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Disaster Risk Management, Ventilated Improved Pit Latrines, and Sanitation Challenges in South Africa

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Abstract: The current paper provides a review and meta-analysis of the practical implications of disaster risk management related to the ventilated improved latrines in South Africa. This technology is evaluated through its legacy and novel challenges of disaster risk reduction. In the current article, the methodology adopted was a literature review and meta-analyses. The results indicate that the in-situ treatment and breakdown of faecal sludge in the ventilated improved pit latrines is not always taking place and that anaerobic digestion might not always be feasible. New strategies are proposed to manage the sanitation-related risks in South Africa by specifying more exact dimensions for the newly built ventilated improved pit latrines by suggesting the use of novel sanitation additives such as fly ash to enhance on-site and in situ treatment, as well as ex situ treatment of the pit latrine faecal sludge. Regular maintenance can lead to prevention of the dysfunctional character of the ventilated improved pit latrines as a functional sanitation technology and a user-friendly hygiene barrier to the spread of sanitation/WASH-related epidemics or infectious diseases. The implementation of the novel strategies should be enhanced by the application of the (Environmental) Technology Assessment in sanitation service delivery in South Africa.

Keywords: faecal sludge; mechanisms of stabilisation; risk equation; health-related impacts of disasters; pit latrines; WASH

1. Introduction

South Africa is a country where sanitation service delivery has for a long time been marred by historical and some political challenges [1,2]. This has often resulted in compromised sanitation provision/hygiene in many settlements and areas around the country [3]. Climate change has been ongoing for several decades and has resulted in many socio-economic changes in the fabric of the South African society. Examples include increased human migration from rural to urban areas, which is driven by the lack of economic opportunities in the rural areas and detrimental effects of climate change on livelihoods there [4]. Besides social and economic shifts, climate change is also important in the context of disaster risk management as the extent of many disasters is affected by it [5]. Detrimental effects of these disasters on the human population are often compounded by substandard hygiene conditions in disaster-prone areas [4,6]. For health-related disasters, inferior hygiene can be encountered in the metropolitan areas of developing countries, where the rate of urbanisation often exceeds the rates of water, sanitation, and public health service delivery [7]. Under these conditions, the probability of outbreaks of infectious diseases or health-related disasters increases [8]. Diarrhoeal diseases are one of many such health-related disasters or outcomes of other disasters that are important in urban areas in the 21st century.

The rates of diarrhoeal diseases were predicted to increase by 9–18% for every 1 °C rise in ambient temperatures during climate change in the Southern African region [9]. This region encompasses South Africa where the population has been shifting from a rural to an urban one, placing ever increasing numbers of people into urban informal settlements with inadequate and poor sanitation provision [4]. Living in those types of settlements can result in segments of the South African population being exposed to inferior hygiene conditions. This in turn can increase the probability of an outbreak of a diarrhoeal or sanitation-related disease, which can be considered as health-related disasters requiring consideration from the disaster risk management point of view. Disaster risk management deals with detrimental impacts of disasters on the human population and seeks to mitigate them [10,11]. Based on the above discussion, climate change and sanitation-related challenges will be, at least partially, interlinked in South Africa. Climate change will thus have disaster risk management implications in the context of sanitation in South Africa, t which in turn will indicate that the disaster risk management methodology can be used to study the sanitation in urban areas of South Africa.

1.1. Disaster Risk and Sanitation Service Delivery in South Africa

Managing and responding to the relevant disaster risks will thus form a critical part of sustainable disaster risk management and municipal planning in South Africa (for example [10,11]). In the context of urban sanitation, the disaster *Risk* (designated as *Ri* in further text) is defined as the potential danger to the human population due to a particular epidemic or infectious disease outbreak related to sanitation. The terms epidemic and infectious disease will be considered synonymous in further text for the context of disaster risk management and sanitation in South Africa. In disaster risk management, the *Ri* value can be mathematically expressed using several equations, but here the one by Tandlich et al. [10,11] will be used as outlined in Equation (1).

$$Ri = \frac{Haz \times Vul \times Exp}{Prep} \approx \frac{Haz \times Exp}{Res} \quad (1)$$

In Equation (1), *Haz* is the potential threat to the human population from a sanitation-related epidemic/disaster. In the context of public health, it can be seen as synonymous with endemicity or the likelihood of sanitation or hygiene-related epidemics [12]. *Vul* is the population's vulnerability to that sanitation-related epidemic in the "disaster-prone/affected area" [11]. *Res* are the values of resilience of the said human population to the epidemic/disaster in question. The term *Prep* represents the values of preparedness of the disaster risk management systems such as the local government to deal with a sanitation-related disease outbreak. Finally, *Exp* is the exposure of the human population (in a given informal settlement) to the causative agent of the particular sanitation related epidemic or *Haz*. This is the population's exposure to bacterial/fungal spores, cells, or helminth ova causing the particular sanitation-related epidemic or infectious disease. The terms of *Prep*, *Vul,* and *Res* are to be seen as intersecting in Equation (1). *Res* can also be defined as "the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the restoration of its essential basic structures and functions" [10,11,13]. Since this definition was operationalized and published, several other definitions of resilience have emerged. Resilience could thus be seen as a combination of resistance, response, and adaptation to disruptions and perturbations in conditions under which sanitation delivery and use by the target population take place.

Equation (1) is slightly different from the commonly adopted expression of *Ri* as a function of *Vul*, *Haz*, *Res*, *Prep*, and *Exp* [14]. The authors feel that this form of Equation (1) is justified for the sanitation and disaster risk management in South Africa. This reasoning is based on the fact that the *Ri* values in a particular case will depend on the proximity or likelihood of human contact with *Haz*, i.e., living in an area with inadequate sanitation infrastructure and inferior hygienic conditions that puts that population at risk of an outbreak or an epidemic of a diarrhoeal or hygiene-related disease. In other words, urban dwellers in informal settlements will reside in an endemic area for sanitation disease outbreaks, due to no fault of their own in many cases. The economic conditions of low-income settlements with limited/overwhelmed sanitation and the resulting inferior hygienic conditions will likely result in a high *Vul* and *Exp* of the population. However, if the local government is prepared and ready to respond efficiently, and the inhabitants of the affected area are made aware of, or possess the response capacity and procedures, then the *Ri* values can be low. At the same time, if the population of informal settlements has sustained access to basic preventive measures against sanitation-related diseases, e.g., a sustained supply of soap and safe potable water, then *Prep* and *Res* are high and *Ri* decreases. As a result, the assessment of *Ri* using Equation (1) applies and is justified in the authors' opinion to the context of this article. At the same time, the risk Equation (1) will be central to the review and meta-analysis that are performed in the current article. Equation (1) forms the philosophical and the most fundamental element of the argument in this review article and meta-analysis. Therefore Equation (1) will be mentioned and used as a reference point at all relevant places in this article.

Being able to predict the *Ri* values and quantify all terms in Equation (1) is a major component of disaster risk management and sustainable urban planning, especially in the context of climate change, the related uncertainties in human existence, and public and environmental health predictions. In South Africa, relevant considerations must take into account informal settlements and the linked secondary effects of their unplanned establishment, e.g., the lack of sanitation and tools to manage greywater and stormwater [15]. Many of the informal settlements are located on land unsuitable for housing purposes [16], making their population vulnerable to flash floods, landslides, slumping, and rockfalls. The effects of these disasters are likely to worsen with climate change and will be exacerbated by the growing backlog in sanitation provision in South Africa. In the immediate aftermath of disasters, the affected population will also suffer from community displacement, an exposure to extreme temperatures, a lack of clean drinking water, basic sanitation, and the unpreparedness or inability of local governments to assist [16,17].

1.2. Ventillated Improved Pit Latrines and the Sanitation Service Delivery in South Africa

The "improved sanitation" in South Africa includes the waterborne sanitation or the ventilated improved pit latrines (VIPs), and these technologies have been the backbone of the sanitation service delivery in South Africa for the last 30 years [1,2]. The VIPs have long been defined as the minimum standard of sanitation delivery by the South African government and are likely to be the preferred technological option in the sanitation service delivery in urban informal settlements and similar settlements, where the reticulation and collection of sanitation wastes must play catch up with the rate of urban development. The reticulation of sanitation wastes is often not even possible to be built, due to the dense and uncontrolled urban development of informal settlements in urban and peri-urban areas. In this article, the authors will attempt to present a description of the meaning and practical significance of the terms in Equation (1) with reference to sanitation in South Africa and with the specific focus on VIPs. Linkages to public health and disaster risk management are made. An effort is made to provide an overview of *Haz*, *Vul*, *Prep*, *Exp*, *Res*, and *Ri* the terms in Equation (1) for the sanitation-related disease as (potential) disasters in South Africa. This is done through a combination of a literature review and meta-analyses. The results are then used to propose new strategies to manage *Ri* for urban sanitation in South Africa by application of novel strategies such as the use of fly ash as a VIP additive.

Pollution is ever present in human surroundings, and it becomes part of one's environment. The pollution type varies with location and the type of human activity. The historical burden of pollution and waste will dictate the type of interactions between humanity, the environment, and the waste or pollution. The pit latrines and VIPs have been a standard of sanitation or the available sanitation throughout South Africa. This was based on the easiness of design and building, the speed of construction in the absence of reticulation, and the relative ease of training a population to do it themselves. The VIPs also offer a certain level of flexibility to construct a sanitation facility and provide improved sanitation when an informal settlement is erected, and sanitation needs to be provided in unreticulated settings. However, there are risks from the usage of VIPs, as the lack of maintenance can result in compromised hygiene of the population that uses the VIPs as improved sanitation. At the same time, there have been so-called 'legacy pits' in South Africa, that are VIPs that were built a long time ago, which should have been discontinued but remained in use as sanitation facilities past their designed lifespan, as no alternatives exist for the end-users. Such pits have become dilapidated throughout their lifecycle and thus pose a potential threat to physical and health security of the South African population. They pose a disaster/environmental hazard that needs to urgently be addressed.

Dealing with these legacy pits is necessary to limit the potential threat to human and environmental health. The legacy pits can be viewed as having started as a tool to improve human health. This increases the dignity of the population that are served by the VIPs in question, i.e., providing a basic but potentially functional sanitation technology that contributes to maintaining hygiene among the South African population. However, over their lifetime the VIP needs to be replaced, e.g., a new VIP pit must/should be dug up and the old one sealed or maintained. This is often not done and so the tool for improvement of human health becomes a threat to human health, as well as a pollution threat to the surrounding environment. The organic pollution, pathogenic bacteria and their dispersal from the abandoned pits, and the odours from the pits can cause a problem as they are untreated and become sources of secondary environmental contamination from the VIPs. The aim of this paper is to provide a modelling estimate and overview of the potential pollution burden that can be posed by the VIPs and especially legacy pits throughout South Africa. A disaster risk management approach is used by the authors, as the legacy pits have been documented to cause what can be classified as cascading disaster impacts on the South Africa population and the environment.

The authors of the current study use the existing knowledge on the management of the VIP faecal sludge, as well as relevant knowledge gaps, to estimate/propose the potential solutions to manage the pit contents from the 'legacy VIPs', as well as from the newly built VIPs. Based on some of the authors' own research, a suggestion is made to use the coal fly ash as a VIP pit additive and to treat the legacy pits sludge and contents in-situ or ex-situ based on local conditions. In addition, the existing data on drying of the VIP faecal sludge ex-situ, the related energy consumption and footprint considerations are analysed for feasibility in dealing with legacy pits. Fly ash is a by-product of the majority of the energy generation in South Africa and the disposal of fly ash currently poses a major environmental challenge and burden on public health in South Africa. The use of fly ash in the pit latrines and the VIPs could be done by using a partial circular-economy approach and potentially allow for the cross-management of two independent sources of environmental contamination in South Africa. Fly ash has been shown to contain various minerals, e.g., clay minerals, and these have been shown to be altered based on the conditions of the modification of the fly ash.

Pit latrines and fly ash constitute 'legacy issues' in terms of public and environmental health in South Africa. The term legacy will apply when they have been going unresolved or tackled sufficiently for an extended period of time. Thus, in the authors' opinion, it is necessary to conduct a disaster risk-based assessment of the VIPs as a form of sanitation in

South Africa and to present potential solutions and challenges that can arise. The aim is, amongst other issues, to try and propose a complex solution(s), which would concurrently address the public and environmental, as well as the related health vulnerability, of the South African population.

2. Materials and Methods

In the current article, literature data on the VIPs as the common standard of sanitation service delivery in South Africa are reviewed. Environmental, treatment, and public health implications of VIPs are discussed, along with possible solutions being presented. The study aims were achieved by a combination of review, theoretical calculations, some experimental data, and meta-analysis. The databases used include SCOPUS, ISI Web of Science, South African government documents, and official statistics. Results of the review, theoretical calculations, and meta-analysis are put into the context of disaster risk evaluation of sanitation in South Africa. Specific attention is placed in the study on the results implications for the sanitation service delivery under the conditions of rapid urbanisation and climate change in South Africa. The existing modelling approaches were used to predict likely filling and the necessary volumes of the pits in the VIPs, that could be expected or optimal for the conditions in South Africa. At the same time, the energy and drying characteristics of the faecal sludge from South Africa are used to examine the practical challenges that can hamper the treatment and management of the faecal sludge after the VIP pits are full. Finally, the economic aspects of the preventative routine maintenance of the VIPs, both new and 'legacy pits', were performed using the principles of interest investment in the VIP as an asset to the users of the VIPs and the government. The relevant equations formed part of the Results section of this article, and they are discussed in the respective parts of the text of the relevant calculation/meta-analyses results.

Based on the results of the meta-analyses, the authors propose the use of (modified) fly ash from coal combustion as a potential VIP pit additive to achieve in situ or ex situ stabilization and/or treatment of the VIP faecal sludge. In order to suggest a treatment mechanism of the VIP faecal sludge, the structural characterization of the fly ash from South Africa is presented based on the Fourier-transformation infra-red spectroscopy (FTIR; (Ash Resources (Johannesburg, South Africa, [18]). The transmission spectra of composite films were recorded from a thin KBr disc of the samples with Perkin Elmer 100 FTIR spectrophotometer (Chemistry Department, Rhodes University, Makhanda, previously known as Makhanda) at room temperatures. The samples were scanned from 4500 to 500 cm^{-1} with a resolution of 0.4 cm^{-1}. Using that information, the mineral composition of the fly ash samples is presented and linked to the possible treatment mechanism for in situ stabilisation of VIP faecal sludge. The composition information is used as the basis to suggest a potential treatment mechanism of the VIP faecal sludge as a pit additive in new and 'legacy' pits.

3. Results

3.1. VIPs as a Sanitation Technology in South Africa as a Source of Ri

To speed up sanitation delivery in South Africa, the democratic government passed legislation after 1994, where the minimum acceptable sanitation standard in urban settlements has for a long time been defined as the VIP [1]. The VIP consists of a pit with a ventilation pipe that facilitates aeration of the pit contents [19]. The pit is enclosed with a top cabin-like structure to provide privacy for the VIP users during urination and defecation [20]. Urine, faecal material, and anal cleansing utensils are collected, and their breakdown takes place during storage in the VIP pit (designated as pit in further text) or vault [20,21]. The pit contents can contain bacterial and nematode pathogens, as well as other infectious particles. This increases the *Ri* values during floods [4], or if there is a lack of regular pit maintenance and the VIPs are in constant use [22]. To assess the *Ri* values, the maintenance and other factors must be understood in detail. Maintenance is dictated by the working volume of the pit (designated as VV_{VIP} in further text). The VV_{VIP} has a unit of m^3 and it is calculated as shown in Equation (2). The terms capita and person are considered interchangeable in the remainder of the manuscript.

$$VV_{\text{VIP}} = FR \times N_{\text{Users}} \times LS \quad (2)$$

In Equation (2), the FR is the filling rate (m^3/person/year) and the N_{Users} is the number of intended users per single VIP (person). The LS is the intended lifespan of a single VIP (year). Some of the relevant literature values for South Africa are as follows: the FR from 0.0185 to 0.0694 m^3/person/year [19], the average N_{Users} is 7 [23]; and the LS from 5 to 25 years [22–24]. The VV_{VIP} dictates the pit waste volume that needs to be treated once the VIP pit is full. At the same time, the VV_{VIP} also has a major impact on the types and concentration of pathogens that the population in urban informal settlements and the VIP maintenance workers can be exposed to. Such an exposure can take place during the manual excavation of the waste, which is the preferred and most-cost effective method of the pit contents removal (see below) [24]. Exposure can also occur during flooding of informal settlements that are built below the flood line [4,16]. Therefore Equations (1) and (2) are inter-related and critical to the evaluation of *Ri*. No standardized VV_{VIP} data have been published for South Africa to the best of the authors' knowledge, and as a result, the relevant estimates were calculated using Equation (2) and these results are shown in Tables 1 and 2.

