Faecal Sludge Management in Low to Middle Income Countries

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Abstract: Faecal Sludge (FS) Sludge Management in low to middle income countries is linked with flaws in several areas, such as institutional, gaps in knowledge, and economic unviability, which reflected in the absence of infrastructures and planned management systems that ensure the treatment and/or safe disposal of sludge and consequently, generate negative impacts in human health and on the environment. On-Site Sanitation systems, which although are predominant in these countries with an expected tendency to grow, are perceived as temporary solutions until sewers are built.

Despite FS and Sewage Sludge are often viewed as valueless residues, both have characteristics and constituents that allow valorization routes, mainly energetic and agricultural, that can enhance the economic viability of sludge management, due to revenues generated through the commercialization of sludge-based products and attraction of external financing and subsidies regarding the additional positive environmental and socio-economic impacts generated.

The present dissertation has the objective to review the most relevant treatment and disposal methods, regarding the low to middle income countries context, and discuss some of the important aspects that should be considered in the early planning stages of a sanitation intervention. Additionally, it will be presented a diagram with the objective of assisting the decision-making process.

Key Words: Faecal Sludge, On-Site Sanitation, Low to Middle Income Countries, Faecal Sludge Management, Treatment, Final Disposal, Valorization.

1. Introduction

Proper sanitation is among one of the greatest achievements in human civilization, regarding human health, considering it opened the possibility of safe management of excreta generated in large urban areas, where the population density is high.

There are two types of sanitation systems implemented worldwide:

- **Sewered-based sanitation**: Centralized systems which direct the wastewater, through a sewer, to a WWTP. Sewage sludge is generated in wastewater purification, generally by applying sedimentation and biological processes.
- **On-site sanitation**: Decentralized systems, such as septic tanks or pit latrines, that store the human excreta in the place where it is generated. Faecal Sludge (FS) is defined as the mixture of excreta and other matter that might enter the compartments, such as black or grey water, anal cleansing material, and other solids. Attending to the nature of these systems, FS management compromises all the stages required for the safe dealing of FS (Figure 1-1).

On-site sanitation systems are cheaper (according to [1] up to 5 times), simpler, and less resource-intensive (water and energy) compared to sewered-based systems, which makes them predominant in low/middle income countries. Controversially, these are often perceived as temporary solutions until the sewers are built [2], which leads to a lack of investment and investigation, and unproper operation of FS management. Furthermore, the construction of centralized sewered systems remains, in most cases, technologically and economically unviable, resulting in several health and environmental impacts associated with unsafely managed excreta. According to [3], more than 50% of the FS generated in 39 low/middle income countries' cities, were found to be illegally dumped into water bodies and even urban areas, while the author of [4] report cases where this number might be above 90%.

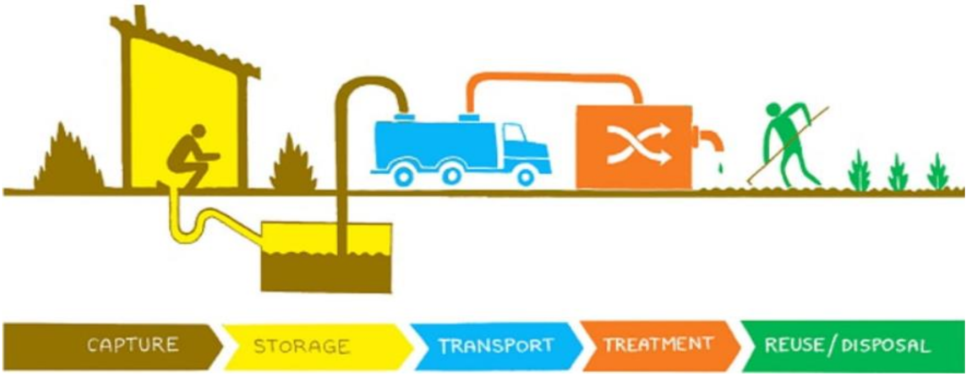

Figure 1: Stages of Faecal Sludge Management [5].

