to all crops*
Raw urine	Stored at 4°C for ≥1 month	○ Applied to food and fodder crops that are to be processed
Raw urine	Stored at 4°C for ≥6 months and 20°C for ≥1 month	○ Applied to food crops that are to be processed and fodder crops
Raw urine	Stored at 20°C for ≥6 months	○ May be applied to all crops*

*This should be applied to food crops that can be eaten raw at least one month before harvesting, ensuring that the fertiliser is incorporated into the ground if edible parts grow above the soil surface.

From an economic point of view, struvite and NUC will be more cost-effective if used on high-value crops that respond well to fertilisers.

4.4.3 Choice of irrigation system

The choice of irrigation system can be based on the material under consideration. For example, raw urine and NUC may be fertigated with drip irrigation system since they are liquids. Special attention must be given to the impacts of urine on irrigation infrastructure since it precipitates a sludge.

4.4.4 Crop management practices

4.4.4.1 Stored urine application

The application of urine as a fertiliser in the field can be done according to guidelines by Johnnsson and Vinerras (2004) and Richert et al. (2010):

- Urine has very low P:N and P:K ratios. Therefore, its application must be based on South African N fertiliser (e.g. urea, ammonium nitrate, limestone ammonium nitrate or ammonium sulphate) requirements for a specific crop, indicated by:
    - Crop N requirements as stipulated in the Fertilizer Society of South Africa (2007) and supplementation with other nutrients (P and K) may be required for specific crops,
    - Plant tissue analysis recommendations from local fertiliser advisory service provider.
- Dilution of urine at 1:1-10:1 (water:urine), with the most common being 3:1, can be done to decrease or eliminate risk of overapplication which might affect crop quality and yield.
- Mixing of urine with water will be based on crop N and water requirements. Precautions should be taken to prevent blockages of irrigation infrastructure as per the International Organisation for Standardisation (2020c) on managing irrigation infrastructure.
- Urine should be applied onto or incorporated into the soil to prevent smells, contamination of crops with remaining pathogens, leaf burn and aerosol spray.
    - The application can be done in small furrows which should be covered later.
    - Application method should prevent foliar contact to avoid foliar burns caused by salts especially as the urine is drying.
    - Spraying urine into the air should be avoided to prevent ammonia emission and public health risks.
    - According to Richert et al. (2010), treated bio solids (such as LaDePa pellets) or compost may be applied (see Section 3.4.4.3) in the field where urine is used to improve soil structure, stimulate biological activity that influences the transformations of nutrients in the soil and allow efficient uptake by plants.
- Depending on the selected management practices, urine may be applied soon after collection and 28 days before planting. Since 97% of N is lost during storage, early urine application (28 days before planting) allows provides storage in the soil.
- In areas where salinisation is problematic urine application should be done only if it gives optimum yields. Salinisation is a problem in arid areas especially if the urine is applied at high rates so it is recommended to:
    - Monitor salinity in urine-amended soils to provide a basis for adjusting management practices such as urine application rates and crop choices adapted to the specific climate.
    - Choose less saline sensitive crops especially in arid areas (Appendix 4.5).
- Urine application timing:
    - A once-off application should be done before planting to stimulate crop growth.

- If applied after planting, the application should not soak the roots of sensitive crops such as tomato. Therefore, the distance from plant roots to urine for annual plants should be 100 mm.
- In two split applications, a second application should be done depending on crop needs.
- Split applications should be done before the reproductive stage as in conventional fertiliser application programs.
- Plants with less extensive root systems, such as carrot, onion and lettuce, should receive multiple split applications during their growing period.

4.4.4.2 Struvite application

Struvite is a powdery, crystalline, solid fertiliser, which should be treated like other solid inorganic fertilisers such as single superphosphate (SSP).

- Struvite contains 4.6% (N),12.8% (P) and 1.8% (K) (Table 4.1) therefore application should meet crop P requirements. The N and K applied should be subtracted from the supplemental fertiliser applied.
- Struvite is a slow-release fertiliser and so it should be applied before planting as a once-off application.
- The fertiliser should be incorporated in the soil and broadcasting should not be done, especially in windy conditions, due to its powdery nature. Depending on its form, granulated struvite may not be affected by wind.
- Due to its low solubility drip fertigation cannot be used.

4.4.4.3 Nitrified urine concentrate

The application of NUC should be based on crop N requirements as per the Fertilizer Society of South Africa (2007) crop nutrient uptake values.