Table 1. The minimum estimates of Working Volume of the pit in ventilated improved pit latrines (VV_{VIP}) in South Africa.

Minimum VV_{VIP} Values for South Africa (Min VV_{VIP})	**Parameters from Equation (1) and Estimated VV_{VIP}**			
	LS (Years)	**FR (m^3/Person/Year)**	**N_{Users}**	**VV_{VIP} (m^3)**
Min VV_{VIP}	5 [a]	0.0185 [d]	4 [e]	0.370
Min VV_{VIP}	10 [b]	0.0185 [d]	4 [e]	0.740
Min VV_{VIP}	25 [c]	0.0185 [d]	4 [e]	1.850
Min VV_{VIP}	5 [a]	0.0185 [d]	7 [c]	0.648
Min VV_{VIP}	10 [b]	0.0185 [d]	7 [c]	1.295
Min VV_{VIP}	25 [c]	0.0185 [d]	7 [c]	3.238
Min VV_{VIP}	5 [a]	0.0185 [d]	14 [e]	1.295
Min VV_{VIP}	10 [b]	0.0185 [d]	14 [e]	2.590
Min VV_{VIP}	25 [c]	0.0185 [d]	14 [e]	6.475
Min VV_{VIP}	5 [a]	0.0185 [d]	21 [e]	1.943
Min VV_{VIP}	10 [b]	0.0185 [d]	21 [e]	3.885
Min VV_{VIP}	25 [c]	0.0185 [d]	21 [e]	9.713

[a] Values extracted from from Still and Foxon [24]. [b] Values extracted from Bhagwan et al. [22]. [c] Values extracted from Brouckaert et al. [23]. [d] Values extracted from Still [19]. [e] Set arbitrarily by authors.

The minimum VV_{VIP} values in Table 1 are based on the fixed FR value of 0.0185 m^3/person/year and the following intervals: the LS from 5 to 25 years and the N_{Users} from 4 to 21 [19,22–24]. The authors added the number of users of a single VIP as 4 (a single household of 4 members uses a single VIP), 7, and 14/21 users per single VIP (a situation that can be expected to occur in an urban/informal settlement, if the sanitation service delivery lags behind demand). The maximum values in Table 2 are based on an FR of 0.0694 m^3/person/year and the same variations in the LS and N_{Users} as in Table 1 [19,22–24]. Increasing the number of users per VIP occurs when there is sharing of toilet facilities in the case of shortages in sanitation service deliveries [25]. These conditions also represent the worst-case disaster risk management scenario(s). Looking at Equation (2), the VV_{VIP} is directly proportional to the LS, FR, and N_{Users} (see values in Tables 1 and 2). The *Min* VV_{VIP} values range from 0.370 to 9.713 m^3, while the *Max* VV_{VIP} values range from 1.388 to 36.44 m^3. As summarised by Mara [20] and as suggested by results of practical studies from South Africa [26], the VIP pit is considered here to be square or rectangular in shape. The width and length vary between 1.0 to 1.5 m ([20] pages 7–8). Based on these dimensions, the pit will have the 3D shape of a square or rectangular prism. Thus, the VV_{VIP} will be related to the shape of the pit as shown in Equation (3).

$$VV_{VIP} = S_{base} \times D = W \times L \times D \tag{3}$$

Table 2. The maximum estimates of Working Volume of the pit in ventilated improved pit latrines (VV_{VIP}) in South Africa.

Maximum VV_{VIP} Values for South Africa (Max VV_{VIP})	Parameters from Equation (1) and Estimated VV_{VIP}			
	LS (Years)	FR (m^3/Person/Year)	N_{Users}	VV_{VIP} (m^3)
Max VV_{VIP}	5 [a]	0.0694 [d]	4 [e]	1.388
Max VV_{VIP}	10 [b]	0.0694 [d]	4 [e]	2.776
Max VV_{VIP}	25 [c]	0.0694 [d]	4 [e]	6.940
Max VV_{VIP}	5 [a]	0.0694 [d]	7 [c]	2.429
Max VV_{VIP}	10 [b]	0.0694 [d]	7 [c]	4.858
Max VV_{VIP}	25 [c]	0.0694 [d]	7 [c]	12.15
Max VV_{VIP}	5 [a]	0.0694 [d]	14 [e]	4.858
Max VV_{VIP}	10 [b]	0.0694 [d]	14 [e]	9.716
Max VV_{VIP}	25 [c]	0.0694 [d]	14 [e]	24.29
Max VV_{VIP}	5 [a]	0.0694 [d]	21 [e]	7.287
Max VV_{VIP}	10 [b]	0.0694 [d]	21 [e]	14.57
Max VV_{VIP}	25 [c]	0.0694 [d]	21 [e]	36.44

[a] Values extracted from Still and Foxon [24]. [b] Values extracted from Bhagwan et al. [22]. [c] Values extracted from Brouckaert et al. [23]. [d] Values extracted from Still [19]. [e] Set arbitrarily by authors.

In Equation (3), S_{base} represents for the surface area of the pit base (m^2). It is equal to the product of the width (W; m) and the length of the pit (L; m). The VV_{VIP} values are then calculated by multiplying S_{base} by the depth of the pit (D; m). In further text, it is assumed that the FR, LS, and N_{Users} only take on values shown in Tables 1 and 2; and W and L vary inside the interval given by Mara [20]. Under such conditions, the VV_{VIP} will vary as a function of D that can be estimated using Equation (4).

$$D = \frac{VV_{VIP}}{W \times L} = \frac{VV_{VIP}}{S_{base}} \tag{4}$$

The minimum D values will be encountered with the VV_{VIP} estimates from Table 1 and if W and L are both equal to 1.5 m ([20] pages 7–8). On the other hand, the maximum D values will be encountered with the VV_{VIP} estimates from Table 2 and if W and L are both equal to 1.0 m ([20] pages 7–8). The relevant estimates of D are summarised in Tables 3 and 4. Consequently, the VV_{VIP} is directly proportional to D and vice versa. Thus, if W and L fall inside the constant interval of 1.0–1.5 m, then D mostly dictates the size of the pit. This in turn means that D is one of the main determinants of cost of the on-site VIP construction, namely the cost of excavating the pit, the cost of the over-ground superstructure of the VIP, and the cost of construction materials needed for the VIP sinking into the ground, e.g., the concrete slab and anchor materials that ground the superstructure in the soil/ground. The D values will also control the maintenance costs, e.g., the cost of the removal and disposal of the pit contents. The D values must thus be known as they will have a strong influence on the cost of sanitation provision, i.e., indirectly control the extent of sanitation provision and public health in urban settlements.

Table 3. The minimum estimates of depth of the pit in the ventilated improved pit latrines for the relevant working volumes and dimensions of the pit in South Africa.

Minimum VIP Depth Values for South Africa (D_{Min})	Parameters for Calculation of D			
	VV_{VIP} (m^3)	W, L (m)	S_{base} (m^2)	D_{Min} (m)
D_{Min}	0.370	1.5	2.25	0.164
D_{Min}	0.740	1.5	2.25	0.329
D_{Min}	1.850	1.5	2.25	0.822
D_{Min}	0.648	1.5	2.25	0.288
D_{Min}	1.295	1.5	2.25	0.576
D_{Min}	3.238	1.5	2.25	1.439
D_{Min}	1.295	1.5	2.25	0.576
D_{Min}	2.590	1.5	2.25	1.151
D_{Min}	6.475	1.5	2.25	2.878
D_{Min}	1.943	1.5	2.25	0.864
D_{Min}	3.885	1.5	2.25	1.727
D_{Min}	9.713	1.5	2.25	4.317

Table 4. The maximum estimates of depth of the pit in the ventilated improved pit latrines for the relevant working volumes and dimensions of the pit in South Africa.

Maximum VIP Depth Values for South Africa (D_{Max})	Parameters for Calculation of D			
	VV_{VIP} (m^3)	W, L (m)	S_{base} (m^2)	D_{Max} (m)
D_{Max}	1.388	1.0	1.00	1.388
D_{Max}	2.776	1.0	1.00	2.776
D_{Max}	6.940	1.0	1.00	6.940
D_{Max}	2.429	1.0	1.00	2.429
D_{Max}	4.858	1.0	1.00	4.858
D_{Max}	12.15	1.0	1.00	12.15
D_{Max}	4.858	1.0	1.00	4.858
D_{Max}	9.716	1.0	1.00	9.716
D_{Max}	24.29	1.0	1.00	24.29
D_{Max}	7.287	1.0	1.00	7.287
D_{Max}	14.57	1.0	1.00	14.57
D_{Max}	36.44	1.0	1.00	36.44

To the best of the authors' knowledge, only rough guidelines exist for the construction of VIPs in relation to D, namely that D is optimized to be at least 2–5 m above the seasonal water table (see page 67 in reference [27]). This needs to be changed and the estimates in Tables 3 and 4 can be used for this purpose. Besides sanitation provision, the D estimates from Tables 3 and 4 are needed to drive disaster risk management and sanitation planning based on the following considerations. VIPs in many settlements where these are installed 'on the go' or as the dwelling and population developments require, i.e., the installation of VIPs often take place without proper maintenance for extended periods of time [22]. This can compromise the public health in and around the affected area in several ways. A disaster hazard and risk can be imminent or delayed, similar in principle of the ignition of wood dust on hot surface and/or in a delayed fashion from a smoldering cigarette [28]. The potential public health impacts of the VIPs can thus be summarised as follows. Firstly, potential leaching and percolation of pathogens and chemicals from the pit into the groundwater can take place (see next paragraph for details). Secondly, the human population of a given settlement can be exposed to pollutants, such as indole, which have been shown to permeate from the VIP pits [29]. In extreme cases, deaths can occur during the usage of the VIPs as reported recently in the Limpopo Province of South Africa [30]. Therefore, the optimisation of D is important for sanitation considerations, urban planning, and the sanitation evaluation of Ri in South Africa.

In a given informal/urban settlement, D will be affected by a combination of several local factors. These will include the soil characteristics at the site of VIP construction, the construction materials used, the depth of the water table, and the municipal financial resources available for sanitation provision/maintenance. In general, a compromise will have to be struck given the above-mentioned factors and the considerations are discussed next. The deeper the pit, the higher the costs of the VIP sinking and wall construction/stabilisation, and the higher the cost of ensuring the physical stability of the VIPs (pit) during its lifecycle. Soil and geological conditions on site will determine if the bottom of the VIP pit allows for the percolation of the pit contents into the soil profile, and whether this can lead to the contamination of groundwater with the faecal sludge components, i.e., whether the VIP pit can become a source of environmental anthropogenic pollution. Uncontrolled urbanisation and the VIP construction can take place in areas where such a soil/environment contamination is possible in South Africa. Consequently, the higher the D value, the higher the cost of pit emptying once the designed VV_{VIP} is reached. The water table is an indication of the depth below ground from which groundwater can be extracted [31] for potable purposes [32]. As many VIP pits are (usually) not sealed at the bottom, faecal material can percolate down through the soil profile [33]. This can in turn result in groundwater contamination with pathogens and/or chemical contaminants of the VIP faecal sludge. The percolation of contaminants down the soil profile occurs at faster rates in sandy soils in comparison to silt loams and clay soils [32]. Flooding can also make the pits a source of groundwater and surface water contamination.

While the groundwater contamination is related to the percolation of the VIP pit contents down the soil profile, there is another way the VIPs can become a source of faecal contamination. This can be based on the fact that many informal and urban settlements in South Africa are built under the flood line. Flooding of the VIP pits can take place during severe thunderstorms. An increase in the soil moisture content in the upper soil horizons during such weather conditions, and the surface flooding of the VIP pits, can occur in South Africa. Once the field moisture capacity is reached, the rate of the pit content percolation is likely to increase by facilitating faster rates of microbial movement and diffusion. The extent and rate of groundwater contamination with the VIP pit contents will then depend on the significance of macropore transport and the pore size distribution of in the on-site soils.

Flooding of the pit, the potential for lateral diffusion of the contaminants from the VIP pit in the soil matrix, and the capillary rise can lead to the components of the pit content contaminating the soil surface horizons. At the same time, the flooding can bring the VIP pit content to the surface and cause contamination of the habitable areas with the VIP faecal sludge in South Africa. Consequently, the Ri values in the aftermath of flooding will likely increase. This will be due to the increased probability of human contact with the spilled faecal material and the possibility of the surface water body contamination due to surface runoff [4]. This will concurrently increase the Exp values from Equation (1) and thus increase Ri. A lower D should make VIPs more aerobic and thus accelerate the stabilisation of the pit contents [22]. However, a lower D will also result in more frequent pit emptying, which could potentially increase the maintenance costs.

All the above-mentioned factors must be considered when looking at the D estimates from Tables 3 and 4, and their practical implications in sanitation planning and disaster risk management in South Africa. The estimated D values range from 0.164 to 36.44 m.

Water tables in the metropolitan areas of South Africa have been reported to range from 0 to below 50 metres [34]. The most relevant practical outcome of the calculations is the fact that even at the smallest D values of up to 2.878 m, the D values overlap with the levels of the water table in South Africa. There is thus a potential for the VIP as a source of environmental contamination of groundwater in South Africa. This will be especially the case if VIPs are not properly maintained, and groundwater contamination and other effects from above become likely. As the rate of urbanisation often supersedes the rate of the sanitation service delivery, there is likely to be pressure to speed up the sanitation delivery as much as possible throughout South Africa. The deeper the VIP, the more the wall-stability would become an issue during the pit construction. During the drilling for groundwater, measures must be put in place to keep out water from the well shaft [35]. The walls of the VIP are by nature meant to be more permeable than those in a groundwater well, and soil properties will play a critical role in ensuring the VIP physical stability during and after construction. This combination of factors will make the use of the highest D estimates impractical to implement under real-life conditions in South Africa. The case for this assumption is further strengthened by the financial costs of VIP maintenance, as discussed already above and as unpacked further below.

The deepest D values from Tables 3 and 4 are thus not likely to be constructed under the real-life scenarios in South Africa. However, the resulting VV_{VIP} values can indicate the highest/real-life volume of faecal sludge from the VIPs, which might accumulate in the pits or their vicinity, or which might need to be treated, if the VIP is unmaintained or becomes dilapidated during its lifecycle, e.g., possibly containing a volume of the VIP faecal sludge that is equivalent to that calculated from the VV_{VIP} value corresponding to the D value of 36.44 m. The relevant depths and faecal sludge volumes, expected to be accumulated in a single VIP pit that is unmaintained, can also be used to estimate several disaster risk management aspects of the sanitation and R_{i} in South Africa. These include potential environmental and public health burdens that would be encountered, or the size of the possible environmental impact, which could occur if the pits or VIPs were not properly maintained. In other words, the maximum D values are hypothetical and can serve as an indication of what can happen in the accumulation of the material in the VIP pit if it goes well beyond design parameters or lifespan, and/or emptying and maintenance of the VIPs is not done in regular intervals, when higher volumes are stored in the VIP pit than it was designed for. In addition, the D values and the related volumes can provide an estimate about the cost of maintenance, which will be an important economic consideration and will be touched on a little more in the next paragraph.

