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SUSTAINABLE FAECAL SLUDGE MANAGEMENT IN INTERNALLY DISPLACED PERSONS (IDPS) SETTLEMENTS IN TROPICAL CLIMATE: A REVIEW

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Abstract
In settlements for internally displaced persons (IDPs), achieving sustainable on-site faecal sludge management is crucial. Effective stabilization and treatment methods are vital, as the wrong choices can result in dire sanitary conditions. Tropical climate, marked by low-income settings and overburdened sanitation facilities, pose unique challenges that demand tailored solutions. This review paper focuses on simplicity, cost-efficiency, and minimal land requirements for stabilization, along with affordability, low health risks, and valuable end-products for treatment. Notable findings include mechanical presses, planted drying beds, and solar greenhouse drying beds as robust stabilization methods, while microwave heating, black soldier fly larvae, and anaerobic digestion show promise as sustainable treatment techniques. Adopting these techniques promises sustainable faecal sludge management and potential improvements in living standards. This paper guides the way toward enhanced sanitation and well-being in the toughest conditions.

1.0 INTRODUCTION
The increased conflict and violence, and natural disasters in different parts of the world have increased the number of refugees and internally displaced persons in various emergency settlements across the globe. In 2019, the United Nations High Commission for Refugees reported that 79.5 million people in the world were forcibly displaced from their homes and this number grew to 82.4 million in 2020 and 89.3 million in 2021 [1]. Brown [2] posited that the number of forcibly displaced persons in the world will rise to 200 million by 2050 due to climate-related occurrences. Refugees and IDP camps are usually faced with a lack of or inadequate basic amenities: poor feeding and lack of access to safe drinking water, poor health care facilities, poor shelter, energy crisis, and unhygienic sanitary facilities [3-5].

This unusually low living standard which characterizes emergency settlements is highly traceable to the high population density in these environments which exerts much pressure on the limited available resources. Their sanitary facilities are usually inadequate and overloaded as about 28-32 persons share one toilet [6] and this usually leads to indiscriminate disposal of faecal sludge and open defecation is very high. The provision of safe sanitary facilities to people is still a major challenge in many countries of the world as many still do not have access to safely managed sanitary facilities as about 3 billion people in the world rely on non-sewered sanitary facilities [7]. In Africa, more than 208 million people are still using open defecation [8]. If this current slow pace of providing safely managed sanitary facilities in the world [9] persists, achieving the 2030 goal of providing safely managed sanitary facilities to all [8] will be difficult to achieve.

In solving faecal sludge management challenges in emergency settlements, non-sewered on-site sanitary facilities that are relatively cheap and easy to set up are usually installed since the installation of flush toilets is difficult due to high cost, high energy, and water requirements. On-site sanitary facilities include pit latrines, pour flush toilets, bucket latrines, aqua privies, septic tanks and ventilated improved pit latrines [10]. However, major challenges with on-site sanitary facilities include the difficulty in desludging the faecal sludge containments [11], poor construction, and inadequate maintenance [12] which can cause the leakage of faecal sludge into the environment, leading to environmental pollution [13]. To safeguard the environment and sustain such over-loaded sanitary systems, there must be regular safe desludging and sustainable treatment for resource recovery or ultimate disposal.

However, the high volume of faecal sludge generated in emergency settlements coupled with the health risk associated with the frequent evacuation, transportation, and treatment for safe disposal is capital-intensive and, in most cases, prohibitive. For example, during the 2010 Haiti earthquake, the cost of disposal of faecal sludge from the emergency settlements was about USD500,000.00 per month [14]. The difficulties and high cost of desludging faecal sludge in containments can constrain operators of these facilities to abandon them and design new ones while the high treatment and disposal costs can force the operators to directly discharge the untreated faecal sludge into the environment.

The discharge of untreated faecal sludge into the environment causes severe health risks as faecal sludge contains viruses, protozoa, bacteria, helminths, and many other dangerous pathogens which can spark a disease outbreak in the environment [11]. The spread of communicable diseases is very high in any densely populated region and this is responsible for about three-quarters of deaths in refugee camps [15]. Urgent attention must therefore be given to mitigate against any condition that will increase the health risk of these over-crowded emergency settlements. Faecal sludge may also have a very high concentration of heavy metals like Pb, Hg, Ni, Zn, and Cd [16] that easily enter the food chain, causing severe health implications to man. Furthermore, faecal sludge contains a large amount of organic matter, which causes offensive odour during the degradation process and further worsens the environmental condition. Faecal sludge also generates a high volume of greenhouse gases (GHGs), which have a harsh impact on the environment and the natural ecosystem [17-18]. Nsiah-Gyambibi et al. [19] reported that the disposal of untreated faecal sludge into the environment generates about 40% of the total GHGs. In water bodies, faecal sludge can also cause the accumulation of organic matter, which causes eutrophication and algal blooms [13].

To encourage and increase the implementation of sustainable on-site faecal sludge management in over-loaded low-income sanitary facilities, faecal sludge must be seen as a resource that should be processed into valuable resources instead of polluting the environment. The majority of people living in refugee and IDP camps have no access to adequate energy supply and are heavily reliant on biomass for cooking [3]. The proper handling and processing of faecal sludge via appropriate processing schemes can convert it into an energy resource that can provide the energy demand for these settlements. Faecal sludge can also be processed into biofertilizers that can improve the farming activities carried out in these environments and hence improve their economies. It is however sad to note that most of the faecal sludge management systems adopted in overloaded low-income sanitary facilities have not adequately solved the challenges in this environment. The constant failure of these over-loaded low-income sanitary facilities is traceable to the globalization of faecal sludge management techniques.