- Field applications of NUC can be done following procedures for raw urine discussed in Section 4.4.4.1 except that:
    - The mixing ratio should be 1 part NUC: 100 parts of freshwater.
    - The NUC may be applied once or twice per month, depending on crop needs.
- The NUC can be used to supply nutrients in hydroponic systems to grow crops but precautions should be taken to manage salinity especially in sensitive crops.

4.4.5 Health risks management

The risk assessment based on the developed sanitation safety plan (Table 4.3) revealed that there is a low pathogen risk to the farmers using urine products. The sources of risk identified were accidental ingestion and dermal exposure which can both be avoided through proper use of personal protective equipment. Consumers are potentially exposed to pathogen risk through consumption; cooking the product reduces the pathogen risk.

The NUC production involves distillation which inactivates all pathogens. Stored urine is considered sterile unless contaminated with faecal matter or menstrual blood. Therefore, both NUC and stored urine meet the pathogen limits for use in agriculture. Pathogen limits for wastewater sludge are 1000 cfu g^{-1} for faecal coliforms and 1 ova per 4 g for helminth ova and struvite meets the requirements for use in crop production. Most pathogens are inactivated during the drying process of struvite production; however, it has been reported that the drying process does not result in helminth ova die off. Therefore, the microbial quality of the produced struvite greatly depends on the quality of the source-separated urine collected.

Heavy metals are not a major concern in urine products as the concentration of these metals are below the permissible concentrations.

Table 4.3: Human health risk assessment and management in urine-derived products amended fields based on the Sanitation Safety Planning approach.

Sanitation step	Hazard identification				Existing control	Risk assessment L: Likelihood S: Severity R: Risk level Allowing for existing control				Comments
	Hazard event	Hazard	Exposure route	Exposure groups*		L	S	Score	R#	
Urine collection	Exposure to untreated urine	Microbial	Dermal	W1	PPE barrier to dermal exposure and Vaccination	2	2	4	LR	Contamination might occur with accidental contact PPE
	Foul smell	Malodour	Inhalation	W1	Face masks	3	2	6	LR	Wearing of face masks is sometimes not observed during urine collection
Treatment	Exposure to untreated urine	Microbial	Dermal	W2	PPE, Vaccination, laboratory induction, Follow SOP	1	1	1	LR	The treatment process involves sophisticated machinery, therefore highly skilled people are involved. Therefore, they pay attention to control measures.
	Foul smell	Malodour	Inhalation	W3	Face mask	2	2	4	LR	Unwillingness to wear face mask
Application of urine fertilisers to agricultural land	Exposure to pathogens	Microbial	Ingestion and dermal	F1	Hand washing after fertiliser handling, PPE	4	4	16	M	Struvite application poses a higher risk than NUC application because its production does not completely remove *Ascaris* eggs.
Consumption of crops grown with urine fertilisers	Micropollutants	Pharmaceuticals and personal care products	Ingestion	C1	None					There is a knowledge gap for the uptake of micropollutants and its associated risk on human health

* W1: Workers who collect urine from UDDTS, W3: Workers who manufacture fertilisers from urine, F1: Farmers who use human urine-derived materials for crop production, C1: Consumers of crops grown with human urine fertilisers by F1 farmers; # Risk: LR: Low risk, M: medium risk.

4.4.6 Environmental pollution management

Nitrogen leaching is a potential problem in soils to which urine-derived products are applied as with conventional fertilisers. Urine N exists in a readily available form which when not well managed may be leached to the groundwater and surface waters. It is therefore recommended to follow these management practices:

- **Irrigation scheduling** – irrigation of crops based on crop water requirements while taking into consideration room for rainfall to avoid over-irrigation.
- **Split application** – prevents loss of nutrients in a single rainfall event especially in high rainfall areas.
- **Nutrient management** –application should be based on crop requirements, soil residual fertility, and crop growth stage to prevent excess nutrients leaching into the groundwater.

4.4.7 Perceptions and attitudes

The perceptions and attitudes that affect the use of urine-derived products are driven by the four factors reported in Sections 3.4.10 and 4.4.1. The use of urine-derived products is generally acceptable in South Africa (Wilde et al., 2019) and internationally (Simha et al., 2020), provided various aspects are addressed (Figure 4.1).

Table 4.4: A summary of factors driving social perceptions in the agricultural use of raw urine, nitrified urine concentrate (NUC) and struvite and corresponding management options.