In 2015, 2,7 billion people worldwide were using on-site sanitation systems, and this number is expected to grow to 5 billion, in 2030 [1], attending to population growth and supplying sanitation services in areas where open defecation is practiced - objective 6 of the SDGs. It is clear the need to act, and to implement safely handed FS management structures.

Although there were identified problems in all stages of FS management, the present article is only going to address those related to treatment and disposal. It is reported in the literature that most areas lack treatment facilities and disposal plans, due to economic unviability, gaps in knowledge, and institutional weak structures [1,2,6,7].

Importance of Faecal Sludge Valorization

To achieve FS management systems feasibility, it is necessary to cover costs throughout the life cycle of the combined infrastructure and services [8], considering the four main forms of income: 1) Tariffs collected to the users of the service; 2) Taxes raised by the government and reinvested in the sanitation systems; 3) External founding of international donors such as NGOs; 4) Revenue generated through the sale of FS based products [8]. On the other hand, there are reported flaws in all four of them:

1. The users cannot afford the high tariff value and choose to illegal dump the FS.
2. The tax money is not reinvested on on-site sanitation systems since it is considered a temporary solution.
3. The reported unplanned sanitation systems do not attract external funding.
4. In the majority of low/middle income countries, the potential of the FS market is untapped due to illegal dumping, landfilling, or selling below value [6].

Despite being perceived as a residue, FS characteristics and composition allow several valorization routes, by applying certain levels of treatment. Moreover, circular economy sanitation could be a driver to implement economically viable FS management systems [9], not only with the direct revenue of the FS-based products but considering that the positive environment and social-economic impacts could enhance internal and external funding [10].

2. Faecal Sludge Composition and Properties

FS composition and properties have a wide range of values, due to macro-scale factors, since different types of on-site interfaces (e.g. septic tanks, dry pit latrines), frequency of sludge removal, and social-cultural factors (e.g. diet, disposal of black or grey water, coarse solids dumping) have a huge impact on FS quality. Moreover, this variability is also verified at micro-scale, considering that samples from the same plant can have significantly different results, due to FS heterogeneity.

FS composition can be distinguished mainly to Total Solids (TS) and moisture content, which have a close to conversely proportional behavior. It is important to quantify them since they determine whether the sludge acts like a liquid (TS <5%), slurry (TS 5-15%), semi-solid (TS 15-25%) and solid (TS > 25%) [3], which is crucial in the selection of treatment and disposal options. TS can be divided either into Suspended and Dissolved Solids or Volatile and Fixed. Fixed solids are often related to the stable fraction of sludge (inorganic) while the volatile solids (VS) to the unstable fraction (organic matter). The relation VS/TS is often used in literature as an indicator of sludge stabilization, where high ratios indicate low stabilization levels. Moisture (water) often represents the largest fraction component in raw FS, and it mainly can be in four main forms: 1) Free water – water in free surface, representing the biggest fraction of water in sludge and easily removed with solid-liquid separations processes [1]; 2) Interstitial water – water inside the flocs bounded with capillary forces, removed either with dryings or strong mechanical forces [4]; 3) Intracellular and Surface water - water inside the cells and attached to the surface of solid particles by adsorbent forces, mainly removed by drying [9].

Chemical Oxygen Demand (COD) accounts for the total mass of oxygen required to oxidize a certain volume of FS, normally expressed in mg/l. This indicator is especially important when discharging the water fraction of sludge, obtained through liquid-separation and dewatering processes, into water bodies. Furthermore, the Biochemical Oxygen Demand (BOD), oxygen required to oxidize a certain volume of FS through biological processes, thus being related with organic matter. Similar to the VS/TS ratio, the BOD/COD ratio is often used to assess the level of sludge stabilization.