The sustainability of a faecal sludge management technique is dependent on the environment where the facility is located and how it can satisfy the immediate needs of the people [20]. Refugees and IDP camps are already difficult environment, constrained by several environmental, social and economic factors [3], hence their faecal sludge treatment facilities can be sustainable if they can address the immediate problems facing the people. In an emergency settlement with an overloaded sanitary facility, the installation of an on-site faecal sludge management system that has low health risk with minimal environmental impact is affordable, simple, produces final products with enhanced agricultural and energy values, and can effectively reduce sludge volume is desirable. For a very long time, on-site sanitary facilities have not been regarded as safely managed sanitary facilities and hence literature in this area is scarce. This late recognition of on-site sanitary facilities is responsible for the very few number of on-site faecal sludge treatment plants around the world. Even the few existing on-site faecal sludge treatment plants rely heavily on passive, land-intensive solutions with low resource-recovery plans. From the literature available, there are no review papers that fully engage the context of the environment and plans to encourage a faecal sludge management system for emergency settlements for refugees and IDPs in tropical climate.

Having these objectives in mind, this paper reviewed current research and publications on faecal sludge management techniques mainly used in on-site faecal sludge facilities to recommend more sustainable techniques for this environment. The adoption of sustainable on-site faecal sludge management techniques will reverse the current trend of frequent failures and unsanitary conditions in this environment, improve health conditions, enhance energy supply and improve agricultural practices.

2.0 METHODOLOGY

The systematic review methodology was adopted in the current paper. A thorough literature search was carried out to source relevant literature with special interests in faecal sludge management, on-site sanitary facilities, and faecal sludge treatment in overloaded low-income emergency settlements like refugees and IDP camps. In the literature search, only works published in the English language were considered. The literature used in this review was sourced from notable databases like Pubmed, Scopus, and Web of Science. The Boolean search technique of combining keywords and MeSH terms for "on-site faecal sludge management", "low-income-environment faecal sludge treatment techniques", "energy demand in refugee and IDP camps", "health risks in on-site sanitary facilities in low-income environments", and several other relevant terminologies that were considered appropriate for this study were used. In the literature search, only relevant studies conducted from 2015 to 2023 were considered. Older studies were properly screened out, except those with critical findings. The literature findings were summarized and analyzed to adopt more suitable and sustainable faecal sludge treatment techniques for these facilities.

3.0 WORLD REFUGEES AND INTERNALLY DISPLACED PEOPLE

Conflict, violence, and disease have forcibly displaced people from their homes around the world. Out of the 89.30 million people in the world who were forcibly displaced from their homes in 2021, 53.20 million are internally displaced persons (IDPs), and 27.10 million are refugees [1]. Sixty-nine (69%) of these forcibly displaced persons are from Venezuela, the Syrian Arab Republic, South Sudan, Myanmar, and Afghanistan [1]. The displaced are usually concentrated in some makeshift settlements as refugees or internally displaced persons with little or no access to basic amenities, especially those hosted by low-income countries [1]. Access to modern sanitary facilities is a global challenge, as over 1.70 billion people lack access to safely managed sanitary facilities, and 494 million people engage in open defecation [21]. The situation is very worrisome in refugee and IDP camps in Africa, with severe economic and health implications for the host communities.

3.1 Characteristics of Faecal Sludge

Unlike coal and some other fuels with uniform physical and chemical characteristics, faecal sludge has varying characteristics owing to the differences in nutrition of individuals, health status, age, sex, body weight [22], duration of storage, temperature of the system, and the containment technology used [12]. This high degree of variability poses severe difficulties in subjecting faecal sludge to repeated experiments with consistent characteristics [10]. Faecal sludge, which is primarily composed of proteins, fats, bacteria, carbohydrates, and some inorganic components, is very difficult to handle due to the presence of the viscous sticky substance from the linings of the intestinal walls [23]. Table 1 characterizes faecal sludge based on some major parameters, while Table 2 shows the elemental composition of faecal sludge.

Table 1: Characteristics of typical faecal sludge

Property/unit	Value	Reference
Ph	5.03-8.35	[24-26]
Water content (wt%)	63-86	[25, 27]
Ash content (% TS)	8.2-14.6	[23, 28-29]
VM (%dry mass)	70.7-76.5	[29-30]
FC (% dry mass)	15.4	[29]
Calorific value (MJ/kg)	17.2-25.1	[23, 28, 31]
Protein (mg/g TSS)	5.2-15.0	[32]
Fibre (wt%TS)	0.5-24.8	[22]
Carbohydrates (wt%TS)	2-5	[22]
Fats (wt%TS)	8.7-16	[22]
E. coli (10^8 CFU/g TS)	4.0 -5.7	[26-27]
BOD (mg/L)	1,450-4,310	[33]
COD (mg/L)	20,800- 121,100	[24]
TN (mg/L)	219-1280	[9, 33]
VS (wt%TS)	92	[22]

Table 2: Elemental characteristics of faecal sludge

Analysis/unit	Element	Average value	Reference
Ultimate (wt%)	C	44-55	[23, 28-31]
	H	7.0-8.0	[23, 28-31]