Factor	Remarks	Approaches/tools
Physical appearance	○ Raw urine is odorous ○ NUC and struvite are compact and non-odorous	○ Training farmers on urine application methods that reduce the impact of smell ○ Production marketing (labelling and packaging) of struvite and NUC
Socio-economic benefits	○ Fertiliser value (NPK) ○ Reduced environmental costs ○ Reduced health costs from water pollution	○ Working with users in the planning, execution, and monitoring activities ○ Acknowledgement of the benefits of using urine-derived products in workshops
Impacts on crop yield	○ Increased crop yields and quality ○ Contribution to food security	○ Farmer training workshops on best agricultural practices ○ Establishment of community demonstration fields ○ Site visits to areas under research using urine-derived products
Health and safety	○ NUC is sterile and pharmaceuticals free ○ Struvite pathogens sometimes partially deactivated ○ Raw urine might have low pathogens depending on storage time	○ Training on best agricultural practices to reduce health risks, post, and pre harvesting management practices to minimise health risks in crops produced using urine-derived materials ○ Public health education and hygiene promotion

4.5 Monitoring and evaluation

4.5.1 Monitoring urine quality

Although the practical guideline does not mention the need to monitor urine quality (Richert et al., 2010), this may be done especially for raw urine and products such as NUC and struvite if made onsite by the farmer. The approaches used for characterising LaDePa pellets as per the guideline for utilisation and disposal of wastewater sludge volume 2 (Snyman et al., 2006), may be adopted where applicable:

- Parameters to be monitored include microbial, physical, and chemical characteristics:
  - **Biological properties** – total coliforms and helminth eggs,
  - **Chemical properties** – pH, EC, macronutrients and micronutrients, chlorides, sulphates, hormones and pharmaceuticals,
  - **Physical properties** – gravimetric water content of struvite
- At least three composite samples should be used for each urine product stream,
  - Care must be taken when sampling stored urine. It must be well mixed because some P might be underestimated as it settles down as part of the sludge.
- Sampling should be done before use to calculate crop nutrient requirements based on actual HEDM nutrient content,
- Analyses can be done according to specific standard methods mentioned by Viskari et al. (2018)

4.5.2 Monitoring soil quality

- Salinity is a problem when urine is applied at high loading rates. Therefore, this should be monitored especially in arid areas after every crop harvest (Richert et al., 2010),
  - A minimum of three composite samples (from five subsamples), labelled and submitted to the nearest salinity laboratory or accredited fertiliser advisory service provider.
- The urine and its products contain bioavailable nutrients, which are taken up by the crops (Richert et al., 2010), therefore residual soil fertility should be monitored to determine preceding cropping application rates.

4.5.3 Monitoring crop quality

It is recommended to monitor different parameters of crop growth and quality:

- Plant tissue analysis after each cropping period to assess fertiliser requirements.
- Crop yield reduction results from myriad factors ranging from nutrient deficiency, salinity, pests and diseases and poor management practices. However, in this case crop yields should be monitored to trace how the crop is responding to urine based fertiliser application.

4.5.4 Record keeping

All the records on monitoring programmes should be kept for intervention programmes, research and decision-making on whether to continue or terminate the use of the fertilisers. Therefore, the following record should be kept:

- Site details
  - Soil physical and chemical properties
  - Geological information
- Urine derived product
  - Chemical, physical and biological properties
- Crop management
  - Crops produced
  - Cropping system
  - Quality and quantity of urine derived fertiliser applied
- Soil quality monitoring
  - Soil chemical properties

5 DISCUSSION, CONCLUSIONS AND FUTURE RECOMMENDATIONS

5.1 Discussion

The project aimed to develop a comprehensive technical guideline on safe use of HEDMs emanating from onsite sanitation technologies of South African rural and urban communities. Therefore, specific objectives were (i) to recommend the best agricultural practices that minimise environmental and human health risks for agricultural land amended with HEDMs, and (iii) to provide a training guide for on-farm good agricultural practices for the safe and environmentally sustainable use of HEDMs.

The South African agricultural use of DEWATS effluents is regulated by the National Water Act (NWA) (Act 36 of 1998). Site selection, registrations and DEWATS effluent monitoring and reporting should be done according to the NWA. However, the NWA did not provide specific requirements for soil irrigability, which have been sourced from Reinders (2010).