3.2. Various Aspects of the Maintenance of VIPs in South Africa and the Relation to R_i

The cost analysis of the VIP maintenance will be mainly determined by the cost of pit emptying. A single emptying of 2 m^3 of the VIP pit in South Africa has been shown to cost approximately 7–226 USD [24,26,36,37]. The exchange rate between 1 USD and 1 ZAR is 7.5–15 to 1 for the 2006–2022 period. The emptying costs will have budgetary challenges in the sanitation provision/planning in South Africa. For example, the eThekwini Metropolitan Municipality was scheduled to empty 50,000 VIPs in 2006–2007 (based on the authors interpretation of the data in reference [37,38]). Using the most cost-effective method, the total cost could be estimated at around 50 million ZAR or 3.3–6.7 million USD [37,38]. The cost of building a single new VIP was reported to range from 399 to 448 USD without the cost of land but escalated to 823 USD with the cost of the land included [36]. If 50,000 VIPs must be built, then the cost will be ranging from 19.95 to 41.15 million USD. Therefore, focusing on emptying pit latrines could lead to savings in the sanitation provision, if carried out properly and at regular intervals. However, this does not always take place [1]. As a result, practically a balance will have to be struck between building new sanitation facilities and the VIP/sanitation infrastructure maintenance. Using the modelling values from the current and other already published studies, can assist the South African government in lowering the sanitation Ri. This is most likely to be achieved with a lower VV_{VIP} and thus lower D values.

Another link between VIPs and the Ri values in Equation (1) comes from the volumes of wastes that need to be managed and contained/processed safely once the pit is full or excavated [39]. Once the VV_{VIP} is to be reached and the VIP pit contents need to be emptied, e.g., by manual excavation, the VIP faecal sludge must be treated. Naidoo et al. [39] found that only 6.5% of excavating workers were positive for *Ascaris* spp. ova/infection, with the ova being viable. At the same time, up to 22% of residents from East London, who provided samples of faecal matter in the study, were positive for helminth parasites (although those were not viable [39]). Therefore, the manual excavation can result in the infection of the workers digging the faecal sludge out of the VIP. After excavation, the VIP faecal sludge is transported to the wastewater treatment plants for safe management and disposal. The content of one (VIP) pit adds an equivalent of about 500 and 1000 m^3 of sewage to the wastewater volumes that reach the municipal sewage treatment plants [22]. These treatment facilities are often dysfunctional around South Africa [4].

The South African Government designed the Green Drop certification system, which measures the performance of the wastewater treatment plants against a set of indicators [40]. It has two evaluation frameworks, namely the Green Drop Assessment of the entire wastewater treatment of the system/value-chain and the Cumulative Risk assessment of the wastewater treatment itself (see Figure 9.5 in reference [40]). In 2013, 248 (30.1%) of the 824 wastewater treatment plants were deemed critical and needed regulatory action [41]. A total of 161 (19.5%) treatment works were in poor condition and required immediate care [41]. This means that over half of South Africa's wastewater treatment plants were not functioning properly and required attention. The Green Drop Certification for a well-functioning wastewater treatment plant was given to only 60 (7%) wastewater treatment plants [41].

By 2015–2016, there was a large paucity of the Green Drop compliance data across South Africa (see Figure 9.6a,b in reference [40]). Thus, it was impossible to ascertain whether some wastewater treatment plants in South Africa were functional and could treat sewage/incoming wastewater/the excavated VIP faecal sludge or not. At the same time, only a small portion of the wastewater treatment plant was in a good functional order, as indicated by the fraction of the total wastewater treatment plants with a Green Drop score of 90% or broadly above 80% in South Africa (see Figure 9.6a,b in reference [40]). Despite the fact that the relevant national government department updated the Parliamentary Water and Sanitation Committee on the status of the Green Drop program in 2018, no information on wastewater treatment works was supplied in monitoring and similar reports for quite a significant part of the country [40,41]. If the wastewater treatment plants are dysfunctional or it is not possible to assess their efficiency, then the sanitation *Haz* and R_i, as well as its related uncertainty, increases in South Africa. This is caused, amongst other reasons, by the fact that the excavated VIP faecal sludge can pass through the wastewater treatment plant without being subjected to the necessary level of treatment to achieve regulatory compliance. Upon the effluent discharge from the wastewater treatment plant, the untreated VIP pit content will become part of the final effluent from the wastewater treatment plant.

In South Africa, (the treated) waste streams from faecal sources are usually discharged into surface water bodies, which are located in close geographic proximity to the particular treatment plant. If the final effluent has not been treated to comply with microbial regulatory standards and it contains sanitation waste residues, then its discharge into the environment could result in environmental contamination with human pathogens, e.g., *Campylobacter jejuni* [4]. This can result in the outbreak of diarrhoeal diseases if human contact with such surface water takes place, e.g., during crossing water bodies such as rivers, thus increasing the sanitation *Haz* and potentially the R_i. Moreover, many informal settlements have no sewage, greywater, or stormwater runoff collection systems in place [42]. The outcome of such conditions is often ponding of the pathogen-containing runoff on the soil surface, providing a breeding ground for various disease vectors [42]. The result is a potential further *Ri* increases as the probability of an infectious disease outbreak can be expected to increase as well, i.e., the disaster hazard and exposure from Equation (1) can be expected to increase.

The VIPs are generally built with permeable walls [36] and the bottom of the VIP pit is generally not lined. Under those conditions and as a function of the soil characteristics on-site of the VIP construction, the VIP pit content, e.g., pathogens and nutrient/chemical contaminants, can percolate into the underlying and surrounding soil [33]. Groundwater contamination with pathogenic microorganisms can be a direct outcome of this process, if the containment of the VIP waste inside the pit is compromised [43,44]. Percolation can also raise the nitrate and ammonia concentrations in groundwater [43,45]. As groundwater has been shown to account for around 13% of the potable water resources in South Africa [32,34], the consumption of contaminated groundwater is feasible in urban, as well as rural areas, in South Africa. If the VIP waste is not contained properly, then groundwater from the vicinity of dysfunctional VIPs used for potable purposes can be contaminated with human pathogens. Once such water is consumed by the urban population, this population is likely to consume infectious particles such as helminth ova or protozoan oocysts. Given the high probability of groundwater contamination with faecal material, the sanitation *Haz* and R_i values increase if the consumed number of infectious particles can exceed in the infectious dose of a particular human pathogen. In addition, the consumption of the nitrate-contaminated groundwater by the human population has been linked to the development of pancreatic cancer in humans [46]. Consequently, the sanitation-related *Ri* will increase and a health-related disaster/an epidemic outbreak can take place [46]. This is especially the case with 'legacy pits', which have not been maintained for extended periods of time.

Based on the data and information presented up to this point, the VIP pit contents should be treated at times when the pit is full and needs to be evacuated, or it could be treated on an ongoing basis as soon after defecation as possible at the production source. All these strategies will help lower the *Haz* values and decrease the *Ri* values. Septien et al. [47] studied the rheological properties of the VIP faecal sludge as a function of its moisture content (grams H_2O per 1 g of the VIP faecal sludge dry weight) in the range from 77 to 90/95%. The viscosity of faecal sludge decreased from just under 100,000 Pa.s at a shear stress of 0.1 s^{-1} and a moisture content to just under 1 Pa.s at a moisture content of 90% and 100–1000 s^{-1} [47]. Faecal sludge in that study behaved like a non-Newtonian liquid [47]. The ash content of the VIP faecal sludge, i.e., a measure of the inorganic residue in the particulate matter of the VIP pit contents, ranged from 28 to around 60% of dry weight of the VIP faecal sludge [47]. The yield stress of faecal sludge was a function of the physical location of the place in the VIP pit where the faecal sludge was extracted from [47]. In the moisture content range from 75 to 95%, the time it took to empty the faecal sludge from the VIP pit ranged from 11 to 73 min, with the time being directly proportional to the VIP faecal sludge moisture content [47]. The power needed to empty the pit was inversely proportional to the VIP faecal sludge moisture content, with the respective value ranging from 40 W at a 95% moisture content to 22,000 W at a 75% moisture content [47].

The values of Septien et al. [47] do allow for some predictions of the practical parameters for the emptying of the VIP pit, once the pit capacity has been reached and under the wider intervals of moisture contents of the VIP faecal sludge in South Africa. The calculated results presented in the Results were calculated using Equations (S1) and (S2), as shown in the Supplementary Information and the calculation results are shown in Table 5.

Table 5. Parameters of emptying 2 m^3 of faecal sludge from a full pit in a South African ventilated improved pit latrine (reproduced from reference [47]).

MC [a] **(%)**	***P*** [b] **(*W*)**	***ET*** [c] **(min)**	***V*** [d] **(m^3)**
58	2,331,9472 [e]	1.3 [e]	Not applicable
75	22,000	11	0
80	3500	15	0.700
85	600	21	1.867
90	100	34	4.200
95	40	73	11.200

[a] The moisture content of the VIP faecal sludge as defined in reference [47]; [b] Power in Watts or Js^{-1} at the moisture content of the VIP faecal sludge as defined in reference [47]; [c] The time needed to empty 2 m^3 of faecal sludge from the VIP pit as defined in reference [47]; [d] The volume of H_2O to be mixed into the VIP pit to facilitate extraction as defined in reference [47]; [e] The values were calculated using Equations (S1) and (S2), and based on data from reference [47].

The results of Septien et al. [47] were then extrapolated to estimate the values of *p* and *ET* for a moisture content of 58% of a hypothetical South African faecal sludge, which had been extracted from a VIP. The relevant data are shown in Table 5 and it is clear that the emptying time decreases, but the power to extract 2 m^3 of faecal sludge would be very high.

Data of Septien et al. [47] indicate that large volumes of fresh water might need to be added to extract the VIP pit contents for treatment, while decreasing the required power of extraction. This will pose practical problems in South Africa that is a water-scarce country and has suffered from recuring droughts in the last several years [48]. The lack of rain has increased the significance of the use of freshwater for irrigation that is needed to ensure sufficient food production [49]. As a result, challenges in disaster risk management will arise if potable water is to be diverted into the extraction of the VIP faecal sludge, especially at the scale as mentioned for the eThekwini Metropolitan Municipality [37,38]. In addition, it would be ethically not feasible to justify diverting the large volumes of potable water, or freshwater in general, that Septien et al. [47] proposed. The diversion would be from other uses such as irrigation in agriculture and from the fulfilment of ecosystem functions, such as water plays, to deal with the pit contents or the VIP 'legacy pits'. As a result, the practical and academic value of the work of Septien et al. [47] is high, as it furthers the understanding about the practical challenges and implications of the faecal sludge management in South Africa. It does, however, also point to the need to develop additional approaches to extraction and treatment/management of the VIP pit sludge in the country and its safe treatment. Such new approaches are also needed based on the combination with the above information.

Based on the discussion so far, it is necessary to maintain VIPs in working conditions to maintain the operational status of this form of sanitation. Maintenance is important to achieve functionality of the VIP as a sanitation technology, and indirectly as a means to prevent potential *Haz* from a public and environmental health point of view. In addition, the maintenance and proper functioning of the VIP is necessary to ensure the use and buy-in from the end-users of the VIP as a sanitation facility, in the place of waterborne sanitation. Maintenance is finally needed to ensure the long-term use of the VIP in question, and to maintain the stability of the VIP and damage prevention to its physical structure. The end-users are not necessarily interested in being part of the maintenance of the VIP or of sanitation facilities in general [36]. Therefore, the building of a VIP should be seen as an investment into the population's hygiene maintenance and decreasing the *Haz* and R_i related to sanitation in South Africa.

3.3. Financial Considerations and Maintenance of VIPs in South Africa and Management of Ri

Regular maintenance of the VIP could then be seen as paying an 'interest' towards decreasing the present and future sanitation *Haz* and R_i in South Africa based on the equation of the current value of a VIP that can be seen as the price of the construction of that VIP (*PV*), while the future value of that VIP is the financial value of that VIP in several years/time after the construction of that toilet and the use of it as a sanitation facility (*FV*). The relationship between *FV* and *PV* can be expressed as shown in Equation (S3) in the Supplementary Information, along with the necessary explanations/model assumptions. The results of these calculations are shown in Tables 6 and 7.

It can be seen from the calculation results in Table 6 that if the annual maintenance is performed and the necessary financial investments are made, then the value of the VIP can increase from 423.5 USD at the time of construction to 790.7 USD after 5 years of the VIPs lifespan. The *FV* value can even increase further to 1476.2 USD after a ten-year lifespan and to 9607.3 USD after 25 years of regular maintenance and pit operation. The respective values with the negative *r* values are equal to 207.5, 101.6, and 12.0 USD, respectively (see Table 7 for details). As a result, the calculation results from Tables 6 and 7 clearly indicate a positive impact of maintenance and the decreased need for new investment if 56.5 USD is invested annually into the maintenance of a single VIP throughout its (1) 5–25-year lifespan. In this way, the need to build a new VIP is eliminated in the long-term space–time and the potential negative environmental impact is prevented.

Table 6. *FV* as a function of the positive value of *r* and no-land *PV* in South Africa (Scenario 1).

N (Year)	*PV* (USD)	*r* (Dimensionless)	*FV* (USD)
1	423.5	0.133	479.8
2	423.5	0.133	543.6
5	423.5	0.133	790.7
10	423.5	0.133	1476.2
15	423.5	0.133	2756.2
25	423.5	0.133	9670.3

Table 7. *FV* as a function of the negative value of *r* and no-land *PV* in South Africa (Scenario 2).

N (Year)	*PV* (USD)	*Negative r* (Dimensionless)	*FV* (USD)
1	423.5	−0.133	367.2
2	423.5	−0.133	318.3
5	423.5	−0.133	207.5
10	423.5	−0.133	101.6
15	423.5	−0.133	49.8
25	423.5	−0.133	12.0

Scenario 1, i.e., where the cost of land is not included in the VIP construction and the cost considerations in Tables 6 and 7 can be practically encountered in South Africa under two conditions. Firstly, the VIP will serve a community and housing developments that are built on public or municipal land. In other words, the contracting party or initiator of building VIPs in an area is the local government/municipality, who owns the land and so the cost of purchasing land for VIP falls away. The second relevance of scenario 1 to real-life conditions in South Africa could be as follows: A VIP without the cost of land can be built in areas where a plot of land has been illegally occupied and an informal settlement has been erected. The investment of the annual VIP maintenance costs could be problematic, based on the general prohibition of the local South African government, to provide municipal services such as sanitation to people without a permanent address or those who occupy land illegally. However, to decrease the *Haz* and R_i in relation to sanitation in South Africa, based on data in Tables 6 and 7 and the discussion preceding these sections, the investment into VIP maintenance is ethically justified and necessary to prevent the outbreaks of sanitation-related diseases.

It can be seen from the calculation results in Table 8 that if the annual maintenance is performed and the necessary financial investments are made, then the value of the VIP can increase from 823 USD at the time of construction to 1148.9 USD after 5 years of the VIPs lifespan. The *FV* value can even increase further to 1603.9 USD after a ten-year lifespan and to 4363.6 USD after 25 years of regular maintenance and pit operation. The respective values with the negative *r* values are equal to 575.6, 402.6, and 137.8 USD, respectively (see Table 9 for details). The calculation results from Tables 8 and 9 clearly indicate a positive impact of maintenance and the decreased need for new investment, if 56.5 USD is invested annually into the maintenance of a single VIP throughout its 5–25-year lifespan. In this way, the need to build a new VIP is eliminated in the long-term space–time and the potential negative environmental impact is prevented. Scenario 2, i.e., where the cost of land is included in the VIP construction and the cost considerations in Tables 8 and 9, can be practically encountered if the VIP will serve a community and housing developments that are built on public or municipal land. However, to decrease the *Haz* and R_i in relation to the sanitation in South Africa, based on data in Tables 8 and 9 and the discussion preceding these sections, the investment into VIP maintenance is ethically justified and necessary to prevent the outbreaks of sanitation-related diseases.

Table 8. *FV* as a function of the positive value of *r* and land *PV* in South Africa (Scenario 2).

N **(Year)**	***PV*** **(USD)**	***r*** **(Dimensionless)**	***FV*** **(USD)**
1	823	0.069	879.8
2	823	0.069	940.5
5	823	0.069	1148.9
10	823	0.069	1603.9
15	823	0.069	2239.1
25	823	0.069	4363.6

Table 9. *FV* as a function of the negative value of *r* and land *PV* in South Africa (Scenario 2).