Regarding the natural nutrient cycle and the fact that FS is an excreta-based residue, it has significant amounts of nutrients in its composition (mostly nitrogen, phosphorous, and potassium), which can be a driver to valorization, e.g. agriculture [1]. On the other hand, raw FS is likely to contain high pathogens concentrations that pose a danger to human health, and thus, to allow valorization, generally requires treatment levels, depending on the foresighted human contact. Although there are several types of pathogens, viable Helminth eggs are the most relevant to quantify, considering that they were identified as the most resistant ones and consequently, low concentrations of them indicate a low concentration of the others [11].

*Table 1: FS versus SS (Sewage Sludge) * parameters according to literature.*

Parameter	Unit	Value				Ref
		Septic Tank	Public toilets	Pit Latrine	SS*	
TS	%	< 3	> 3,5	3 - 20	1 - 90	4, 12
VS/TS		45-73	65 -70	45-60	60 - 80	1, 4, 12
COD	mg/l	<13 500	20 000-50 000	30 000-225 000	500 - 2500	1, 4, 15
BOD		840 – 2 600	7 600	-	200 - 1000	1, 4
Ammonia		< 1 000	<5 000	2 000 - 9 000	2 - 168	1, 4, 11
Phosphorous		150	400	450 - 500	9 - 63	1, 4
Helminths	nº / L	600-16000	2500-60000	30000-40000	300 - 2000	1 ,4

Heavy metals are also present in FS composition, and despite normally being in low concentrations, it is important to monitor them, especially when FS is co-treated with sewage, or a potential source of contamination is identified. Heavy metals can limit land application, either on agriculture or non-agriculture land, and impose problems on landfill disposal. Furthermore, the thresholds should be based on the toxicity of the metal, considering that some are more harmful than others, e.g. iron, zinc, chromium are micronutrients and can be beneficial in small concentrations versus cadmium and mercury that even in small concentrations are prejudicial [3].

Among all thermal properties, the calorific value of FS is particularly important to establish energetic recovery methods. It is based on fixed carbon and volatile solids and considering that FS has generally low amounts of fixed carbon, FS calorific value is highly dependent on volatile solids concentration. Henceforth, digested sludge has usually a significantly lower calorific value when compared to fresh FS. According to [13], the values range from 8,3 to 19,1 MJ/kg.

On the other hand, FS stabilization has also a significant effect on the sludge capacity to dewater, especially in liquid-solid separation, with digested sludge performing better and fresh sludge more poorly [4].

3. Faecal Sludge treatment

The main objective of FS treatment is to reduce or eliminate the characteristics and constituents that make the disposal option either unsafe or inviable (e.g. pathogenic, unstable organic matter, and excessive moisture content). Moreover, when considering valorization routes, the treatment scheme should be projected in order to retain or enhance the ones that are beneficial (e.g. nutrients or heating value).

The main three concepts associated with FS treatment are:

- Moisture Reduction: Considering most raw FS volume is often moisture content, it is highly relevant to reduce it to consequently reduce haulage, further treatment, and disposal costs. In addition, it is beneficial/required to achieve certain values of TS content to apply some treatments and disposal methods, usually in valorization routes.
- Sludge Stabilization: Unstable organic matter is often associated with odors, vector attraction, and pathogens, which pose danger to human health. Thus, it is important to apply sludge stabilization methods, especially in valorization routes.
- Sludge Sanitation: Although the stabilization methods reduce the pathogenic load, some of them do not guarantee the required target, considering the disposal method. In these situations, sludge sanitation processes are applied, which are conceived to further reduce/eliminate them.

Pre-Treatment - screening processes are designed to remove coarse solids (e.g. paper, rags, plastic, and glass), and generally represent a crucial step in FS treatment in order to prevent clogging of downstream equipment and/or to enable further treatment processes.

Grit removal, homogenization, or equalization tanks might be used in particular situations.