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	N	1.1-18	[23, 28-31]
	O	21-32	[23, 28-31]
	S	0.5-1.6	[25, 30]
Ash analysis (g/kgDM)	P	2.73-15	[28, 30]
	Si	0.68	[28]
	Na	5.1	[29]
	K	5.5	[29]
	Ca	8.9-10	[29-30]
	Fe	0.2	[29]
	Cl	9.1	[29]
Trace elements (mg/kgDM)	As	<12.5	[29]
	Ni	<12.5	[29]
	Zn	188.8	[29]
	Cu	21.7	[29]
	Cd	<12.5	[29]
	Cr	<12.5	[29]
	Pb	<12.5	[29]

3.2 Sustainable Faecal Sludge Management in Emergency Settlements

To ensure the sustainable management of faecal sludge in emergency settlements with overloaded sanitary facilities, careful evaluation of dewatering and treatment techniques is essential. In refugee and IDP camps, specific objectives take precedence in selecting stabilization and treatment methods, considering the environment's active role in technique sustainability. Key objectives for stabilization technique selection encompass land requirements, dewatering duration, efficiency, ease of automation, climate dependence, initial and operating costs, and energy efficiency [34]. For treatment techniques in overloaded sanitary facilities, crucial objectives include low health risk, affordability, simplicity, and the ability to yield high-value final products such as energy and biofertilizer [9, 27]. Since faecal sludge is pathogen-rich, a sustainable treatment method must significantly reduce the number of pathogenic organisms. Considering the energy needs of residents relying on biomass, a sustainable treatment approach should convert faecal sludge into solid fuel or gas for electricity, simultaneously producing biofertilizers to enhance agricultural activities in this environment.

3.3 Stabilization of Faecal Sludge

Faecal sludge management in non-sewered sanitary facilities requires regular desludging and transportation for treatment and disposal to mitigate health risks linked to faecal-oral pathogens [35]. Preceding desludging, dewatering, and drying processes are employed to reduce moisture content and transportation costs [34]. Dewatering achieves approximately 20% of total solids, reducing sludge volume and enhancing transport affordability and safety. Stabilization, involving liquid-solid separation, is imperative before resource recovery or disposal. It also decreases the organic matter content [36]. Dewatering, particularly leachate percolation or drying, is efficient in reducing sludge volume. Leachate percolation, suitable for high free water content, removes 50%–80% of water [37]. Dewatering benefits from conditioners, minimizing wastewater volume and treatment costs [38]. However, conditioner dosage requires careful consideration, warranting further research due to the limited literature [39]. Drying, a slower technique using thermal or solar energy yields a granular product with enhanced agricultural and energy value.

Desludging poses challenges due to faecal sludge's complex rheology, exacerbated as sludge ages, hindering mixing and pumping [40]. Dilution eases desludging but raises transportation costs. Regular evacuation of fresh faecal sludge is recommended to counter this. Age influences dewatering characteristics, with fresh sludge faring better [40]. Extra polymeric substance (EPS) concentration, a byproduct of biological growth, complicates dewatering due to its water-binding capacity [41]. Higher EPS concentrations hinder stabilization [32].

Various dewatering techniques like unplanted drying beds, planted drying beds, solar drying beds, mechanical drying beds, and permeable membranes exist, with consideration for land requirement, dewatering rate, climate, technology, and cost [34, 42] being essential in their implementation in faecal sludge management. To obtain sustainable stabilization techniques for faecal sludge facilities in these emergency settlements, the most commonly used dewatering techniques were discussed concerning the aforementioned key objectives.

(i) Unplanted drying beds

The technique involves spreading faecal sludge in thick layers on sun-exposed surfaces, enhancing percolation and evaporation. Leachate then percolates through beds; wastewater undergoes treatment before disposal. Unplanted drying beds decrease sludge volume via natural evaporation and liquid infiltration through filter-media lining [43]. The technology is simple, cheap to operate with low energy input [44], can destroy pathogens due to solar radiation, and can reduce faecal sludge volume by about 50% (v/v) to 80% (v/v) [42].The technique is however, land-intensive and takes a very long time, usually weeks or months [45]. The technique is sustainable for the management of faecal sludge in emergency settlements.

(ii) Planted drying beds

Planted drying beds, featuring plant cultivation, offer more efficient faecal sludge dewatering than their unplanted counterparts due to enhanced evaporation

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and maintained filter porosity by plant roots. Common forage plants include *Echinochloa colona*, *Echinochloa crus-galli*, *Echinochloa pyramidalis*, *Paspalum vaginatum*, and *Paspalidium geminatum*. Careful selection, considering resource recovery and cost, is vital for offsetting operating and maintenance costs [43]. Despite high land requirements, the technique's shorter processing time, heightened evaporation in hot tropical climate, and resource recovery capacity make it sustainable in low-income tropical environments.

(iii) Solar drying beds

Solar drying beds utilize solar energy to efficiently reduce faecal sludge volume through evaporation and microbial activity suppression. Among the solar drying beds, greenhouse dryers are the most effective, enhancing evaporation with forced ventilation and optimal solar irradiation [46]. With low energy input and operational costs, simple technology, and a threefold higher evaporation rate than conventional drying beds, solar dryers are highly effective in low-income environments [47]. Greenhouse drying beds, requiring less land than traditional beds and having near-zero operating maintenance, are a highly sustainable technique for managing faecal sludge in emergency settlements [13].