N **(Year)**	***PV*** **(USD)**	***Negative r*** **(Dimensionless)**	***FV*** **(USD)**
1	823	−0.069	766.2
2	823	−0.069	713.3
5	823	−0.069	575.6
10	823	−0.069	402.6
15	823	−0.069	281.6
25	823	−0.069	137.8

Calculations of *FV* for a single VIP, along with results in Tables 8 and 9, indicate that a well-maintained VIP can result in the production of value with time *n*. This will practically mean that if the maintenance is done than the VIP can continue to function as a sanitation technology and the buy-in from end-users of it is likely to increase in the VIP as an appropriate sanitation technology, which ensures the hygiene of the VIP end-users. A lack of investment or maintenance, by ignoring the annual costs of VIP maintenance, could result in the deterioration of the condition of the VIP in question. This would then likely lead to the creation of a 'legacy pit' and the need to construct a new VIP. The buy-in of the end-users into such a new VIP would likely be minimal and the environmental contamination and public health burden from the 'legacy pit' would also cause cascading disaster risk management effects in the specific area in South Africa. The treatment of the faecal sludge will form a crucial part of the appropriate maintenance of the VIPs in South Africa. It will have to be a viable treatment option in conditions where the wastewater treatment plants might be dysfunctional. Pumping to extract the VIP sludge from the pits might be a problem, as the freshwater might not be available in the necessary volumes to allow for efficient extraction from the VIP pit. At the same time, it would be ethically problematic as activities such as food production in South Africa might be compromised. Ethical challenges could also arise from the need to divert water in a drought-stricken area in South Africa from fulfilling ecological functions that the freshwater plays, e.g., from providing a river habitat for freshwater organisms.

At the same time, the intestinal parasites must be inactivated before the VIP faecal sludge can be extracted from the pits (by manual excavation) to protect the sanitation workers doing the excavation [39]. The rates of helminth contamination in the sanitation workers after VIP excavation have been shown to be low, but the infectious dose for these pathogens is lower than for bacteria and viruses [50], and could be as low as a single ovum. At the same time, it is difficult to provide a prediction about the urban growth and thus to predict the demand for sanitation services in South Africa, as the population becomes more and more urban and existing settlements often grow in an unplanned manner. Based on these considerations, the maximum *D* value in South Africa could be extended to 4.858 m, in other words the depth of the standard VIP pits should be increased to maximize the volume of a single VIP pit. The national government should mandate that bottom of the pits be lined, and the conversion of the VIP pit into a vault (a sealed receptacle space for the urine and faecal sludge from sanitation) should be investigated. The design of such VIPs could resemble in principle a urine-diversion toilet and cheap and recyclable yet mechanically impermeable material should be investigated for this purpose to build the vault walls from.

The minimum standard of compliance in the building of the VIP vaults must be set by the national government and complied with by the local/district municipalities. In this way, the *Res*, *Exp*, *Vul*, and *Prep* can be optimised [10,11], and this could be done in the field of sanitation in South Africa [36]. A good balance could be struck between the costs of emptying and the availability of sustainable/hygienic sanitation to the urban populations in informal settlements. However, if resources are limited then the treatment in situ and the options to carry out under diverse and unpredictable conditions in South Africa should be considered. Some treatment strategies for this purpose are suggested in Section 3.4 (see below). Practical implications, links to climate change, the novel *Ri* management strategies, and the research questions to be answered are discussed below. In terms of pending or ongoing climate change, the energy footprint of the treatment of the VIP sludge should be minimized and done in a sustainable fashion. If possible, it would be desirable to exploit positively the principles of circular economy.

To decrease the cost of treatment, to allow the investment of interest of annual maintenance costs in the VIP, to prevent the development of 'legacy pits', and to facilitate an increase in the sense of ownership of the sanitation facilities in urban settlements by their end-users, the VIP treatment should be performed at the source and as soon after production of the sanitation wastes as possible. If the end-users of the VIPs as sanitation facilities are not interested in participating in the treatment or the biosafety considerations prevent this (see Section 3.4 for details), then the treatment must be carried out by properly trained sanitation workers with the relevant personal protective equipment. The optimum *D* values and the design of VIPs must guarantee separation between the VIP user and the excrements. However, *D* should be low enough to facilitate quick, complete, and cost-effective VIP maintenance.

Several *Haz* and R_i aspects with relation to sanitation in South Africa remain unknown at the moment. As mentioned already above, the intestinal parasites must be inactivated before the VIP contents are extracted from the pits (by excavation) [22,39]. Some of the standard and currently in use in situ treatments do not allow for the removal of the helminth threat [51], i.e., new strategies are needed to manage the VIP waste. At the same time, some reports of the evolution of pollutants such as indole from the VIP latrines require urgent attention [29], as the particular *Vul* and *Exp* values are unknown and need to be quantified in South Africa as soon as possible. Rather, it indicates that the dose and concentration of the evolved indole should be estimated or measured under field conditions in South Africa, and this is necessary in order to fully understand the R_i/*Haz* related to a common sanitation technology in South Africa. Therefore, to continue the discussion in the current study, the principles and current knowledge about the stabilisation of the VIP faecal sludge are reviewed and analysed in the next section. The advantages and drawbacks of the treatment methods are outlined and analysed as well. Then, a novel pit latrine additive for ex situ and in situ treatments, to protect public health and to prevent environmental pollution/contamination from VIPs, is proposed based on the reuse of coal-fly ash and its modification using alkaline hydrothermal treatment. The energy, financial, and drought considerations from this section are also taken into account in the next section of the current study.

3.4. Microorganisms and Strategies to Manage Ri Related to the VIP Sanitation in South Africa

Ri and its management will depend on the VIP wastes treatment (at the point of production) and factors controlling the pathogen die-off inside the pit. Therefore, the current knowledge on the VIP sludge stabilisation inside the pit and the fundamental scientific processes involved are discussed first. The top few centimeters of the pit content should be aerobic from the air supply via the ventilation pipe. The resulting supply of O_2 should facilitate rapid conversion of the nutrients and organic matter by microorganisms in the top layer of the pit content [52]. The nutrients would be utilized for the synthesis of biological macromolecules and breakdown products, which have been linked to biological stabilisation of faecal sludge. Most of the pit content at lower depths is presumed to be anaerobic and stratified, with the properties of the pit content varying significantly as a function of *D* [21,53]. If anaerobic biological processes do take place in the pit, then the stabilisation rates will depend on the pit contents' residence time, the oxygen concentration, the moisture content, the pH, and the temperature [52,54]. Stabilisation is the conversion of the nutrient and organic matter of the pit contents into the less biodegradable compounds.

With respect to the pit moisture content, the recommended interval is from 50 to 60% (*w*/*w* pit contents) [55,56]. In South Africa, some data indicate that the average pit moisture content ranges from 58 to 82% (*w*/*w*) [21,55] and up to 95% [47,55,57], i.e., that is partially outside of the recommended interval for moisture content of the VIP faecal sludge/pit content. If there is no water perturbation into the pit from the soil or the groundwater, the moisture content decreases significantly with an increasing *D* down to 0.5 m and becomes constant at 1.5 m [21]. The increased water content could be the result of greywater disposal in the pit or seepage of stormwater into the VIP pit. This is often the result of the lack of greywater and stormwater management infrastructure in informal urban settlements in South Africa [42]. An increased moisture content and stratification of the pit content will decrease the mass transfer rates for oxygen and biodegraded materials. Therefore, biological stabilisation of the VIP pit contents might also not take place under optimum and/or homogenous conditions. However, an increased water content might stimulate the rates of hydrolysis. An increased moisture content might also be one of the explanations for the extended survival of the helminth infectious particles.

Buckley et al. [53] formulated a general theory of the VIP pit sludge stabilisation, where, in line with other authors, they stated that anaerobic digestion is the primary sludge stabilisation process [19,20,58]. During this process, cellulose and other biopolymers can be hydrolysed into monosaccharides, which are then converted into volatile fatty acids [20,59]. Cellulose will originate from the toilet paper or newspapers used in anal cleansing and discarded into the VIP pit [59]. The majority of the VIP pit content should then be biodegraded during stabilisation, as the organic matter/material in the pit is biodegradable [53]. These processes liquefy the semi-solid pit contents in the VIPs [60], which can lead to the production of leachate. If the pit is unlined and/or the water table reaches it, the contamination of the groundwater or underlying soil environments can take place with the leachate [20,53]. Such leachate can be expected to contain infectious particles of helminths and pathogenic bacteria (see Section 3.1 for details). The final products of anaerobic digestion after further biodegradation and conversion of the volatile fatty acid are CO_2, H_2S, and CH_4 [61].

The microflora and microbial species present in the pit will determine the rate of sludge stabilisation and other partial processes involved in it. The majority of the microorganisms present in the pit sludge, and also the majority of the microflora active during the faecal sludge stabilisation, will originate from the human excrements, and to a smaller extent from the ambient environment. From this point of view, the focus on anaerobic digestion is justified to a certain extent, as the strict anaerobes outnumber the facultative anaerobes by 15 to 1 and the aerobes by 34 to 1 in human faeces [62]. The individual species of bacteria that are excreted in the faeces, along with the pH, temperature, and other environmental variables will determine the rates of anaerobic digestion. As a result, the dominant species that have been found in human faeces and gut are outlined below.

With adult faeces, the following bacterial species have been isolated [63]: *Lactobacillus acidophilus*, *Lactobacillus crispatus*, *Lactobacillus delbrueckii* (ssp. *Bulgaricus* and ssp. *Lactis*), *Lactobacillus fermentum*, *Lactobacillus gasseri*, *Lactobacillus jensenii*, *Lactobacillus paracasei* (ssp. *Paracasei* and ssp. *Tolerans*), *Lactobacillus plantarum*, *Lactobacillus reuteri*, *Lactobacillus rhamnosus*, and *Lactobacillus salivarius* (ssp. *salicinius* and ssp. *salivarius*). In the faeces of newborns, the isolated bacterial strains included *Lactobacillus paracasei*, *Lactobacillus delbrueckii* spp., and *Lactobacillus acidophilus* [64]. The concentrations of *Lactobacillus* spp. could decrease if those cells become overgrown by Bacteroides spp., *Prevotella* spp., and *Faecalibacterium prausnitzii* under certain conditions, which are relevant to the discussion here [65]. In paediatric patients, the faecal microflora becomes enriched in *Clostridium* spp. and *Bifidobacterium* spp. during constipation [66]. Data on the microbial composition of infant and newborn faeces is important for the sludge stabilisation in the pit if the diapers from infants/newborns are disposed of in the pit. The disposal of diapers in the VIP pit latrines is not encouraged because it increases the mass of the contents of the pit latrines and also causes problems with clogging during emptying with the vacuum truck/honey suckers, thus increasing the maintenance cause while contributing to service delivery backlogs. However, some anecdotal evidence from the Eastern Cape Province, collected by authors during field observations, indicates that it does sometimes take place. The results of the terminal-fragmentation pattern PCR analysis of the gut microflora in humans and various animals showed that dominant species are [67]: Eubacterium biforme, Eubacterium limosum, Peptostreptococcus productus, *Lactobacillus acidophilus*, Bacteroides thetaiotaomicron, *Bacteroides vulgatus*, *Bacteroides distasonis*, *Clostridium clostridiiforme*, *Clostridium leptum*, *Clostrudium perfringens*, and *Escherichia coli*.

The activity of the bacterial species mentioned in the previous paragraph will depend on the substrates available for biodegradation or as sources of carbon and energy, i.e., the composition of the VIP pit sludge. Members of *Bacteroides* spp. and *Bifidobacterium* spp. have been shown to produce inducible intracellular enzymes that degrade various polysaccharides [68]. If strains of *Lactobacillus* spp. are present in the microflora of the biological wastewater treatment facilities, they enhance the efficiency of the anaerobic digestion of sewage, even at high hydraulic loading rates [69]. The consumption of prebiotics in the human diet, such as xylose and soya, can make bifidobacteria the dominant bacteria in human faeces [70], possibly due to the expression and synthesis of inducible enzymes. Some recent reports indicate that most of the dietary prebiotics are fructans and galactans [71], which are digested anaerobically in the human large intestine, resulting in the production of volatile fatty acids [71]. Lignin and cellulose have been detected in the faeces of humans if cereal is consumed in the diet [72], while results of in vitro studies indicate the production of oligosaccharides (in feces) after the enzymatic hydrolysis of agarose [73]. The chemical and microbial composition of the faeces will be dictated, at least in part, by the diet of the VIP users. This in turn will have a strong influence on the composition of the VIP pit inoculum, the organic matter present in the faecal sludge, and indirectly this will govern the rates of the VIP faecal sludge in situ stabilisation.

The dynamics of the faecal microflora is dependent on the covalent structure of polysaccharides that are available for biodegradation in the immediate environment of the microbes [74]. At the same time, multiple anaerobic digestion experiments have shown that the production of volatile fatty acids is maximised if the hydraulic retention times of digested material is around 27 h [74]. The supply of the substrate, i.e., the faecal sludge, into the VIP pit is semi-continuous and occurs during defecation or through other uses of the VIP. Under such conditions, and if the faecal sludge retention time were in the range of 8–16 days, then the concentrations of bacteria producing cellulases, xylanases, pectinases, proteases, and lipases would increase to up to 40 days of digestion [75]. After this peak, their concentrations decline steadily [75]. This will be the case if the following bacterial species were present inside the pit [75]: *Bacteroides* spp., *Eubacteria* spp., *Fusobacteria* spp., *Lactobacillus* spp., *Propionibacterium* spp., and *Selenomonas* spp.

The results of the 16S rRNA genetic analysis showed that human faeces contain 5.4×10^{10} cells/1 g dry weight of *Bacteroides spp.* and 7.2×10^{10} cells/1 g dry weight of the *Clostridium coccoides*–*Eubacterium rectale* group [76]. In the same study, the combined concentrations of *Clostridium histolyticum*, *Clostridium lituseburense* and the *Streptococcus-Lactococcus* group were inside the interval spanning from 1×10^7 to 7×10^8 cells/1 g dry weight of faeces [76]. The sensitivity and reproducibility of the genetic analysis, based on the 16S rRNA gene sequencing, can be significantly improved for human faecal samples in combination with the FISH-protein microscopy [77]. Bacteria have been reported to account for 49.5% of all uncultured viral sequences from human faeces, which were accounted for by bacteria/bacterial viruses (see Figure 2 in reference [78]).

Madikizela [79] studied the VIP pit sludge chemical and microbiological composition from the Hlalani Township in Makhanda in the Eastern Cape Province of South Africa. The author also attempted to investigate the potential reuse of the VIP faecal sludge as a fertiliser and/or a co-feed in anaerobic digestion [79]. There was some success in recovering biogas from the anaerobic digestion and it was combusted to be used for pasteurisation of the effluent from the anaerobic digester [79]. Metagenomic analyses of the composition of the microbial community from the VIP faecal sludge were performed by Madikizela as a function of depth in the pit [79]. Anaerobic bacteria from the family *Clostridiaceae* were among the most abundant microorganisms, along with microbes that are involved in nitrogen fixation, denitrification, and iron/sulphate reduction [79]. The potential for the presence of human pathogens with low infectious doses and a high threat to public health, were indicated by the detection of genetic material from the families *Mycobacteriaceae*, *Staphylococcaceae*, *Leptospiracea*, *Listeriaceae*, and *Brucellaceae* [79].

The results of the metagenomic analysis by Madikizela indicate that there is a need to stabilise the VIP faecal sludge before it can be manipulated or extracted from the VIP pit. The sterilisation of 300 g of the VIP faecal sludge pasteurised was achieved by a combination of 285 litres of biogas (generated in anaerobic digestion of 33–66% of faecal sludge and a balance of pasteurised effluent form anaerobic digestion) and 365 litres of LPG gas [79]. Sterilisation was achieved at 70 ± 2 °C after a sixty-minute treatment [79]. The treatment by Madikizela indicates that the extraction of the VIP faecal sludge from the pit is necessary to de-activate some of the pathogens such as *E. coli*. Some studies in the literature have indicated that retention times of the faecal sludge in the VIP pit are in the range of 8–16 days, then the concentration of methanogens increased as well inside the VIP pit [75]. If methanogenesis is occurring on the order of days, then this could provide a possible explanation for the lack of observed stabilisation of the VIP pit sludge in South Africa. If the retention times of the VIP pit contents, which is on the order of month or years (see Section 3.1 for details), is indicated by the frequency of emptying of the VIP faecal sludge or a lack thereof. Another reason for the lack of sludge stabilisation is that the mass transfer rates are extremely low in the stratified VIP contents, resulting in low rates or the complete inhibition of acidogenesis and methanogenesis. If acidogenesis and methanogenesis do not proceed at sufficient rates, then the entire anaerobic digestion process becomes inhibited. This leads to a lack of VIP sludge and contents stabilisation.