Previously, the South African Water Quality guidelines (Department of Water and Sanitation (formerly DWAF), 1996) were used as the reference point for irrigation water quality, providing limits for microorganisms, trace elements, nutrients and other chemical properties. However, recently the SAWQG Decision Support System (DSS) (DuPlessis et al., 2017) was developed to assess the suitability of certain waters for agricultural use based on site specific parameters such as climate, irrigation system, crop type, crop system, soil type, management practices and water quality. This tool was used to provide a basis for interventions to manage negative impacts of DEWATS effluents on crops (excessive nutrients, root zone salinity and microbial contamination) and soils (soil salinity, permeability and oxidisable carbon loading). The use of DEWATS effluents does not affect soils and plants except for managing nutrient ratios to meet crop requirements.

The DSS is a tool that assists fertiliser management in terms of estimating possible nutrient loading, effluent application rates and management of nutrient imbalances. In addition, the tool provides a water balance to estimate leaching, and storage and land area requirements. This tool complements the Sludge Application Rate Advisor (SARA) developed from the guideline for utilisation and disposal of wastewater sludge Volume 2 (Tesfamariam et al., 2018). The SARA model is a generic, simple and site-specific model used to estimate sludge application rate. The tool was adopted for estimating LaDePa pellets application rates when applied at agronomic rates. However, urine and its derived products (struvite and NUC) are sources of nutrients, which are in readily available forms. Therefore, application of urine-derived products should be based on crop requirements and soil analysis results, just like other conventional fertilisers, regardless of location.

The calculation of effluent storage requirements considers various factors such as available irrigable land, annual crop water requirements and effluent flow rates. This is not covered in the SAWQG and the NWA. Therefore, calculation of storage requirements were adopted from the United States Environmental Protection Agency (2006) guidelines.

There are challenges with storing effluent if fertigation is done based crop water requirements. Effluent storage is likely to increase with time, leading to overflows and subsequent requirement for emergency effluent utilisation. However, possible interventions include application of effluent at rates exceeding crop water requirements with subsequent groundwater monitoring and excess nutrient management and diversifying the use of effluent, e.g. in hydroponics and duckweed production. Studies have shown that the AF effluent can potentially provide water and nutrients for hydroponic crops (Magwaza, 2019). However, the use of DEWATS effluent on salad crops, e.g. tomato and lettuce, is restricted by its microbial loads but ornamental crops, e.g. flowers may be produced using DEWATS effluent hydroponically.

Previously health impacts in wastewater fertigation were assessed qualitatively based on water quality, choice of crops and irrigation system (World Health Organisation, 2006, Food and Agriculture Organisation, 1992, Department of Water and Sanitation (formerly DWAF), 1996). Recently the WHO developed the Sanitation Safety Planning (SSP), which is a risk based approach to manage health implications of using treated wastewater and HEDMs across the whole value chain of containment, conveyance, treatment, end use and consumption (World Health Organisation, 2016). This approach has not yet been used for safe agricultural use of DEWATS effluent and HEDMs (faecal sludge-derived products and urine-derived products) in South Africa, and thus this was adopted for all excreta streams.

Social perceptions of the agricultural use of HEDMs and treated wastewater are important to understand. Simha et al. (2020) did a multinational survey and reported that the majority of people are willing to consume food produced from human excreta-based fertilisers. At farm level, people are willing to use HEDMs and DEWATS effluent if they are sure that their yields will not be affected, the practice does not pose health risks during handling the fertiliser and consuming the products, and they are user-friendly to handle without any foul odours. Nitrified urine concentrates, LaDePa pellets and sometimes struvite and stored urine are the most acceptable products which have no health implications. Microbial loads pose a major challenge in safe handling and utilisation of DEWATS effluent. Stored urine has a foul odour, which makes it unattractive to use. Therefore, acceptance can be enhanced through farmer health and hygiene education, good agricultural practices in the use of human excreta-based fertilisers, community demonstration plots, adequate marketing through wastewater sites/processing plants tours and engagement of farmers with experts, scientists and other relevant stakeholders in the various stages of project development (planning, organisation, execution, monitoring and evaluation, and reporting).

Monitoring and evaluation should be done to track progress made toward the use of HEDMs. The different HEDMs have different monitoring parameters. Pathogens are the most important parameters which should be monitored in soils, plants and DEWATS effluent. Depending on how the effluent is applied, especially when applied exceeding crop water requirements, nutrients (N, P and K) should be monitored in soils, field leachates, nearby groundwater and surface water resources. The same nutrient monitoring programs applies to LaDePa pellets if applied continuously at high application rates. The monitoring strategies differ with urine-based fertilisers, whereby salinity is the major aspect of concern. Environmental pollution monitoring need not be done when there is evidence of no risk. However, records must be kept for possible interventions.