(iv) Mechanical dewatering techniques

Mechanical dewatering, utilizing screw presses, centrifuges, or belt presses, effectively reduces faecal sludge volume, achieving a 70% reduction. It exhibits higher efficiency and shorter processing times than drying beds [42]. These simple and cost-effective technologies, preferring fresh sludge due to dewatering challenges posed by aged sludge hydrolysis [41], prove sustainable for managing faecal sludge in overloaded sanitary facilities.

(v) Permeable membranes

Permeable membranes, such as geotubes, offer rapid faecal sludge dewatering within hours, contrasting with weeks or months for traditional drying beds [45]. Rhodes-Dicker et al. [34] achieved 3- hour dewatering with approximately 20% total solids and minimal drainage. Effective performance relies on proper conditioner dosage. However, being single-use renders this technology expensive and unsustainable in low-income settings like refugee and IDP camps.

3.3.1 Faecal sludge treatment and health risks

Excessive faecal sludge production in low-income regions poses health and environmental risks, necessitating cost-effective and rapid treatment technologies [48]. Financial constraints in Africa impede desludging and treatment, leading to the direct discharge of untreated faecal sludge, polluting land and water bodies. Only 22% of global pit latrine sludge is safely managed, contributing to severe water pollution and diseases [49]. Cost-effective, rapid faecal sludge treatment is vital for health in low-income sanitary facilities.

3.3.2 Faecal sludge treatment and resource recovery

The mere desludging of faecal sludge containments for disposal should be discouraged as valuable materials can be recovered from the waste. In the design of sustainable faecal sludge treatment techniques in low-income environment, resource recovery is sacrosanct. Energy and biofertilizers are the key resources recoverable from faecal sludge. The detailed description of faecal sludge resource recovery techniques as well as their pros and cons are discussed in the following sub-sections.

3.3.3 Energy recovery from faecal sludge

Faecal sludge, a significant biomass in the environment, holds immense energy potential to address severe energy challenges in emergency settlements. Research by Eliyan et al. [9] indicates that a wetland receiving 32,500m^3 of faecal sludge annually from two settlements could yield up to 165 GWh of energy. Low-income environments face a critical shortage of energy for heating and cooking, often relying heavily on wood, leading to deforestation issues, particularly in Africa and South America. About 1.6 million tons of wood charcoal are produced annually, causing environmental pollution due to its high smoke content [50]. Substituting wood-derived biomass with faecal sludge is not only cost-effective but also environmentally friendly, offering a sustainable solution. Faecal sludge proves to be a viable biomass source for energy generation, with its char exhibiting comparable energy content to wood charcoal [23]. Table 3 presents a comparison of key fuel properties between faecal sludge and selected solid fuels.

Table 3: Proximate analysis of faecal sludge fuel properties and major biomass

Biomass	Ash (wt%)	VM (wt%)	FC (wt%)	MC (wt%)	HHV (MJ/kg)	Reference
Faecal sludge	8.2-14.6	70.7-76.5	15.4	63-86	17.2-25.1	[23, 28-30]
Wood	0.4-1	82	17	-	18.6	[51-52]
Bituminous coal	8-11	35	45	11	34	[51]
Wheat straw	16	59	21	16	17.3	[51]
Barley straw	6	46	18	30	16.1	[53]
Switchgrass	4.3	79	10.7	8.3	17.3	[53]
Lignite	6	29	31	34	26.8	[51]
Peat	21.29	32.82	41.1	4.79	-	[54]
Charcoal	1.73	20.67	72.65	4.95	28.0	[55]
Cow dung	25.30	54.55	12.40	7.75	-	[56-57]

It can be deduced from Table 3 that faecal sludge has a very high energy value which is comparable to or even higher than wood biomass and very close to bituminous coal and lignite.

3.4 Challenges and Possible Solutions for Recovering Energy from Faecal Sludge

A major factor that limits energy recovery from faecal sludge is its high moisture content which is in the range of 63 wt%-86 wt% dry basis [23, 28-30]. The high moisture content of faecal sludge lowers its heating value significantly. While ordinary dewatering of the faecal sludge may be enough for some energy recovery techniques, some may require intense drying or torrefaction, which increases the process cost. Another challenge of faecal sludge as an energy source is its low bulk density. The low bulk density of faecal sludge poses handling, storage, and transportation problems and this also limits its energy density.

Blending faecal sludge with sawdust reduces moisture by 40%, improving ignition [58]. Co-combustion with biomass enhances fuel properties and reduces emissions [48]. Densification technologies like pellet mills or briquette presses, as seen with cow dung [59], improve energy density, overcoming low bulk density.

3.4.1 Biofertilizers from faecal sludge

In refugee and IDP camps, faecal sludge, rich in vital elements like phosphorus and nitrogen, can enhance soil fertility, offering a sustainable source for agriculture [30]. Implementing a biofertilizer recovery scheme enhances regional economies and establishes a highly sustainable solution by improving soil structure and microbial activities. Faecal sludge, with its balanced nutrient supply, can substitute chemical fertilizers, promoting soil fertility.

3.5 Challenges and Possible Solutions in using Faecal Sludge as Biofertilizer

Indiscriminate faecal sludge use as fertilizer poses severe health risks due to heavy metals, pathogens, and harmful substances, leading to water pollution, crop death, eutrophication, and greenhouse gas emissions [30]. This highlights the need for proper treatment and controlled application to mitigate adverse environmental and health impacts.