Hawkins and O'Doherty [80] stated that the human microbiome is not stable with time and the bacterial species in it can vary with time. More recently, the variability in the composition of a human microbiome is stronger in the gastro-intestinal tract of a single individual and not between the GITs of different patients, with the faeces moisture content being the most important determining factor of microbial speciation [81]. Bourquin et al. [82] studied the removal of plant material consisting of pectin, hemicelluloses, and cellulose under mixed aerobic and anaerobic conditions. As a function of source, the dry matter was fastest eliminated during the fermentation of carrot (63.7%) and lowest for cucumber (49.4%). Monosaccharides and their acids, namely arabinose, galactose, glucose, mannose, xylose, and uronic acids, were eliminated to 4 to 46% of the original concentrations within 24 h [82]. The volatile fatty acids were produced at the rate of 10.5 mmol per gram dry matter fermented, with acetic acid accounting for 74% of all volatile fatty acids produced [82]. The water retention capacity of faeces was constant and independent of metabolised vegetable fibre, with the actual values equal to 2.04 g of water per gram of substrate dry matter [82]. This water retention capacity is probably caused by the presence of arabinoxylans in the structure of dietary fibres [83]. The type of fibre used can be used to modify the bacterial species composition inside the gut and indirectly in the faeces, as provided by the data of Wang et al. [84].

During the anaerobic digestion of wastewater from pig processing, acidogenesis occurred due to the activity of *Lactobacillus delbrueckii*, while *Clostridium ultunense* and *Clostridium kluyveri* were the main methanogenes [85]. Adegunloye and Oladejo [86] tested the effect of the addition of beans husks, cassava peels, and tissue from plantains and yams on the anaerobic stabilisation of pig faeces. In these mixtures, the total bacterial concentrations ranged from 1.5×10^{11} to 3.5×10^{11} CFUs/mL, while the concentrations of fungi varied between 0.8×10^{11} and 1.4×10^{11} CFUs/mL [86]. The fermented material contained the following bacterial species: *Clostridium tyrobutyricum*, *Escherichia coli*, *Klebsiella pneumoniae*, *Proteus morganii*, *Clostridium sphenoides*, *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus laterospores*, *Micrococcus roseus*, *Leuconostoc mesentenroides*, *Acetobacter orleanensis*, *Methanobacillus spp.*, *Flavobacterium ferrugineum*, *Enterobacter aerogenes*, *Streptococcus pyogenes*, and *Lactobacillus leichmannii* [86]. Fungal species in the stabilised faeces/plant mixture included *Mucor mucedo*, *Rhizopus nigricans*, *Aspergillus flavus*, *Aspergillus niger*, *Cladosporum* spp., and *Saccharomyces cerevisiae* [86]. The process pH ranged from 5.20 to 7.10, while the process temperature varied between 26 °C and 34 °C [86]. Methane accounted for 70.6% of the biogas volume produced [86].

The literature data above indicate that bacterial species found in human faeces/the gastro-intestinal tract can catalyse several steps of anaerobic digestion. *Lactobacillus* spp. and other relevant bacterial species are the most biologically active under acidic, neutral, or mildly alkaline pH values. These bacteria could theoretically contribute to the in situ anaerobic digestion of the pit contents. This conclusion is supported by the published pH of human faeces that has been reported to be around 7.5 [87], which is likely to resemble the pH values inside the pits. The rates of biodegradation, i.e., the pit content stabilisation, can be measured using the chemical oxygen demand of the faecal sludge/pit content (COD) and the volatile suspended solids content in solids isolated from the pit sludge (VSS) [21]. The dependence of both parameters on *D* was analogical to the trend observed for moisture content (see above and in reference [21]). The biodegradability of the faecal sludge material decreased with increasing the *D* values from 62% to around 19% [21]. It has to be said here, however, that this conclusion is based on limited data. Therefore, the data above indicate that many challenges exist in achieving an effective on-site treatment and stabilisation of the sanitation wastes inside the VIPs. An enhancement of the efficiency through the use of sanitation pit additives has been suggested as a possible solution.

Based on the discussion above, the significance of anaerobic digestion inside the pits is, however, likely going to be limited due to the following factors. The mass transfer rates will be significantly lower in the stratified VIP pit than in a continuously mixed anaerobic digester that much of the literature data on anaerobic degradation of organic matter is based on. As a result, steps of anaerobic digestion such as acidogenesis and methanogenesis will take place at very low rates. This in turn can substantially limit the stabilisation of the VIP sludge. The hydraulic residence times of the sludge in the pit might also pose problems for effective anaerobic digestion of the pit contents as they are on the order of years and not the effective values of days.

3.5. Further Potential Problems with Microbial Stabilisation of the VIP Faecal Sludge as a Strategy to Manage Ri Related to the VIP Sanitation in South Africa

It has been suggested by some authors that the efficiency of faecal sludge stabilisation inside the pits can be increased by the inoculation of the pit with soil particles or leaves [19,88]. On the other hand, some anaerobic material from the bottom of the pit should be left in place during the VIP emptying to provide inoculum for biodegradation and stabilisation of future material that will enter the VIP pit [89]. Soil bacteria/microorganisms are the most active in the surface soil horizons, i.e., the highest concentrations of microorganisms can be found in the depth between 0 and 30 cm under the soil surface in a particular soil profile. This type of inoculation could be possible under the following conditions: if the concrete VIP foundation/slab only enters the surface horizons of the soil in which a VIP is sunk into, and the walls of the VIP pit are generally permeable with the VIP bottom unlined, then the VIP superstructure/cabin structure only sits on the concrete slab and/or on top of the soil and some wooden beams [90,91]. Under these conditions, the soil particles from the surface horizons that contain the highest concentrations of microorganisms can enter the pit and inoculate its content. This has been observed by authors during field sampling of the pit contents in the Eastern Cape Province of South Africa (unpublished data).

However, an acclimation period would have to be expected, so that the soil microorganisms could adapt to the new organic materials from the VIP faecal sludge as a source of energy. In addition, soil bacteria from the 0–30 cm soil horizons are mostly aerobic in nature and any stabilisation of the VIP faecal sludge by such soil inoculation would be negligible. It is doubtful that these bacteria would adapt quickly enough to the biodegradation of the faecal matter inside the VIP pit to have any significant influence on the rate of the pit contents stabilisation. Leaves could be used as an additive into the pit. However, they would most likely function as a source of carbon that would stimulate growth of the in situ anaerobic bacteria rather than as an active inoculum as most of the bacteria in the soil litter are again aerobic in nature. If the VIP is built as a vault and the bottom of the pit is lined, then inoculation of the pit from the soil horizons with active microflora is impossible.

If the VIP is built by sinking side walls into the ground, the surface soil horizon is covered with the walls in the top part of the VIP, and the VIP pit is unlined at the bottom, then soil bacteria will only be able to enter the VIP pit contents through capillary rise of soil moisture through the vadose zone into the pit, or by rising groundwater and flooding of the pit. In the latter case, the soil bacteria could be brought into contact with the pit contents. However, only limited numbers of the soil bacteria would inoculate the pit, as the flooding would occur from soil horizons with a low microbial activity. As discussed in the previous section, perturbation of water into the VIP pit could result in the mobilization of the pit contents and this would in turn lead to environmental contamination and public health issues. This scenario is also undesirable as the entry of groundwater into the pit would compromise one of the main goals of building a VIP, i.e., to prevent groundwater contamination with the pit contents [32] and to separate the VIP users from the pit contents [88]. The stratification of the pit contents will limit any mass transfer inside it. Therefore, the transport of microorganisms (inoculation) and chemical components will thus be limited between the individual strata of the pit contents. This would further limit the ability of any soil and aerobic bacteria to adapt to the biodegradation of the pit contents.

If the VIP foundation is missing and the side walls of the VIP are not properly constructed or missing completely, then the VIP as a sanitation facility can collapse all together. Under these conditions, the efficiency of soil inoculum is also in doubt and the health of the VIP users could be put at risk as they could physically fall into the pit. In this way, the VIP ceases to be a hygienic barrier and the users of the VIP can be exposed to the pathogenic microorganisms from the pit contents again. Therefore, the efficiency of soil particles as the VIP pit inoculum does not seem practically advisable or very efficient. The lack of properly constructed sanitation facilities has been reported in South Africa. Calculation results from Section 3.1 can be used as basis for the establishment of more rigorous guidelines on the faecal sludge management. This should be done together by evaluating the soil types on-site and the transport of faecal microorganisms in them.

The conditions inside the pits will be conducive for anaerobic digestion based on the likely pH values and the presence of the bacterial species from human faeces that can biodegrade the pit contents and are the dominant microbial components of it. However, the environmental temperatures inside the pit can be expected to fluctuate significantly throughout the year and between the day and the nighttime. This will have a strong effect on the activity and survival of the bacteria of species such as *Lactobacillus* spp., which are highly sensitive to the shifts in environmental conditions and can only survive outside the human host's body for limited periods of time. The efficiency of the faecal species in the anaerobic stabilisation of the pit contents is questionable. Some authors have advocated that the natural attenuation-type processes, i.e., the stabilisation of the pit contents without any outside interference, is the best treatment option [53]. This is again likely to be unfeasible as both anaerobic digestion and natural attenuation are problematic as they do not seem to stabilise the pit contents even after 5 years or more [19]. However, their efficacy is questionable as viable helminth ova have been isolated from the clothing or faecal/tissue samples of the sanitation workers during the manual emptying of VIPs in South Africa [39], when the residence time of the sludge inside the pits was around 15 years [22]. One of the explanations could be that the moisture content remains above the 5% threshold (w/w) required for the helminth ova inactivation [51]. At the same time, the data from studies, such as that by Madikizela [79], indicate that the extraction of the VIP faecal sludge is necessary and the ex situ treatment would be needed to stabilise the faecal sludge.

3.6. Use of Novel Pit Additive to Manage Ri Related to the VIP Sanitation in South Africa

Harsher conditions must be created inside the VIP pits to facilitate the removal of these and other infectious particles. This could be done by using VIP pit latrine additives. The addition of 3–11% of lime has, however, shown that inactivation can take up to months inside faecal material [92]. In situ treatment could still be achieved, and the relevant *Ri* effectively managed using different additives, such as fly ash. In 2019, Collings et al. reported on the application of the untreated fly ash in the elimination of 92% of the initial concentration of faecal coliforms from the synthetic faecal material under the ambient conditions and within 3 weeks of incubation at ambient temperatures [93]. Modification of the coal fly with sodium hydroxide resulted in the production of an additive that has been shown to decrease the concentration of faecal coliforms below 545 colony-forming units per gram of synthetic faecal sludge [94]. The period of stabilisation ranged from 2 to 6 weeks based on the pit additive used. Six weeks was achieved as a stabilisation period for an additive of 120 g of fly ash into 200 g of synthetic faeces material, while the period stabilisation was shortened to 2 weeks, if 50 g of lime was added to the fly ash [94]. The use of such additives would be possible to apply even if the moisture content of the pit sludge reaches 80%, as the coal-fly ash has been shown to sterilize the greywater in a modified mulch tower-type reactor [95]. This could be applicable to South Africa, where the limited data indicate that the average pit moisture content ranges from 58 to 82% (w/w) [21,55] and up to 95% [47,55,57]. This is based on the comparison with data of Jensen et al. [92] and the fact that harsher conditions have been achieved, where the inactivation of helminth ova should be possible. Fly ash should thus be studied as a potential VIP additive for on-site treatment of the sanitation wastes derived from the VIPs.

Fly ash is a waste product from the combustion of coal [96]. It is the combustion residue that can be recovered from the separators between furnaces and their smokestacks and have a particle size ranging from 0–1 mm [96] (p. 9). This by-product of coal-burning is a heterogeneous ferro-aluminosilicate material, with "amorphous, crystalline and powder phases" [97]. Globally, around 10% of the fly ash produced annually is recycled [98,99]. The main use is in the production of lightweight construction materials [98,99]. This immobilizes the potential environmental contaminants inside of fly ash and renders it environmentally harmless [96] (p. 9). Other main uses of fly ash include heat insulation and the filling of empty spent cast mines [96] (p. 9). Concerns have been raised about the storage of fly ashes in landfills [96] and ash ponds [97]. This is due to the release of leachates with heavy metals such as hexavalent chromium [100], which can contaminate groundwater [97]. Thus, a large majority of the impounded fly ash ends up posing environmental management problems and novel applications are required to resolve this problem.

The recycling of fly ash is of particular interest in South Africa as 77% of the total energy production originated from the combustion of coal in 2012 [101]. The inorganic fraction of fly ash has been reported to contain the following minerals ([96] page 11-Table 1): kaolinite, halloysite, illite, montmorillonite, pyrite, marcasite, pyrrhotine, halite, sylvite, quartz, gypsum, orthoclase, biotite, diaspore, kyanite, calcite, dolomite, ankerite, siderite, and apatite. At the elemental level, the majority of the mass is accounted for by atoms of aluminum, potassium, silicon, calcium, iron, manganese, sodium, sulphur, and magnesium ([96] page 11-Table 1). The addition of fly ash to the pit and mixing with the VIP sludge is likely to facilitate the in situ removal of (pathogenic) microorganisms and the phosphate ions by precipitation with Ca^{2+} and Mg^{2+} cations [98]. The chemical composition and the source of fly ash can lead to the presence of potential environmental pollutants, such as heavy metals. Therefore, leachability and mobilization tests for Cr^{6+}, Hg, Tl, and As ([96] page 29-Table 8) have to be conducted for fly ash in contact with faecal sludge, greywater, and storm water before standardization of any in situ treatment onsite [102]. However, recent data indicate that fly ash addition to sewage sludge indicated that the percentage of the Cr, which was extractable with a HF/HNO_3 mixture or otherwise the least mobile portion of the metal in the fly-ash-sludge mixture, increased by 41.85% of the total Cr content at the beginning of the experiment to 67.28% of the total Cr^{6+} content after 28 days of incubation (see data for dosage rate of 1.0 kg/kg dm in Tables 4–6 in reference [103]). Further information about the chemical composition of fly ash and related (sanitation) considerations are presented in references [104–111], and further discussed in the Supplementary Information. Similar observations were made for the metals such as lead, nickel, and cadmium. These findings indicate that mixing fly ash into the VIP faecal sludge would, over the treatment periods suggested by Madikizela et al. [94], lead to a limited mobility of heavy metals from fly ash into the surrounding faecal sludge or that soil/groundwater could be limited. This indicates that the fly ash treatment could pose a viable option to treat the VIP faecal sludge.

This is further supported by the findings of Collings et al., who reported that there were no detectable and culturable bacteria on the fly ash from South Africa [93]. This, along with the pH values between 10 and above in the synthetic faecal sludge after fly ash addition [90], indicated the antimicrobial activity of the coal-fly ash. There have been recent reports that indicated that the addition of bleach to aqueous environments does result in the inactivation of the *Ascaris* spp. *ova* (for example see [39]). This could be applicable under the VIP pit conditions, but the efficacy of the bleach-based additives could be impaired by the reaction of the faecal organic matter with the bleach, the depletion of the HClO molecules, and the prevention of the helminth ova inactivation. Therefore, the addition of coal-fly ash would provide a contact surface that can inactivate (pathogenic) microorganisms on fly ash surfaces. At the same time, the inactivation of the helminth ova and antibacterial/sterilisation of the bacteria present in the VIP pit sludge might be possible due to a highly alkaline pH after the coal-fly ash had been added. Sorption sites on the surface of the coal-fly ash will also provide a possible removal mechanism.

Pretreatment of the coal-fly ash with alkali under elevated temperatures could make the surfaces of the fly ash particle more prone to function as sorption uptake sites and sites of precipitation [94,103]. Therefore, to investigate the chemical composition of the coal-fly ash from South Africa before and after alkaline hydrothermal treatment, the coal-fly ash of Madikizela et al. was examined [94]. More Information can be found in the Supplementary information. The coal-fly ash modified by alkaline hydrothermal treatment could be used to develop a new antimicrobial and anti-pathogenic additive for the VIP faecal sludge management. This could be used in situ or after transport to a functional wastewater treatment plant. The administration or dosing of the modified flay ash could be done on-site by the end-users of the VIPs after a defecation, but a more practical solution would be to dose the modified fly ash into the VIP pits by trained sanitation workers. Such workers should be equipped with the necessary personal protective equipment, which should allow for the protection against the VIP faecal sludge as an infectious material.