5.2 Conclusions

- A comprehensive and consolidated guideline to promote good agricultural practices, safe, environmentally sound, and acceptable agricultural use of DEWATS effluent, LaDePa pellets and of urine-derived products has been developed.
- The guideline includes best agricultural practices to improve crop yields and quality using DEWATS effluent, LaDePa pellets and urine-derived products.
- Approaches to minimise health and environmental risks when DEWATS effluent, LaDePa pellets and urine-derived products are used have been comprehensively documented.
- Methods for promoting the social acceptance of the use of DEWATS effluent, LaDePa pellets and urine-derived products, and consumption of the resulting products have been suggested for the various individuals along the food and waste value chains.

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7 APPENDICES

Appendix 2.1: General characteristics of various South African land irrigability classes. Adapted and modified from Reinders (2010).

Land class	Remarks
1	○ Highly suitable for irrigation ○ Few or no limitations ○ Flat topography ○ Deep, moderately permeable, and well-drained soils ○ Medium textured and good water holding capacity
2	○ Slight limitations, e.g. undulating topography ○ Moderately well-drained soils ○ Slow or moderately rapid permeability ○ Moderately deep soils
3	○ Low suitability, moderately severe limitations, e.g. significant rolling topography ○ Imperfect excessively drained soils ○ Slow or rapid permeability ○ Shallow soils
4	○ Not suitable under most conditions ○ Severe limitations
5	○ Severe limitations, e.g. soils in natural waterways, river floodplain, presently eroded or showing the presence of permanent or potential water table

Appendix 2.2: An example of simulated impacts of DEWATS effluent on soil quality for the Pretoria area on a sandy loam soil in a sorghum and spinach rotation system

Tier 2: Fitness-for-Use
Soil Quality of a Sandy loam soil with 1093 mm irrigation p.a.

	Fitness-for-use	ECe (mS/m)	% of time root zone salinity is predicted to fall within a particular Fitness-for-use category
Root zone salinity	Ideal	0 - 200	100
	Acceptable	200 - 400	
	Tolerable	400 - 800	
	Unacceptable	> 800	

	Fitness-for-use	Degree of reduced Permeability	% of time soil permeability is predicted to fall within a particular Fitness-for-use category	
			Surface Infiltrability	Soil Hydraulic Conductivity
Soil Permeability	Ideal	None	53	28
	Acceptable	Slight	47	4
	Tolerable	Moderate		2
	Unacceptable	Severe		67

	Fitness-for-use	COD Load (kg/ha per month)	% of time Chemical Oxygen Demand (COD) Load is predicted to fall within a particular Fitness-for-use category
Oxidisable Carbon Loading	Ideal	0 - 400	76
	Acceptable	400 - 1000	24
	Tolerable	1000 - 1600	
	Unacceptable	>1600	

	Fitness-for-use		Number of years of 1093 mm irrigation before Trace Elements reach accumulation threshold in topsoil			
Trace Element Accumulation	Ideal		> 200 years to reach soil accumulation threshold			
	Acceptable		150 to 200 years to reach soil accumulation threshold			
	Tolerable		100 to 150 years to reach soil accumulation threshold			
	Unacceptable		< 100 years to reach soil accumulation threshold			
	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold	Trace Element	Soil Accumulation Threshold (mg/kg)	No of years to reach Soil Accumulation Threshold
	Al	2500	Infinite	Li	1250	Infinite
	As	50	Infinite	Mn	100	Infinite
	Be	50	Infinite	Hg	1	Infinite
	Cd	5	Infinite	Mo	5	Infinite
	Cr	50	Infinite	Ni	100	Infinite
	Co	25	Infinite	Se	10	Infinite
	Cu	100	Infinite	U	5	Infinite
	F	1000	Infinite	V	50	Infinite
	Fe	2500	Infinite	Zn	500	Infinite
	Pb	100	Infinite			

Appendix 2.3: The effects of wastewater quality (fitness for use) on crop yield reduction, degree of leaf scorching, contribution to nutrient balance in the soil and human microbial risks

Tier 2: Fitness-for-Use
Yield and Quality of a Spinach crop with 674 mm irrigation per season

	Fitness-for-use	Relative crop yield (%)	% of time yield is within relative crop yield category, as affected by:			
			Salinity (EC)	Boron (B)	Chloride (Cl)	Sodium (Na)
Root Zone Effects	Ideal	90 - 100	100	No parameters	100	No parameters
	Acceptable	80 - 90				
	Tolerable	70 - 80				
	Unacceptable	<70				