To curb the problem associated with the disposal or unscientific use of faecal sludge in agriculture, proper treatment practices must be adopted before re-use or disposal. For example, some treatment techniques such as pyrolysis and vermicomposting have been reported to reduce the concentration of heavy metals in faecal sludge [60].

3.6 Faecal Sludge Treatment Techniques

The review prioritizes cost, technology level, processing rate, health risk, and resource recovery in selecting faecal treatment techniques. This section discusses commonly used faecal sludge treatment techniques, evaluating them based on these sustainability criteria for informed decision-making in planning and implementing management strategies in low-income facilities. Techniques considered include:

3.6.1 Incineration

Incineration is an oxidation process that involves the controlled combustion of organic wastes in special combustion units at high temperatures, usually in the range of 800 °C–950 °C. The primary goal is to reduce waste volume beforefinal disposal [61]. Incineration significantly reduces sludge volume, with about 90% of waste potentially destroyed [62]. The resulting solid residue, containing plant nutrients like phosphorus and potassium, can be used for agricultural purposes [61].

Although nitrogen and sulfur are lost in the fume gas during faecal sludge incineration, phosphorus and potassium remain in the ash, making it suitable for agriculture [61]. However, the high moisture content of faecal sludge limits its use in incineration, necessitating intense drying before the process, thereby increasing energy demand. This challenge can be addressed by co-incinerating faecal sludge with coal or municipal solid waste.

While incineration is widely adopted due to its ability to reduce sludge volume significantly, the resulting residue, classified into bottom residue and fly ash, contains heavy metals, trace elements, and other toxic compounds with high health risks. Research by Zajac et al. [61] on the influence of incineration temperature on heavy metal concentrations in ash derived from biomass incineration revealed decreased metal concentrations at elevated temperatures. However, iron, chromium, and nickel were found to be thermally stable. Fly ash, constituting 3%–10% of the total solid residue, has a higher concentration of heavy metals than bottom ash due to chemical partitioning [63]. The separation and stabilization components required for fly ash treatment increase the treatment cost, making incineration cumbersome and unsuitable for application in overloaded, low-income environments.

Incineration of faecal sludge, while generating valuable biofertilizer-rich ash, requires intensive pre-

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drying due to its high moisture content, demanding significant energy. Given the high production rate of faecal sludge in emergency settlements, pre-drying is impractical, making incineration unsustainable for overloaded sanitary facilities. Incineration is best suited for sludge with no agricultural value [64], contributing to environmental pollution through greenhouse gas emissions [46].

3.6.2 Smouldering

Smouldering, an effective treatment for high-moisture solids like faecal sludge, involves slow combustion, producing valuable by-products [31]. This self-sustaining process efficiently treats waste, with forced forward smouldering being prevalent. Oxygen concentration, airflow rate, and biomass porosity influence smouldering efficiency [65]. Faecal sludge, lacking porosity, benefits from added sand to enhance the smouldering process [66]. Controlling temperature and moisture content is crucial, impacting gas quality and heating value. Studies show self-sustaining smouldering of faecal sludge mixed with sand is effective, destroying pathogens with lower energy input than incineration [67]. Faecal sludge, with a higher energy value than wood biomass, proves suitable for smouldering treatment.

Smouldering uses cheap and simple technology and can handle moist waste, hence, does not require intense pre-drying operations like incineration. The high temperature of the process destroys all pathogens, thus producing a pathogen-free biofertilizer. However, energy recovering in smouldering is low and though it can handle relatively moist waste without intense pre-drying, unlike some other thermal treatment techniques, subjecting the large volume of faecal sludge to even little pre-drying consumes a significant amount of input energy and hence not a sustainable faecal sludge treatment technique in overloaded emergency sanitary facilities.

3.6.3 Pyrolysis/gasification of faecal sludge

Pyrolysis, a heat treatment of organic materials, produces valuable products (liquids, solids, and gases) in the absence of oxygen [68 -71]. Gasification, akin to pyrolysis, mainly yields gaseous products and serves as an effective on-site treatment for non-flush sanitary facilities [31]. The key pyrolysis products are bio-oil (considered the most valuable), biochar (solid residue), and gaseous products. Conditions, classified as slow, fast, and flash pyrolysis, impact product quality and yield. While slow pyrolysis, or carbonization, at about 400ºC and low heating rates results in secondary cracking and increased biochar and gas yields, fast pyrolysis at higher temperatures (200ºC - 1000ºC) and shorter residence times produces a high bio-oil yield with low char and gas yields. Flash pyrolysis, at >1000 ºC, produces a high bio-oil yield with low char and gas.

Though energy-intensive, pyrolysis proves economical and sustainable, offering products for heat supply in cogeneration units [72]. Biochar, a porous carbon material, finds use in soil amendments, climate change mitigation, and pollutant removal due to its high cation exchange capacity and surface area [73]. Biochar acts as a carbon sink, reducing greenhouse gas release [74]. Pyrolysis temperatures influence element volatilization, enabling arsenic removal and lead and cadmium volatilization. Pyrolysis alters biochar properties, enhancing its nutrient release for use as a fertilizer. The process's high temperatures and oxygen-free environment destroy microbes and pathogens [30].