Metagenomics data of Madikizela indicate that a spot sample of faecal sludge from a VIP in the Makana Local Municipality in South Africa contained DNA from bacterial families of *Mycobacteriaceae*, *Staphylococcaceae*, *Leptospiracea*, *Listeriaceae,* and *Brucellaceae* [79]. However, the VIPs used in South Africa and the presence of genetic material from those bacterial does not necessarily mean that live bacteria could cause brucellosis or tuberculosis for the end-users of VIPs as a sanitation technology, or the sanitation workers who maintain the VIPs. Rather that metagenomics data should be seen as an indication that a disaster *Haz* exists from the possibility of the human contact with the VIP faecal sludge that might contain such bacterial families. However, if the VIP as a sanitation technology is properly maintained then the sanitation R_i for the VIP end-users and for sanitation workers would be partially unknown, but most likely low for end-users of the VIP and medium in the case of sanitation workers. This would be the case if the maintenance of the VIPs resulted in an adequate separation between the respective humans and the VIP faecal sludge. This would require personal protective equipment, which is equivalent to working with the microbiological laboratory with biosafety level 2 (see page 24 in reference [112]). The mixing of the modified fly ash into the bulk of the VIP faecal sludge would have to be accomplished for adequate treatment [93,94].

3.7. Other Novel and Potential Strategies to Manage Ri Related to the VIP Sanitation in South Africa

Besides the proposed use of the modified coal-fly ash as a pit latrine additive, other treatment options have been proposed for the VIP faecal sludge. The stabilisation of the in situ or ex situ VIP faecal sludge treatment has been suggested to be related to the moisture content of the VIP sludge. Getahun et al. [57] studied the drying characteristics of various sanitation wastes, including the VIP faecal sludge from South Africa. The authors reported that the moisture content was equal to 95% and the drying time (see Table 1 in reference [57]), i.e., the time after which the weight of dried VIP faecal sludge material did not change by more the 1 mg/min, ranged from 10 to 80 min [57]. The drying time was inversely proportional to the temperature between 50 and 200 °C [57]. The (specific) drying heat ranged from 2.6 ± 0.2 MJ/kg of evaporated water to 4.3 ± 0.9 MJ/kg of evaporated water, as the drying temperature increased from 50 to 200 °C (see Figure 4 in reference [57]). The authors did not report statistical testing on whether the (specific) drying heats were significantly different with the different drying temperatures.The statistical testing and drying energy requirements are calculated as shown in Supplementary Information, more specifically in Equations (S4)–(S6) and some information was also extracted from additional literature sources [113].

The calculation results for drying as a stabilisation method for the VIP pit sludge are shown in Table 10 for 2 m^3 of the faecal sludge, and for 4.858 m^3 of faecal sludge they are summarised in Table 11. Therefore, the weight of 4.858 m^3 of the VIP faecal sludge ranged from 4858–10687.6 kg. The results of the calculations from Tables 10 and 11 indicate that the energy needed to dry and stabilise/inactivate 2 m^3 can be expected to range from 3.866 to 13.30 MW. At the same time, the energy needed to dry and stabilise/inactivate 4.858 m^3 can be expected to range from 9.390 to 33.85 MW. If 50,000 VIPs were to be fully extracted, then the total energy requirements for the stabilisation by H_2O would be equal to 193 GW. This is higher than the entire South African energy supply of around 58 GW [114]. These numbers indicate that the energy requirements of drying the faecal sludge might pose practical problems in the implementation, as South Africa has been suffering from loadshedding or planned power blackouts since 2008. However, the extraction of the VIP pit contents and the treatment of the resulting faecal sludge could be done on a limited local scale through drying. The coal-fly ash modification would require energy requirements in the hydrothermal treatment, and this could pose practical problems as well. However, unmodified fly ash could still be used as a pit latrine additive and stabilisation could be accomplished in the order of weeks [93,94]. The implementation of any successful VIP faecal sludge treatment will require a policy and end-user engagement. This is discussed in the final section of this article (see below).

Table 10. Drying characteristics for 2 m^3 of the VIP faecal sludge in South Africa.

Z	H_{spec}^{mean} (MJ/kg)	H_{spec}^{unit} (MJ/kg)	E (W/kg)	*Total E* (MW)
0.58	4.0 ± 0.3	2.32	1933	3.866–8.119
0.60	4.0 ± 0.3	2.40	2000	4.000–8.400
0.70	4.0 ± 0.3	2.80	2333	4.666–9.799
0.75	4.0 ± 0.3	3.00	2.500	5.000–10.50
0.80	4.0 ± 0.3	3.20	2667	5.334–11.20
0.95	4.0 ± 0.3	3.80	3167	6.334–13.30

Table 11. Drying characteristics for 4.858 m^3 of the VIP faecal sludge in South Africa.

Z	H_{spec}^{mean} (MJ/kg)	H_{spec}^{unit} (MJ/kg)	E (W/kg)	*Total E* (MW)
0.58	4.0 ± 0.3	2.32	1933	9.390–20.66
0.60	4.0 ± 0.3	2.40	2000	9.716–21.38
0.70	4.0 ± 0.3	2.80	2333	11.33–24.93
0.75	4.0 ± 0.3	3.00	2.500	12.15–26.72
0.80	4.0 ± 0.3	3.20	2667	12.96–28.50
0.95	4.0 ± 0.3	3.80	3167	15.39–33.85

4. Discussion

Service delivery shortfalls, including those related to sanitation in South Africa, often occur in urban and peri-urban areas, as indicated by the text of this study so far. The lack of sanitation service delivery can create situations where the resulting compromised hygiene of the South African population can intersect with other public health challenges, e.g., the high HIV/AIDS infection rates among the population [4]. If such an intersection occurs, then this can result in disaster compounding, as increased rates of HIV/AIDS require more stringent maintenance of sanitation facilities. At the same time, the demand and need for proper hygiene and adequate sanitation must be maintained even when the rates of HIV/AIDS are low and regardless of the type of settlement that people reside in. This can be in the general domain derived from the Constitution of South Africa Act no. 108 of 1996 and the Local Government: Municipal Systems Act no. 32 of 2000, which state that the service provision by a local government to its citizens must be made sustainably [115,116]. This is the case, as everyone in South Africa has the right to live in an environment that is safe and not detrimental to their health according to those pieces of legislation (as summarised in part in reference [40]). To maintain those rights of South African residents, local government must empty the faecal sludge from the VIP pits once these are full [1] or seal the VIP pit in an appropriate manner. Recent research, however, indicates that the necessary sanitation skills are or have until recently been scarce at the local government level in South Africa [1,117]. Sanitation provision has also been hindered by the lack of buy-in from the community and the end-users of the sanitation facilities [1,36,117]. In such situations, the local government's failing to fulfill its legislative obligations and the respective provincial administration should set in to improve the sanitation service delivery [115,116].

Calculations from Sections 3.1 and 3.3, namely Equation (S3) and the related data from Tables 8 and 9, indicate that the lack of investment of the annual maintenance fees into the installed VIPs leads to the development of 'legacy pits'. This in turn has potential negative public health and environmental health impacts in the area, where the VIP has become dilapidated, is installed, and might still be in use as an improved sanitation technology. If the annual investment of 56.5 USD per VIP is done, then the VIP grows in financial and sanitation value, increasing throughout the lifespan of any particular VIP. In this way, the buy-in from the end-users into accepting the VIP as an adequate sanitation technology is more likely. At the same time, the sanitation provision is more affordable and financially sustainable at the local government level in South Africa, as the building of new VIPs or sanitation facilities can be delayed. Finally, the sanitation *Haz* and R_i values in South Africa can be decreased. A combination of these routine maintenance, preparedness, and mitigation measures can help improve the sanitation resource management at the local government level, and they can facilitate in part the management of public health and environmental contamination from the dilapidated VIP pits. Those actions together could possibly contribute to the maintenance of the provision of sanitation services in local municipalities in South Africa.

With climate change and the ever-present uncertainty of the often-uncontrolled urban development in developing and middle-income countries, new approaches are needed to address the sanitation-related *Haz* and R_i in South Africa. From a disaster risk management point of view, flexible approaches are needed that are affordable and that are also integrated, i.e., they facilitate the multi-hazard management or mitigation strategies. Based on this and the previous section of the current study, more fundamental scientific research is needed into the management of the *Ri* and the other terms stated in Equation (1) and sanitation in South Africa. This would be in the context of the on-site and in situ treatment of the VIP faecal sludge, where this is possible, and with a focus on newly built VIPs and on the 'legacy pits'. The coal-fly ash, after alkaline hydrothermal treatment, could be dosed and mixed into the VIP pit contents as part of the routine maintenance. The best way to implement such a treatment strategy should be based on the optimised dosage rates for South African local conditions. The safety measures should be optimized for the potential use of the fly ash on-site, or its excavation and for treatment in an off-site (solid) waste management facility. The aim would be to ensure the maintenance of VIPs, ideally through active engagement and with the support of the end-users. If such approaches are implemented, the *Ri* values for South Africa will decrease. On the ground, this will mean a lowered probability of the outbreaks from infectious diseases related to sanitation.

A sufficient technical capacity, such as enough of the properly trained sanitation workers who are equipped with the appropriate level of personal protective equipment for the manual excavation of the VIP faecal sludge after stabilisation with fly ash in situ, must be ensured at the local government level. Alternatively, the sufficient number of honey-sucker vehicles should be available for the extraction of the raw VIP faecal sludge, but with a limited and necessary volume of freshwater added to facilitate extraction. This should be combined with training of the municipal officials and the end-users of the sanitation facilities on the correct and safe use of the novel pit latrines additives. However, the excavation or extraction of the VIP faecal sludge and the addition of fly ash off-site might be preferred, as the safety and environmental management considerations are more likely to be ensured. As the current study is mainly a combination of the literature review and meta-analyses/modelling based on literature data, the limitations of the current study will lie in the need to confirm the application of some of the proposed strategies under field conditions in South Africa. An example of this would be the need to confirm the dosage rates of fly ash and/or fly ash-lime from the study by Madikizela et al. [94], under field conditions or for the treatment of real faecal sludge from the VIP pits. However, these limitations do not detract from some of the crucial findings of the current study.

Fly ash and its application could be combined with the principles of Technology Assessment [118]. Technology Assessment has been defined as "A category of policy studies, intended to provide decision-makers with information about the possible impacts and consequences of a new technology or a significant change in an old technology. It is concerned with both direct and indirect or secondary consequences, both benefits and disadvantages, and with mapping the uncertainties involved in any government or private use or transfer of a technology. Technology Assessment provides decision-makers with an ordered set of analysed policy options, and an understanding of their implications for the economy, the environment and the social, political and legal processes and institutions of society" [118]. Technology Assessment must be linked to concurrent activities aimed at minimizing the sanitation *Ri* in South Africa. These activities include basic research into the application of modified coal-fly ash to minimize the *Ri* values and stabilisation/management of the VIP pit contents, and achieving buy-ins from VIP users/stakeholders for effective implementation in sanitation across South Africa.

Some problems with Technology Assessment have been identified by Ludwig [119], van Eijndhoven [120], and Assefa et al. [121]. Thus, a modification led to the recent movement towards Technology Assessment focusing primarily on environmental impacts, as is promoted by a UNEP program called the Environmental Technology Assessment [118]. The UNEP [118] defines the Environmental Technology Assessment as, "a process that can assist decision-makers in making informed choices that are compatible with sustainable development by examining and describing the environmental implications of new technologies". They further state that the Environmental Technology Assessment also provides information that allows public policy makers, NGOs, and the VIP end-users to be better informed about technology choice decisions. This system, however, does not take into consideration the main issues faced by a district/local municipality and there is limited consultation with stakeholders in developing such an assessment tool [120]. Using a combination of various approaches to ensure the provision of appropriate sanitation in South Africa and the protection of human and public health related to it, will facilitate the decrease in the R_i value related to sanitation in South Africa. This consultation must be executed as inclusively as possible to ensure complete transparency and understanding of the safety hazards related to VIPs, to the proposed treatment of the VIP faecal sludge based on the use of the modified coal-fly ash as a pit additive. It is critical that the implementation of the use of novel pit latrine additives in South Africa.

5. Conclusions

The current article provides an overview of the disaster risk management implications of the minimum standard/common form of urban sanitation in South Africa. The analysis of data from the literature, some experimental data, and results of model calculations indicate that novel approaches into the VIP waste management and faecal sludge stabilisation, with the potential involvement of the VIP end-users, should be performed on-site and in-situ where possible. The regular maintenance and investment of resources into the VIPs can help achieve successful strategies to obtain the buy-in from the VIP user community into the pit latrines as a viable and water-free, as well as effective, disaster risk management strategy in maintaining the population's hygiene in South Africa. The VIP faecal sludge treatment must be achieved as to decrease the pathogen concentrations, to immobilize the faecal sludge component, as to prevent the environmental pollution from the VIP pits. Novel pit latrine additives should be mixed into the VIP faecal sludge to achieve stabilisation of the VIP pit contents. This could be achieved by the mixing of the modified coal-fly ash that had undergone alkaline hydrothermal treatment. The use of fly ash, which contains clay minerals, is free of microbial contamination and increases the pH value of the VIP faecal sludge to alkaline values. In this way, pathogen die-off can be stimulated, which could result in the stabilisation of the VIP faecal sludge and decrease the leachability of the VIP pit contents/fly ash components, e.g., heavy metals. Instead of the primary process of the VIP faecal sludge stabilisation being anaerobic digestion, the mechanism would be a combination of disinfection upon contact with the fly ash, sorption/precipitation of the chemical and microbial components of the VIP faecal sludge onto the fly ash particles and their immobilisation. Alkaline hydrolysis might also play a role in the stabilisation of the VIP faecal sludge. The VIP faecal sludge should be excavated from the pit without the use of potable water or freshwater, followed by the faecal sludge transport to a landfill or waste management facility. The execution of the proposed strategies, for decreasing the sanitation-related R_i and *Haz*, can be achieved through approaches such as Technology Assessment, the Environmental Technology Assessment, and the Jemez principles of democratic organizing in South Africa. The main findings of the current study are that if properly maintained and built, ventilated improved pit latrines can provide a sanitation barrier to the potential spread of sanitation-related epidemics, as well as a user-friendly sanitation technology. The potential and safe application of fly ash in the treatment of faecal sludge from the VIP pits could provide a solution to the sanitation and environmental 'legacy challenges' in South Africa.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14116934/s1, Figure S1: FTIR spectra of unmodified coal-fly ash from South Africa as described by Madikizela et al. [94]. Figure S2: FTIR spectra of the modified coal-fly ash after alkaline hydrothermal treatment with 7 M NaOH, as described in more detail by Madikizela et al. [94].