	Fitness-for-use	Degree of leaf scorching	Degree of leaf scorching under sprinkler irrigation caused by:	
			Chloride (Cl)	Sodium (Na)
Leaf scorching when wetted	Ideal	None	Foliage not wetted	Foliage not wetted
	Acceptable	Slight		
	Tolerable	Moderate		
	Unacceptable	Severe		

	Fitness-for-use	Contribution to estimated N P K Removal by crop	Mean applied N P K at harvest and % of time N P K removal at harvest is within fitness-for-use categories (High nutrient concentrations may impact development of sensitive crops)					
			Nitrogen (N)		Phosphorous (P)		Potassium (K)	
			Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)	Time (%)	Applied (kg/ha)
Contribution to NPK removal	Ideal	0 - 10%					No param	95.7
	Acceptable	10 - 30%						
	Tolerable	30 - 50%						
	Unacceptable	>50%	100	386	100	63		

	Fitness-for-use	Excess infections per 1000 persons p.a.	Predicted excess infections per 1000 people p.a.
Microbial Contamination	Ideal	<1	Spinach not wetted by irrigation
	Acceptable	1 - 3	
	Tolerable	3 - 10	
	Unacceptable	>10	

	Fitness-for-use	Atrazine load (Spinach, SaLm) (g/ha)	% of time Atrazine load is predicted to fall within particular fitness-for-use category
Qualitative Atrazine Damage	Ideal	<90	100
	Acceptable	90 - 130	
	Tolerable	130 - 180	
	Unacceptable	>180	

Appendix 2.4: Maximum acceptable trace element concentrations of irrigation water for short (20 years) and long term (100 years) application in South Africa according to Department of Water and Sanitation (formerly DWAF) (1996) guidelines with respective concentrations and loads of trace elements in the soil. Adapted from DuPlessis et al. (2017).

Trace element	Irrigation water		Irrigated soil concentrations		Irrigated soil load	
	100 years	20 years	100 years	20 years	100 years	20 years
	($mg\ L^{-1}$)		($mg\ kg^{-1}$)		($kg\ ha^{-1}$)	
Aluminium	5	20	2500	2000	5000	4000
Arsenic	0.1	2	50	200	100	400
Beryllium	0.1	0.5	50	50	100	100
Boron	0.5	vary	250	*	500	*
Cadmium	0.01	0.05	5	5	10	10
Chromium	0.1	1	50	100	100	200
Cobalt	0.05	5	25	500	50	1000
Copper	0.2	5	100	500	200	1000
Fluoride	2	15	1000	1500	2000	3000
Iron	5	20	2500	2000	5000	4000
Lead	0.2	2	100	200	200	400
Lithium	2.5	*	1250	*	2500	*
Manganese	0.2	10	100	1000	200	2000
Mercury	**0.002	*	1	*	2	0.4
Molybdenum	0.01	0.05	5	5	10	10
Nickel	0.2	2	100	200	200	400
Selenium	0.02	0.05	10	5	20	10
Uranium	0.01	0.1	5	10	10	20
Vanadium	0.1	1	50	100	100	200
Zinc	1	5	500	500	1000	1000

**The 0.002 value for mercury was derived from the Australian guidelines (DuPlessis et al., 2017) .

Appendix 4.5: The relative tolerance of common plants to salinity. Adapted from Brady and Weil (2016).

Tolerant	Moderately tolerant	Moderately sensitive	Sensitive
Barley (grain)	Ash (white)	Alfalfa	Almond
Bermuda grass	Aspen	Broad bean	Apple
Black cherry	Barley (forage)	Cauliflower	Apricot
Cotton	Beet (garden)	Cabbage	Bean
Date	Broccoli	Celery	Blackberry
Olive	Cow pea	Clover	Boysenberry
Rosemary	Fescue (tall)	Corn	Carrot
	Fig	Cucumber	Celery
	Harding grass	Grape	Grapefruit
	Kale	Lettuce	Lemon
	Orchard grass	Pea	Onion
	Oats	Peanut	Orange
	Pomegranate	Radish	Peach
	Rye (hay)	Rice (paddy)	Pear
	Ryegrass (perennial)	Squash	Pineapple
	Safflower	Sugar cane	Potato
	Sorghum	Sweet clover	Raspberry
	Soybean	Sweet potato	Strawberry
	Squash (zucchini)	Turnip	Tomato
	Wheat		