Research on faecal sludge pyrolysis and gasification yields promising results. Onabanjo et al. [31] achieved a gaseous product with a high heating value (HHV) of 17.2 MJ/kg. Yacob et al. [28] reported a char yield of 35.1wt% - 35.8wt% and non-condensable gases in the range of 17.2wt% - 29.6wt%. Hadroug et al. [75] reported increased phosphorus stability and potassium transformation. Bleuler et al. [29] recovered nutrients from faecal sludge, obtaining biochar with low pollutants and significant nutrient content. Vali et al. [30] studied sewage sludge pyrolysis, finding enriched phosphorus char and reduced heavy metals under optimized conditions.

Pyrolysis, while effective for faecal sludge treatment, poses challenges due to its complex and energy-intensive nature, requiring substantial pre-drying. Unsuitable for high-moisture waste like faecal sludge, its energy demands for drying outweigh combustion benefits [38]. Sustainability, evaluated through emergy assessment, must weigh economic, social benefits, and environmental impact [64]. Despite nutrient-rich char potential as a biofertilizer, pyrolysis releases pollutants like PAHs and VOCs, detrimental to crop yields [76]. In overloaded low-income environments, especially in emergency settlements, pyrolysis is not a sustainable treatment option.

3.6.4 Microwave

Microwave technology proves highly reliable for the thermal treatment of waste, especially in the recovery of essential organic gases from dried faecal sludge. Its efficacy lies in selective heating and increased reaction rates due to rapid volumetric heating at the molecular level [36]. Employed for pathogen inactivation, microwave irradiation utilizes energy wavelengths from 1mm to 1m and a frequency range of 300MHz to 300GHz in the magnetic spectrum. The induction of heat in microwave treatment depends on the partial transparency of the material to microwave radiation and its ability to absorb the energy, influenced by the dielectric loss factor and dielectric constant [77].

Materials with high water content, dipolar molecules, and organic complexes possessing a high dielectric loss property can be effectively treated with microwaves. The elimination of bacteria and harmful pathogens occurs through electromagnetic radiation and thermal destruction. Electromagnetic radiation disrupts microbial cells by breaking hydrogen bonds and causing denaturation, while thermal destruction ruptures microbial cells as water rapidly heats to the boiling point under an oscillating electromagnetic field [78].

Microwave treatment leads to the hydrolysis of primary faecal sludge components, reducing foul odour and simplifying molecules. Proteins, lipids, and carbohydrates are hydrolyzed into simpler forms (monomers). Carbohydrates yield sugar, proteins result in amino acids, ammonia, and carbon (IV) oxide, and lipids break down into palmitic and oleic acids. Sulfur-bearing compounds contributing to odour are solubilized during this process. Moreover, microwave heating proves effective in reducing heavy metal concentrations in faecal sludge by enhancing thermal hydrolysis and solubilization reactions, leading to the leaching of heavy metals in ionic forms and reducing metal ion mobility in the aqueous phase [77]. In a study by Mawioo et al. [27], a domestic microwave oven was employed to treat faecal sludge from Kenyan slums, focusing on pathogen reduction, sludge volume, and organic matter. Results indicated the microwave technique's rapid and effective reduction of *E. coli* and Ascaris lumbricoides eggs, along with an over 70% volume reduction in faecal sludge.

Microwave treatment effectively reduces volume, destroys pathogens, and produces valuable biofertilizer from faecal sludge. While energy-intensive, it satisfies key objectives for on-site sanitary facilities in emergency settlements, making it a sustainable option.

3.6.5 Composting

Composting, a biological decomposition of organic wastes in oxygenated or oxygen-starved environm-ents, stands out as a cost-effective and eco-friendly technique for processing faecal sludge in agriculture [79]. Composting methods vary in decomposition time, stability, maturity, and sanitization, with four phases: mesophilic, thermophilic, cooling, and maturation. The process raises the compost temperature, fostering the growth of thermophiles that efficiently eradicate pathogens. At maturation, the resulting compost becomes friable, inodorous, humus-like, rich in nutrients, and ideal for use as fertilizer, making it effective for agricultural applications by stabilizing faecal waste and rendering pathogens inactive.

Despite the effectiveness of anaerobic digestion in treating faecal waste, its low gas production rate and high nitrogen content pose challenges [80]. Composting, while requiring land space and presenting handling and disposal challenges, offers a solution by producing clean energy from anaerobic digestion, potentially reducing greenhouse gas emissions [72]. To ensure pathogen-free compost, a crucial factor is the temperature-time relationship, with temperatures above 55°C for 6 - 8 weeks ensuring pathogen eradication during faecal sludge composting [11].

Additional thermal treatment, like valorization, is recommended for manures obtained from sewage composting to further reduce health risks [81]. Integration of a pyrolysis unit and anaerobic digestion, as demonstrated by Gonzalez et al. [82], enhances the treatment of digestate from swine manure. Co-composting, involving different mixes of faecal sludge and plant materials, results in low health risks, enriched nutrients, and reduced heavy metal concentrations [83]. Nartey et al. [84] achieved enhanced growth and productivity by applying manure derived from co-composting faecal sludge and agricultural wastes. Similarly, Grau et al. [85] found improved crop growth and survival when applying faecal sludge and municipal solid waste compost under strenuous conditions, while Aluko et al. [25] obtained nutrient-rich compost with reduced pollutant concentrations through co-composting faecal sludge and market wastes.