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Abbreviations

D	Depth of the pit in the ventilated improved pit latrine
FR	Filling rate of the pit in the ventilated improved pit latrine
Exp	Disaster exposure
Haz	Disaster hazard
L	Length of the base of the pit in the ventilated improved pit latrine
$Prep$	Disaster preparedness
Res	Disaster resilience
Ri	Disaster risk
S_{base}	Area of the base of the VIP pit
VIP	Ventilated improved pit latrines
VV_{VIP}	Volume of the pit in the ventilated improved pit latrine
W	Width of the pit in the ventilated improved pit latrine
WASH	Water, sanitation, and hygiene

References

1. Hoossein, S.; Whittington-Jones, K.; Tandlich, R. Sanitation policy and prevention of environmental contamination in South Africa. *Environ. Eng. Manag. J.* **2014**, *13*, 1335–1340. [CrossRef]
2. Statistics South Africa. *General Household Survey 2013*; Statistical Release 0318; Statistics South Africa: Pretoria, South Africa, 2014. Available online: http://beta2.statssa.gov.za/publications/P0318/P03182013.pdf (accessed on 31 January 2022).
3. Hoossein, S. The Development of Sustainability Criteria to Facilitate the Selection of Sanitation Technologies within the Buffalo City Municipality (Eastern Cape Province, South Africa). Master's Thesis, Rhodes University, Makhanda, South Africa, 2009.
4. Luyt, C.D.; Muller, W.J.; Wilhelmi, B.S.; Tandlich, R. Health implications of flood disaster risk management in South Africa. In Proceedings of the 18th Annual Conference of the International Emergency Management of Society, Bucharest, Romania, 7–10 June 2011; pp. 376–385.
5. World Health Organisation. *Climate Change and Human Health—Risks and Responses*; Published Report; WHO Press: Geneva, Switzerland, 2003.
6. Taylor, J.; Lai, K.M.; Davies, M.; Clifton, D.; Ridley, I.; Biddulph, P. Flood management: Prediction of microbial contamination in large-scale floods in urban environments. *Environ. Int.* **2011**, *37*, 1019–1029. [CrossRef]
7. Hoffman, P. Access to Water Supply and Sanitation Services at the Low-Income Households in the Peri-Urban Interface of Developing Countries (Chapter 5). In *Urban Development Debates in the New Millennium: Studies in Revisited Theories and Redefined Practices*; Gupta, K.R., Ed.; Atlantic Publishers and Distributors: New Delhi, India, 2005. Available online: http://books.google.co.za/books?hl=sk&lr=&id=UgkI2rhcKKwC&oi=fnd&pg=PA58&dq=lack+of+urban+sanittion+leads+to+inferior+hygiene&ots=NPdqV721YC&sig=Ooj8Zr7LehIm53QiSiN8w8AQgDI#v=onepage&q&f=false (accessed on 31 January 2022).
8. Lamond, E.; Kinyanjui, J. OXFAM: Cholera Outbreak Guidelines: Preparedness, Prevention and Control. 2012. Available online: http://www.unicef.org/cholera/Annexes/Supporting_Resources/Annex_6B/OXFAM_Cholera_guidelines.pdf (accessed on 31 January 2022).
9. Kolstad, E.W.; Johansson, K.A. Uncertainties Associated with Quantifying Climate Change Impacts on Human Health: A Case Study for Diarrhea. *Environ. Health Perspect.* **2011**, *119*, 299–305. [CrossRef]
10. Tandlich, R.; Chirenda, T.G.; Srinivas, C.S. Gender aspects of disaster risk management in South Africa. *J. Disaster Risk Stud.* **2013**, *5*, 84. [CrossRef]
11. Tandlich, R.; Hoossein, S.; Whittington-Jones, K.; Moyo, F. Emerging Issues in Environmental Security and Disaster Risk Management in South Africa. In Proceedings of the 4th Virtual Scientific Conference on Scientific Reflection on New Trends in Management, Czech and Slovak National Police Academies, Prague, Czech Republic, 23 September 2013.
12. Ginsberg, G.M.; Berger, S.; Shouval, D. Cost-benefit analysis of the nationwide inoculation of programme against viral hepatitis B in an area of intermediate endemicity. *Bull. World Health Organ.* **1992**, *70*, 757–767.
13. United Nations Office for Disaster Risk Reduction. 2009 UNISDR Terminology on Disaster Risk Reduction. Available online: https://www.undrr.org/publication/2009-unisdr-terminology-disaster-risk-reduction (accessed on 31 January 2022).
14. National Disaster Risk Management Framework of South Africa. Available online: http://www.westerncape.gov.za/text/2013/July/sa-national-disaster-man-framework-2005.pdf (accessed on 12 August 2014).
15. Moagi, A. A Functional Explanation of Poverty: The Case Study of Informal Settlements in South Africa. In Proceedings of the "Towards Carnegie3: Strategies to Overcome Poverty & Inequality", Cape Town, South Africa, 3–7 September 2012.
16. Zuma, B.M.; Luyt, C.D.; Chirenda, T.G.; Tandlich, R. Flood Disaster Risk Management in South Africa: Legislative Framework and Current Challenges. In Proceedings of the 2012 International Conference on Applied Life Sciences (ICALS2012), Konya, Turkey, 10–12 September 2012; pp. 127–132.
17. South African Local Government Association. *Disaster Risk Management Status Assessment at Municipalities in South Africa*; South African Local Government Association: Pretoria, South Africa, 2011.
18. Woolard, C.D.; Strong, J.; Erasmus, C.R. Evaluation of the use of modified coal ash as a potential sorbent for organic waste streams. *Appl. Geochem.* **2002**, *17*, 1159–1164. [CrossRef]
19. Still, D.A. After the Pit Latrine is Full . . . What Then? Effective Options for Pit Latrine Management. In Proceedings of the WISA Biennial Conference, Durban, South Africa, 20 May 2002.
20. Mara, D. *The Design of Ventilated Improved Pit Latrines*; The World Bank and the United Nations Development Programme—TAG Technical Note No. 13, Interregional Project INT/81/047; The International Bank for Reconstruction and Development/The World Bank: Washington, DC, USA, 1984; Available online: http://www.pseau.org/outils/ouvrages/world_bank_the_design_of_ventilated_lmproved_pit_latrines_1984.pdf (accessed on 31 January 2022).
21. Bakare, B.F.; Foxon, K.M.; Brouckaert, C.J.; Buckley, C.A. Variation in VIP latrine sludge contents. *Water SA* **2012**, *38*, 479–486. [CrossRef]
22. Bhagwan, J.N.; Still, D.; Buckley, C.; Foxon, K. Challenges with up-scaling dry sanitation technologies. *Water Sci. Technol.* **2008**, *58*, 21–27. [CrossRef]
23. Brouckaert, C.J.; Foxon, K.M.; Wood, K. Modelling the filling rate of pit latrines. *Water SA* **2013**, *39*, 555–562. [CrossRef]
24. Still, D.A.; Foxon, K. Tackling the Challenges of Full Pit Latrines. In *Volume 1: Understanding Sludge Accumulation in VIPs and Strategies for Emptying Full Pits*; WRC Report No. 1745/1/12; Water Research Commission: Pretoria, South Africa, 2012.

25. Tsinda, A.; Abbott, P.; Pedley, S.; Charles, K.; Adogo, J.; Okurut, K.; Chenoweth, J. Challenges to Achieving Sustainable Sanitation in Informal Settlements of Kigali, Rwanda. *Int. J. Environ. Res. Public Health* **2013**, *10*, 6939–6954. [CrossRef] [PubMed]
26. Macleod, N.A. The Provision of Sustainable Sanitation Services to Peri-Urban and Rural Communities in the eThekwini Municipality. In Proceedings of the 3rd International Ecological Sanitation Conference, Durban, South Africa, 23–26 May 2005; pp. 47–51.
27. Department of Water Affairs and Forestry and Norwegian Agency for Development Cooperation. Guidelines on Protecting Groundwater from Contamination. 2004. Available online: https://www.dws.gov.za/Groundwater/NORADToolkit/3.4%20Guidelines-on-protecting-groundwater.pdf (accessed on 31 January 2022).
28. Tureková, I.; Marková, I. Ignition of Deposited Wood Dust Layer by Selected Sources. *Appl. Sci.* **2020**, *10*, 5779. [CrossRef]
29. Lin, J.; Aoll, J.; Niclass, Y.; Velazco, M.I.; Wünsche, L.; Pika, J.; Starkenmann, C. Qualitative and quantitative analysis of volatile constituents from latrines. *Environ. Sci. Technol.* **2013**, *47*, 7876–7882. [CrossRef]
30. Eye Witness News. Boy Dies Falling into Limpopo Pit Toilet. 2014. Available online: http://ewn.co.za/2014/01/21/Boy-dies-falling-into-Limpopo-pit-toilet (accessed on 31 January 2022).
31. Fabrizi, L. Groundwater. 2014. Available online: http://www.lenntech.com/groundwater/definitions.htm (accessed on 31 January 2022).
32. Department of Water Affairs and Forestry and Norwegian Agency for Development Cooperation. A Framework for Groundwater Management of Community Water Supply. 2004. Available online: https://www.gov.za/sites/default/files/gcis_document/201409/dwafanrep0304.pdf (accessed on 31 January 2022).
33. Graham, J.P.; Polizzotto, M.L. Pit Latrines and Their Impacts on Groundwater Quality: A Systematic Review. *Environ. Health Perspect.* **2013**, *121*, 521–530. [CrossRef] [PubMed]
34. Department of Water Affairs. Status of Groundwater Levels January–March 2013. 2013. Available online: https://www.dws.gov.za/Groundwater/maps/QuarterlyGW2013.aspx (accessed on 31 January 2022).
35. United Nations Children's Fund. Understanding Groundwater & Wells in Manual Drilling. 2010. Available online: https://www.pseau.org/outils/ouvrages/practica_groundwater_wells_manual_drilling_2010_en.pdf (accessed on 31 January 2022).
36. Manga, M.; Bartram, J.; Evans, B.E. Economic cost analysis of low-cost sanitation technology options in informal settlement areas (case study: Soweto, Johannesburg). *Int. J. Hyg. Environ. Health* **2020**, *223*, 289–298. [CrossRef]
37. Bhagwan, J.N.; Still, D.; Buckley, C.; Foxon, K. When Last Did We Look down the Pits? Available online: https://wisa.org.za/wp-content/uploads/2018/12/WISA2008-P007.pdf (accessed on 31 January 2022).
38. Durban.gov.za. Draft Water Services Development Plan: Volume 2 for the eThekwini Municipality Prepared by the eThekwini Water and Sanitation Unit. 2004. Available online: http://www.durban.gov.za/Documents/City_Government/IDP_Policy/22.2%20water%20services%20plan.pdf (accessed on 31 January 2022).
39. Naidoo, D.; Archer, C.; Louton, B.; Rodda, N. Testing household disinfectants for the inactivation of helminth ova on surfaces and in spills during pit latrine emptying. *Water SA* **2016**, *42*, 560–570. [CrossRef]
40. Edokpayi, J.N.; Enitan-Folami, A.M.; Adeeyo, A.O.; Durowoju, O.S.; Jegede, A.O.; Odiyo, J.O. Chapter 9—Recent Trends and National Policies for Water Provision and Wastewater Treatment in South Africa. In *Water Conservation and Wastewater Treatment in BRICS Nations*; Singh, P., Milshina, Y., Tian, K., Gusain, D., Bassin, J.P., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 187–211. [CrossRef]
41. Helen Suzman Foundation. Available online: https://hsf.org.za/publications/hsf-briefs/the-state-of-sanitation-and-wastewater-treatment-services-in-south-africa#_ftn11 (accessed on 1 February 2022).
42. Carden, K.; Armitage, N.; Winter, K.; Sichone, O.; Rivett, U. *Understanding the Use and Disposal of Greywater in the Non-Sewered Areas in South Africa*; Research Report 1524/1/07; Water Research Commission of South Africa: Pretoria, South Africa, 2007.
43. Dzwairo, B.; Hoko, Z.; Love, D.; Guzha, E. Assessment of the impacts of pit latrines on groundwater quality in rural areas: A case study from Marondera district, Zimbabwe. *Phys. Chem. Earth* **2006**, *31*, 779–788. [CrossRef]
44. Verheyen, J.; Timmen-Wego, M.; Laudien, R.; Boussaad, I.; Sen, S.; Koc, A.; Uesbeck, A.; Mazou, F.; Pfister, H. Detection of adenoviruses and rotaviruses in drinking water sources used in rural areas of Benin, West Africa. *Appl. Environ. Microbiol.* **2009**, *75*, 2798–2801. [CrossRef]
45. Vinger, B.; Hlophe, M.; Selvaratnam, M. Relationship between nitrogenous pollution of borehole waters and distances separating them from pit latrines and fertilized fields. *Life Sci. J.* **2012**, *9*, 402–407.
46. Department of Water Affairs and Forestry. South African Water Quality Guidelines: Domestic Use (Vol. 1). 1996. Available online: https://www.dws.gov.za/Groundwater/documents/Pol_saWQguideFRESHDomesticusevol1.pdf (accessed on 31 January 2022).
47. Septien, S.; Pocock, J.; Teba, L.; Velkushanova, K.; Buckley, C.A. Rheological characteristics of faecal sludge from VIP latrines and implications on pit emptying. *J. Environ. Manag.* **2018**, *228*, 149–157. [CrossRef]
48. World Food Programme. El Niño Set to Have A Devastating Impact on Southern Africa's Harvests and Food Security. 2016. Available online: https://www.wfp.org/news/el-nino-set-have-devastating-impact-southern-africas-harvests-and-food-security (accessed on 11 February 2022).
49. Meza, I.; Rezaei, E.E.; Siebert, S.; Ghazaryan, G.; Nouri, H.; Dubovyk, O.; Gerdener, H.; Herbert, C.; Kusche, J.; Popat, E.; et al. Drought risk for agricultural systems in South Africa: Drivers, spatial patterns, and implications for drought risk management. *Sci. Total Environ.* **2021**, *799*, 149505. [CrossRef]