Composting, while simple and cost-effective, is unsuitable for faecal sludge due to its low C/N ratio, low energy recovery, long processing time (6 - 8 weeks), and high health risks. Co-composting and further thermal treatment are necessary, making it impractical in overloaded sanitary facilities in emergency settlements.

3.6.6 Vermicomposting

Vermicomposting, an aerobic stabilization of organic waste facilitated by earthworms, produces vermicompost, a bio humus or earthworm fertilizer with enhanced plant nutrient solubility and reduced heavy metal concentrations [86]. Earthworms actively participate in the process, influencing carbon, water, and nutrient cycles and transforming organic matter into vermicompost containing readily absorbable nitrates, phosphates, calcium, potassium, and magnesium for plants. Species like Eisenia foetida are preferred for their high reproductive rates, quick organic matter processing, long lifespan, and resistance to temperature drops [87].

Vermicompost, rich in nitrogen, phosphorus, potassium (NPK) combinations, micronutrients, nitrogen-fixing bacteria, and beneficial bacteria, enhances soil aeration, moisture content, and the biodiversity of plant nutrients [88]. The mature vermicompost is odourless, non-sticky, and brown, with 25 - 30% moisture content, serving as an ideal substrate for plants and yielding high-grade fertilizers. The application of vermicompost in agriculture improves soil aeration, water-holding capacity, and nutrient levels, with researchers utilizing vermicompost from various organic wastes to enhance agricultural production [89].

Despite its benefits, immature vermicompost application may lead to crop toxicity and an increased risk of disease-causing pathogens, as vermicomposting lacks a thermophilic phase. To address these challenges and enhance efficacy, researchers integrate vermicomposting with other treatment techniques. Mengistu et al. [79] found that combining window composting and vermicomposting effectively reduced pathogens in municipal solid organic waste and dried faecal sludge. Amouei et al. [90] demonstrated the agricultural value of vermicompost from wastewater sludge and household solid waste, resulting in increased plant nutrient concentrations and reduced heavy metals. Nsiah-Gyambibi et al. [19] enriched the substrate with organic soils and coconut coir during faecal sludge vermicomposting, creating a more suitable microclimate for earthworm development and improving the end product's quality.

Vermicomposting is a simple technology and is suitable for moist organic wastes like faecal sludge. It has very high agricultural value as it produces very rich compost with reduced heavy metals concentration, and can improve aeration, water holding capacity and aggregation stability in farmlands. Vermicomposting doesn’t guarantee energy recovery and it has a high risk of pathogen contamination due to the absence of a thermophilic stage. Based on these, since vermicomposting should not be seen as a final treatment technique, it is not a sustainable faecal sludge treatment technique in refugee and IDP camps.

3.6.7 Anaerobic digestion of faecal sludge

Anaerobic digestion, commonly known as fermentation, is a process of organic waste decomposition in the absence of oxygen, resulting in the production of biogas and an effluent with reduced organic content [91]. Employing specific microorganisms, anaerobic digestion converts organic substrates into methane, carbon dioxide, and trace gases. The process involves four growth phases: lag, log, stationary, and death or decline [92]. The activities of anaerobic microorganisms lead to three biochemical processes: hydrolysis, acidification, and methanogenesis.

The hydrolysis phase breaks down complex molecules into simpler ones, and during acidification, these molecules are converted into organic acids and alcohols, ultimately forming acetic acid. In the methanogenesis phase, acetic acid is transformed into methane and carbon dioxide. Temperature fluctuations are common in anaerobic digestion, with mesophilic digestion occurring at around 37°C and thermophilic digestion at 50 - 60°C [93]. Mesophilic digestion is less sensitive to temperature changes but may not eliminate certain pathogens, prompting the application of sterilization or pasteurization to reduce pathogenic risks in the digestate [91].

Thermophilic digestion removes harmful microorganisms effectively, but it demands more energy due to the elevated temperature. The important factors influencing the anaerobic digestion of faecal sludge include substrate C/N ratio, temperature, total solid concentration, pH, bioavailability of compounds, retention time, mixing facility, and digester design. The age of faecal sludge and its C/N ratio are crucial for efficient digestion [94]. Aged faecal sludge may produce less gas, prompting the addition of fresh sludge to increase gas production [94].

Co-digestion with other organic waste materials can enhance the C/N ratio, thus increasing biogas yield. The mixing ratio in co-digestion is vital for optimal results. The benefits of anaerobic digestion in treating faecal sludge are numerous, making it sustainable in overloaded sanitary facilities, such as those in refugee and IDP camps [95]. The process offers low operational costs, positive energy balance, nutrient reuse, and the ability to withstand high organic loading rates. The daily energy generation of an individual can address the energy problem in such camps [91].

While the health risk associated with anaerobic digestion is relatively low, thermal treatment of the digestate before agricultural use can further mitigate potential risks [91]. However, economic evaluations are essential to assess whether the benefits of co-digestion, such as improved gas production, outweigh the costs incurred in transportation, pretreatment, and storage of the organic feedstock [96].

Additionally, anaerobic digestion can contribute to waste management and environmental sustainability. It reduces the volume of faecal sludge, minimizing the need for landfills and decreasing the environmental impact. The resulting effluent, when properly treated, can be safely discharged or reused, further promoting environmental conservation.