50. Jain, R.; Camarillo, M.K.; Stringfellow, W.T. Threats. In *Drinking Water Security for Engineers, Planners, and Managers (Chapter 3)*; Butterworth-Heinemann: Oxford, UK, 2014; pp. 45–67, ISBN 9780124114661. [CrossRef]
51. World Health Organisation. *Guidelines for Safe Use of Wastewater, Excreta and Greywater*; WHO Press; World Health Organisation: Geneva, Switzerland, 2006. Available online: https://www.who.int/publications/i/item/9241546859 (accessed on 31 January 2022).
52. Foxon, K.M. *Scientific Support for the Design and Operation of VIPs*; Report number K5/1630; Water Research Commission: Pretoria, South Africa, 2008. Available online: http://www.wrc.org.za/wp-content/uploads/mdocs/TT357-08%20-Developing%20communities.pdf (accessed on 31 January 2022).
53. Buckley, C.A.; Foxon, K.M.; Brouckaert, C.J.; Rodda, N.; Nwaneri, C.; Balboni, E.; Couderc, A.; Magagna, D. *Scientific Support for the Design and Operation of Ventilated Improved Pit Latrines (VIPs) and the Efficacy of Pit Latrine Additives*; WRC Report TT 357/08; Water Research Commission of South Africa: Pretoria, South Africa, 2008.
54. Raimbault, M. General and microbiological aspects of solid substrate fermentation. *Electron. J. Biotechnol.* **1998**, *1*, 26–27. [CrossRef]
55. Septien, S.; Mirara, S.W.; Makununika, B.S.N.; Signh, A.; Pocock, J.; Velkushanova, K.; Buckley, C.A. Effect of drying on the physical and chemical properties of faecal sludge for its reuse *J. Environ. Chem. Eng.* **2020**, *8*, 103652. [CrossRef] [PubMed]
56. United States Environmental Protection Agency. Decision Maker's Guide to Solid Waste Management, Volume 2. United States Environmental Protection Agency. 1995. Available online: www.epa.gov/osw/nonhaz/municipal/dmg2 (accessed on 25 October 2013).
57. Getahun, S.; Septien, S.; Mata, J.; Somorin, T.; Mabbett, I.; Buckley, C. Drying characteristics of faecal sludge from different on-site sanitation facilities. *J. Environ. Manag.* **2020**, *261*, 110267. [CrossRef]
58. Chaggu, E.J. Sustainable Environmental Protection Using Modified Pit-Latrines. Ph.D. Thesis, Wageningen University, Wageningen, The Netherlands, 2004. Available online: http://library.wur.nl/WebQuery/clc/1713000 (accessed on 31 January 2022).
59. Carver, S.M.; Hulatt, C.J.; Thomas, D.N.; Tuovinen, O.H. Thermophilic, anaerobic co-digestion of microalgal biomass and cellulose for H2 production. *Biodegradation* **2011**, *22*, 805–814. [CrossRef]
60. Verma, S. Anaerobic Digestion of Biodegradable Organics in Municipal Solid Wastes. Master's Thesis, Columbia University, New York, NY, USA, 2002.
61. Franceys, R.; Pickford, J.; Reed, R. *A Guide to the Development of On-Site Sanitation*; WHO Press; World Health Organisation: Geneva, Switzerland, 1992.
62. Hentges, D.J.; Maier, B.R.; Burton, G.C.; Flynn, M.A.; Tsutakawa, R.K. Effect of a high beef diet on the fecal bacterial flora of humans. *Cancer Res.* **1977**, *37*, 568–571. [PubMed]
63. Song, Y.; Kato, N.; Liu, C.; Matsumiya, Y.; Kato, H.; Watanabe, K. Rapid identification of 11 human intestinal *Lactobacillus* species by multiplex PCR assays using group- and species-specific primers derived from the 16S-23S rRNA intergenic spacer region and its flanking 23S rRNA. *FEMS Microbiol. Lett.* **2002**, *187*, 167–173. [CrossRef]
64. Morelli, L.; Cesena, C.; De Haën, C.; Gozzini, L. Taxonomic Lactobacillus composition of feces from human newborns during the first few days. *Microb. Ecol.* **1998**, *35*, 205–212. [CrossRef]
65. Van Tongeren, S.P.; Slaets, J.P.J.; Harmsen, H.J.M.; Welling, G.W. Fecal microbiota composition and frailty. *Appl. Environ. Microbiol.* **2005**, *71*, 6438–6442. [CrossRef]
66. Zoppi, G.; Cinquetti, M.; Luciano, A.; Benini, A.; Muner, A.; Bertazzoni Minelli, E. The intestinal ecosystem in chronic functional constipation. *Acta Paediatr. Int. J. Paediatr.* **1998**, *87*, 836–841. [CrossRef]
67. Khan, A.A.; Nawaz, M.S.; Khan, S.A.; Cerniglia, C.E. Identification of predominant human and animal anaerobic intestinal bacterial species by terminal restriction fragment patterns (TRFPs): A rapid, PCR-based method. *Mol. Cell. Probes* **2001**, *15*, 349–355. [CrossRef] [PubMed]
68. Salyers, A.A.; Palmer, J.K.; Wilkins, T.D. Degradation of polysaccharides by intestinal bacterial enzymes. *Am. J. Clin. Nutr.* **1978**, *31*, S128–S130. [CrossRef]
69. Ghosh, S.; Klass, D.L. Anaerobic sludge digestion in the presence of lactobacillus additive. *AIAA Pap.* **1980**, 295–317, (Conference report number: CONF-800129-3). Available online: https://www.osti.gov/biblio/5529251-anaerobic-sludge-digestion-presence-lactobacillus-additive (accessed on 31 January 2022).
70. Gibson, G.R. Dietary modulation of the human gut microflora using prebiotics. *Br. J. Nutr.* **1998**, *80*, S209–S212. [CrossRef] [PubMed]
71. Cummings, J.H.; MacFarlane, G.T. Gastrointestinal effects of prebiotics. *Br. J. Nutr.* **2002**, *87*, S145–S151. [CrossRef]
72. Kris, E.S.; Marlett, J.A. Measuring lignin and neutral sugars in neutral detergent soluble and insoluble fractions of human and rat feces. *J. Agric. Food Chem.* **1990**, *38*, 1218–1223. [CrossRef]
73. Hu, B.; Gong, Q.; Wang, Y.; Ma, Y.; Li, J.; Yu, W. Prebiotic effects of neoagaro-oligosaccharides prepared by enzymatic hydrolysis of agarose. *Anaerobe* **2006**, *12*, 260–266. [CrossRef]
74. Macfarlane, S.; Quigley, M.E.; Hopkins, M.J.; Newton, D.F.; Macfarlane, G.T. Polysaccharide degradation by human intestinal bacteria during growth under multi-substrate limiting conditions in a three-stage continuous culture system. *FEMS Microbiol. Ecol.* **1998**, *26*, 231–243. [CrossRef]
75. Sarada, R.; Joseph, R. Characterization and enumeration of microorganisms associated with anaerobic digestion of tomato-processing waste. *Bioresour. Technol.* **1994**, *49*, 261–265. [CrossRef]

76. Franks, A.H.; Harmsen, H.J.M.; Raangs, G.C.; Jansen, G.J.; Schut, F.; Welling, G.W. Variations of Bacterial Populations in Human Feces Measured by Fluorescent In Situ Hybridization with Group-Specific 16S rRNA-Targeted Oligonucleotide Probes. *Appl. Environ. Microbiol.* **1998**, *64*, 3336–3345. Available online: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC106730/ (accessed on 22 February 2022). [CrossRef]
77. Vaahtovuo, J.; Korkeamäki, M.; Munukka, E.; Viljanen, M.K.; Toivanen, P. Quantification of bacteria in human feces using 16S rRNA-hybridization, DNA-staining and flow cytometry. *J. Microbiol. Methods* **2005**, *63*, 276–286. [CrossRef] [PubMed]
78. Breitbart, M.; Hewson, I.; Felts, B.; Mahaffy, J.M.; Nulton, J.; Salamon, P.; Rohwer, F. Metagenomic Analyses of an Uncultured Viral Community from Human Feces. *J. Bacteriol.* **2003**, *185*, 6220–6223. [CrossRef]
79. Madikizela, P. The Applicability of Anaerobically Digested Pasteurized Pit Latrine Faecal Sludge as a Fertilizer to Grow Radish and Garden Cress. Master's Thesis, Rhodes University, Makhanda, South Africa, 2017. Available online: http://vital.seals.ac.za:8080/vital/access/manager/Repository/vital:27487?site_name=GlobalView&view=grid&f0=sm_creator%3A%22Madikizela%2C+Phindile%22&f1=sm_type%3A%22Master%27s+theses%22&sort=null (accessed on 22 February 2022).
80. Hawkins, A.K.; O'Doherty, K.C. "Who owns your poop?": Insights regarding the intersection of human microbiome research and the ELSI aspects of biobanking and related studies. *BMC Med. Genom.* **2011**, *4*, 72. [CrossRef]
81. Vandeputte, D.; De Commer, L.; Tito, R.Y.; Kathagen, G.; Sabino, J.; Vermeire, S.; Faust, K.; Raes, J. Temporal variability in quantitative human gut microbiome profiles and implications for clinical research. *Nat. Commun.* **2021**, *12*, 6740. [CrossRef]
82. Bourquin, L.D.; Titgemeyer, E.C.; Fahey, G.C., Jr. Vegetable fiber fermentation by human fecal bacteria: Cell wall polysaccharide disappearance and short-chain fatty acid production during in vitro fermentation and water-holding capacity of unfermented residues. *J. Nutr.* **1993**, *123*, 860–869. [CrossRef]
83. Edwards, S.; Chaplin, M.F.; Blackwood, A.D.; Dettmar, P.W. Primary structure of arabinoxylans of ispaghula husk and wheat bran. *Proc. Nutr. Soc.* **2003**, *62*, 217–222. [CrossRef]
84. Wang, X.; Brown, I.L.; Khaled, D.; Mahoney, M.C.; Evans, A.J.; Conway, P.L. Manipulation of colonic bacteria and volatile fatty acid production by dietary high amylose maize (amylomaize) starch granules. *J. Appl. Microbiol.* **2002**, *93*, 390–397. [CrossRef]
85. Shin, S.G.; Yoo, S.; Hwang, K.; Song, M.; Kim, W.; Han, G.; Hwang, S. Dynamics of transitional acidogenic community along with methanogenic population during anaerobic digestion of swine wastewater. *Process Biochem.* **2011**, *46*, 1607–1613. [CrossRef]
86. Adegunloye, D.V.; Oladejo, B.O. Effect of ratio variation of crop wastes on the production of poultry dung bio-gas. *Niger. J. Parasitol.* **2010**, *31*, 130–134. [CrossRef]
87. Lopez Zavala, M.A.; Funamizu, N.; Takakuwa, T. Characterization of faeces for describing the aerobic biodegradation of faeces. *J. Environ. Syst. Eng. JSCE* **2002**, *720/VII-25*, 99–105. [CrossRef]
88. Morgan, P. *"The Answer Lies in the Soil." In An Ecological Approach to Sanitation in Africa—A Compilation of Experiences, EcoSanRes*; Stockholm Environmental Institute: Stockholm, Sweden, 2004.
89. Henze, M.; Harremoës, P.; Jansen, J.; Arvin, E. *Biological and Chemical Processes in Wastewater Treatment*; Springer: Berlin, Germany, 1997.
90. Hoossein, S.; Tandlich, R.; Whittington-Jones, K.; Laubscher, R.K.; Madikizela, P.; Zuma, B.M. Disaster Management policy options to address the sanitation challenges in South Africa. *J. Environ. Health* **2016**, *78*, E1–E7. Available online: https://www.jstor.org/stable/26330432 (accessed on 5 February 2022).
91. Tandlich, R.; Ngqwala, N.P.; Boshoff, A.; Madikizela, P.; Srinivas, C.S.; Pyle, D.M.; Oosthuizen, R. Challenges and curriculum transformation in the higher education sector in South Africa: A case study in WASH to improve the training of pharmacists. *Acta Educ. Gen.* **2018**, *8*, 3–32. [CrossRef]
92. Jensen, P.K.M.; Konradsen, F.; Klank, L.T.; Dalsgaard, A. Survival of Ascaris ova and hygienic quality of human excreta in Vietnamese composting latrines. *Environ. Health* **2009**, *8*, 57. [CrossRef]
93. Collings, D.; Tandlich, R.; Dube, C.S.; Madikizela, P.; Ngqwala, N.P.; Ahmed, M. Preliminary study on the potential use of fly ash as a ventillated improved pit latrine additive. *J. Solid Waste Technol. Manag.* **2019**, *45*, 395–402. [CrossRef]
94. Madikizela, P.; Iheanetu, C.; Laubscher, R.; Britton, J.; Tandlich, R. Assessment of alkali modified coal fly ash as a potential pit latrine additive for elimination of pathogens using synthetic faeces as proxy. *J. Solid Waste Technol. Manag.* **2022**, *48*, 75–89. [CrossRef]
95. Nondlazi, S.; Ngqwala, N.P.; Zuma, B.M.; Tandlich, R. Investigating the viability and performance of the pilot scale fly ash/lime filter tower for onsite greywater treatment. *Desalin. Water Treat.* **2017**, *91*, 349–364. [CrossRef]
96. Fečko, P.; Kušnierová, M.; Raclavská, H.; Čablík, V.; Lyčková, B. *Fly Ash*; VŠB—Technical University of Ostrava, Faculty of Mining and Geology: Ostrava, Czech Republic, 2005.
97. Lokeshappa, B.; Dikshit, A.K. Disposal and Management of Fly Ash. In Proceedings of the 2011 International Conference on Life Science and Technology (IPCBEE), Singapore, 26–28 February 2011; IACSIT Press: Singapore, 2011; Volume 3, pp. 11–14. Available online: http://www.ipcbee.com/vol3/4-L009.pdf (accessed on 1 February 2022).
98. Zuma, B.M. The Efficacy and Applicability of Low-Cost Adsorbent Materials in Wastewater Treatment. Ph.D. Thesis, Rhodes University, Grahamstown, South Africa, 2012.
99. Akhtar, M.N.; Tarannum, N. 'Flyash as a Resource Material in Construction Industry: A Clean Approach to Environment Management'. In *Sustainable Construction and Building Materials*; Hemeda, S., Ed.; IntechOpen: London, UK, 2018. [CrossRef]

100. Dayan, A.J.; Paine, A.J. Mechanisms of chromium toxicity, carcinogenicity and allergenicity: Review of the literature from 1985 to 2000. *J. Hum. Toxicol.* **2001**, *20*, 439–451. [CrossRef]
101. Reynolds-Clausen, K.; Singh, N. South Africa's Power Producer's Revised Coal Ash Strategy and Implementation Progress. *Coal Combust. Gasif. Prod.* **2019**, *11*, 10–17. [CrossRef]
102. Madikizela, P. Use of Water Hyacinth in the Treatment of Greywater. Bachelor's Thesis, Rhodes University, Makhanda, South Africa, 2013.
103. Czechowska-Kosacka, A.M.; Niedbała, G.; Kolarzyk, P. Influence of fly ash addition on the immobilisation of heavy metals in sewage sludge. *Int. J. Conserv. Sci.* **2021**, *12*, 765–780.
104. Andoni, A.; Delilaj, E.; YIli, F.; Taraj, K.; Korpa, A.; Xhaxhui, K.; Como, A. FTIR spectroscopic investigation of alkali-activated fly ash: A test study. *Zast. Mater.* **2018**, *59*, 539–542. [CrossRef]
105. Dube, C.S.; Tandlich, R.; Wilhelmi, B.S. Adsorptive Removal of ciprofloxacin and isoniazid from aqueous solution. *Nova Biotechnol. Chim.* **2018**, *17*, 16–28. [CrossRef]
106. Palomo, A.; Grutzeck, M.W.; Blanco, M.T. Alkali-Activated fly ashes; A cement future. *Cem. Concr. Res.* **1999**, *29*, 1323–1329. [CrossRef]
107. Fernandez-Jimenez, A.; Palomo, A. Mid-infrared spectroscopic studies of alkali-activated fly ash structure. *Microporous Mesoporous Mater.* **2005**, *86*, 207–214. [CrossRef]
108. Kovalchuk, G.; Fernández-Jiménez, A.; Palomo, A. Alkali-activated fly ash: Effect of thermal curing conditions on mechanical and microstructural development—Part II. *Fuel* **2006**, *86*, 315–322. [CrossRef]
109. Visa, M.; Bogatu, C.; Duta, A. Tungsten oxide-fly ash oxide composites in adsorption and photocatalysis. *J. Hazard. Mater.* **2015**, *289*, 244–256. [CrossRef]
110. Hower, J.C.; Groppo, J.G.; Graham, U.M.; Ward, C.R.; Kostova, I.J.; Maroto-Valer, M.M.; Dai, S. Coal-derived unburned carbons in fly ash: A review. *Int. J. Coal Geol.* **2017**, *179*, 11–27. [CrossRef]
111. Alterary, S.; Marei, N.H. The impact of coal fly ash purification on its antibacterial activity. *Minerals* **2020**, *10*, 1002. [CrossRef]
112. U.S. Centers for Disease Control and Prevention. *Biosafety in Microbiological and Biomedical Laboratories*, 5th ed.; 2009. Available online: https://www.cdc.gov/labs/pdf/CDC-BiosafetymicrobiologicalBiomedicalLaboratories-2009-P.pdf (accessed on 24 February 2022).
113. Penn, R.; Ward, B.J.; Strande, L.; Maurer, M. Review of synthetic human faeces and faecal sludge for sanitation and wastewater research. *Water Res.* **2018**, *132*, 222–240. [CrossRef]
114. USAID. South Africa Energy Sector Overview. 2019. Available online: https://www.usaid.gov/powerafrica/south-africa#:~{}:text=According%20to%20the%20Ministry%20of,(MW)%20from%20all%20sources (accessed on 24 February 2022).
115. *Report on the Submission of Gareth Van Onselen (Complainant) Versus the Moqhaka Local Municipality*; File Ref No: FS/2010/0231; South African Human Rights Commission: Pretoria, South Africa, 2010.
116. Republic of South Africa. Constitution of South Africa. 1996. Available online: https://www.gov.za/documents/constitution-republic-south-africa-1996 (accessed on 31 January 2022).
117. Abrams, A.L.; Carden, K.; Teta, C.; Wågsæther, K. Water, Sanitation, and Hygiene Vulnerability among Rural Areas and Small Towns in South Africa: Exploring the Role of Climate Change, Marginalization, and Inequality. *Water* **2021**, *13*, 2810. [CrossRef]
118. United Nations Environment Programme. Environmental Technology Assessment. 2001. Available online: https://wedocs.unep.org/bitstream/handle/20.500.11822/8167/Environmental%20Technology%20Assessment%20%28EnTA%29%20-%20Workshop%20Report-20011390.pdf?sequence=2&isAllowed=y (accessed on 31 January 2022).
119. Ludwig, B. The Concept for Technology Assessment—An Entire Process to Sustainable Development. *Sustain. Dev.* **1997**, *5*, 111–117. [CrossRef]
120. Van Eijndhoven, J.C.M. Technology Assessment: Product or Process. *Technol. Forecast. Soc. Chang.* **1997**, *54*, 269–286. [CrossRef]
121. Assefa, G.; Bjorklund, A.; Eriksson, O.; Frostell, B. ORWARE: An aid to Environmental Technology Chain Assessment. *J. Clean. Prod.* **2005**, *13*, 265–274. [CrossRef]