In conclusion, anaerobic digestion stands as a promising and sustainable solution for treating faecal sludge in various settings. With its potential to generate energy, reduce waste volume, and contribute to environmental sustainability, the benefits of anaerobic digestion outweigh the challenges associated with its implementation. As advancements in technology and process optimization continue, anaerobic digestion is likely to play an increasingly vital role in addressing faecal sludge management challenges globally. Anaerobic digestion effectively processes high moisture content wastes, including faecal sludge, with low operational costs, high energy recovery, and the ability to meet people's energy demands. It produces nutrient-rich manure with low pathogen concentration, making it a sustainable treatment technique despite the 8-week digestion time.

3.6.8 Black soldier fly (BSF) larvae composting

The Black Soldier Fly (*Hermetia illucens L.*) is a native species of the Americas, widely found in temperate and tropical regions globally. Its larvae exhibit a remarkable ability to consume a variety of organic materials, including faecal sludge, animal manure, agricultural wastes, and brewery by-products [97]. This bioconversion process by Black Soldier Fly larvae has gained recognition as an effective circular bioeconomy strategy, converting organic waste into valuable resources. The primary products of this bioconversion are the larval biomass and a nutrient-rich residue known as frass [98]. The larvae, boasting high protein (35% - 50%) and lipid (17% - 36%) content, are utilized in fish feed, offering economic gains and improving fish health and growth rates [99]. Simultaneously, the frass, rich in nutrients, serves as an organic fertilizer, preferred for its low energy and water demands compared to inorganic fertilizers, contributing to reduced environmental impact [100]. Compared to vermicomposting, which is notably slow, requiring a minimum of 8 weeks for a modest reduction in organic wastes, BSF larvae bioconversion achieves a substantial 70% volume reduction in just 2 weeks [39]. This quick process aids in reducing solid waste in landfills, subsequently lowering landfill costs and greenhouse gas emissions. BSF larvae can effectively mitigate odorous compounds emitted during the decomposition of faecal sludge and other organic wastes. The larvae also exhibit the ability to reduce microbial contaminants, heavy metals, non-essential elements, and pharmaceuticals during bioconversion, contributing to a sanitized end product [101-102].

However, challenges arise from potential pathogen contamination in the frass and heavy metal accumulation in larvae. Thermal treatment of frass before agricultural use and the use of mature larvae in animal feed help address these concerns [98, 103]. In conclusion, the Black Soldier Fly larvae's bioconversion of faecal sludge presents an innovative and sustainable approach, offering economic benefits, nutrient-rich by-products, and environmental advantages. As technologies continue to advance, integrating BSF larvae into waste management practices holds promise for more efficient and environmentally friendly systems.

The Black Soldier Fly larvae efficiently process moist waste like faecal sludge, reducing volume by up to 70% in 2 weeks. The resulting frass is nutrient-rich with minimal heavy metals. The larvae, rich in protein and lipids, serve as valuable animal feed, promoting a bio-economy. The technique poses low health risks due to larval antibacterial properties, making it a sustainable solution for waste management in refugee and IDP camps.

5.0 CONCLUSION

This review examined the commonly used on-site faecal sludge management techniques to determine their suitability in the management of on-site sanitary facilities in emergency settlements for refugees and IDP in tropical climate. Refugees and IDPs camps are categorically low-income environment with a very high population density that places much pressure on their inadequate sanitary facilities. The design and implementation of sustainable on-site faecal sludge management in such an overloaded low-income environment must consider the nature of the environment and objectives that affect the people directly. Hence, the most used on-site faecal sludge stabilization and treatment techniques were investigated based on the nature of emergency settlements and the peoples' needs. The use of mechanical presses, planted drying beds, and solar greenhouse drying beds were found to be sustainable stabilization techniques due to their high efficiency, simple and cheap technology, and capacity to significantly reduce sludge volume. Planted drying beds have the additional advantage of offsetting some percentage of the operating and maintenance costs of the plant while solar greenhouse drying beds which are very suitable in the tropics due to the high solar radiation, can significantly destroy pathogens in the sludge.

On the treatment of the dewatered faecal sludge, although some thermal treatments can effectively destroy pathogens and produce nutrient- rich char, they should not be considered sustainable faecal sludge treatment options in these emergency settlements due to the intense pre-drying requirement which increases the input energy, complex technology, and high GHG pollution. The microwave treatment, anaerobic digestion and the black soldier fly larvae appear to be the most sustainable faecal sludge treatment techniques in these environments. Microwave treatment of faecal sludge is a sustainable technology because it can handle the moist faecal sludge, can significantly reduce waste volume, destroys pathogens and produces nutrient-rich biofertilizer with reduced heavy metals concentration. Microwave technique also generates gases for energy generation to solve the energy crisis in these environments. Although microwave uses relatively high technology, the maintenance cost is low and can be installed easily even in low-income environments. Anaerobic digestion is suitable for handling high moisture content, has a low operational cost, can withstand high organic loading rates, has high energy recovery that can sufficiently meet the energy demand of the people, and can produce very rich manure with low pathogen concentration.

The black soldier fly larvae are effective for handling moist faecal sludge and have the capacity to significantly reduce sludge volume by up to 70% in just 2 weeks to produce frass enriched with plant nutrients with very low heavy metal concentration. The resulting larvae are used as animal feed due to their rich protein and lipid contents and hence a major driver of bio-economy. The technique has a very low health risk as the larvae produce antibacterial that destroys pathogens. The adoption of these recommended techniques in the management of faecal sludge in emergency settlements will greatly improve the conditions of sanitary facilities in these environments and also improve their economies.

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