Thickening – processes that are designed to remove free water, via solid-liquid separation, to reduce the moisture content of the sludge to levels around 5-15% TS. The most used/relevant technology, attending the low/middle income countries context, are settling tanks, which are based purely based on gravity force [14]. The system consists of a tank where: 1) An inflow of sludge enters the tank on one side; 2) The retention time on the tank allows the retention of most settable solids (solid phase); 3) A supernatant outflow leaves the tank on the opposite side of the inflow. Although this technology is cheap and easy to implement, in some cases, usually in large-scale FSTP, the low sludge processing rate (due to the high retention times) might hinder the operation. Thus, it should be considered gravity thickeners, widely used in WWTP, which are based on the same principles, but with a mechanical sludge removal system and higher treatment capacity. On the other hand, the costs are higher.

Settling ponds are based on the same mechanism as settling tanks, but with higher retention times (normally 6 months). Although this might pose logistic problems, the anaerobic conditions at the bottom of the pond, allow natural anaerobic digestion to occur and to stabilize the sludge. The main reasons for applying settling ponds and not settling tanks are to partially stabilize sludge to improve the dewatering capacity or as a pre-treatment step to co-treat FS with wastewater, in order to reduce the pollutant load (e.g. BOD) [15].

Dewatering - processes that are applied to reduce moisture content, by removing free-water, interstitial water, and in most cases intracellular and superficial water.

Unplanted Drying Beds: Widely used technology in which sludge is discharged in a bed, with a filter media (usually made of sand and gravel) with a bottom drainage system to remove the leachate. The system is based on percolation to remove mainly free water and sun drying to further dewatering. The treatment cycles are in order of weeks, with the sludge being removed at usually 20-30% TS. The treatment efficiency is highly dependent on climate, with hot and dry weather being beneficial to the method [1]. With higher retention cycles and optimal conditions, sludge can dewater to 90% TS [16]. This technology is cheap and easy to implement, but with large area requirements.

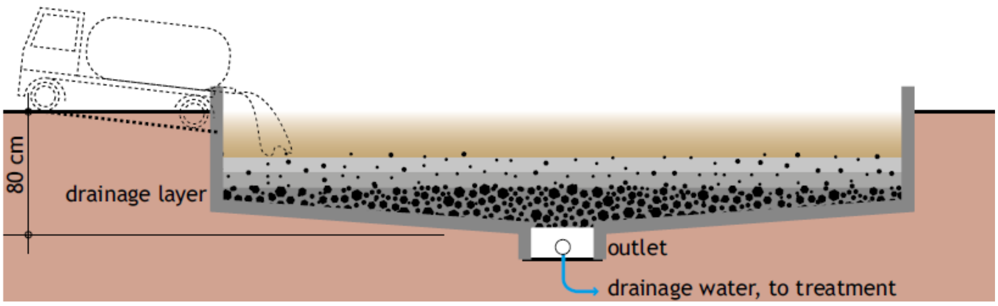

Figure 2:Schematic overview of unplanted drying bed configuration [1].

Planted Dryings Beds: Similar configuration to unplanted dryings beds, but with macrophytes plants planted in the media, that are beneficial to prevent clogging and enhance stabilization processes [1]. Unlike unplanted drying beds, sludge is continuously fed to the bed (normally two times a week) where it can be retained for years (normally 4 or 5). Due to the high retention time, the treated sludge is stabilized with some characteristics being similar to matured compost, although further sanitation processes might be necessary [17]. This technology is not yet proven to FS treatment at a large scale and is associated with large area requirements.

Mechanical Dewater: Usually these systems consist of three phases: 1) Mechanical Thickening, to remove free water; 2) Sludge conditioning, which is the addition of a substance (normally a polymer) to improve the dewaterability; 3) Dewatering processes by application of a mechanical force [18]. Due to the high capital and operational costs, there are few applications of these methods in low/middle income countries, being the Screw Press and Belt Filter Press the most used [14]. These systems dewater sludge to 15-25% TS [18] and should only be considered with dryings beds are unviable (usually due to area requirements).

Solar Drying: Similar configuration to unplanted dryings beds but without the filter media and drainage system since these systems are purely based on solar dryings to remove moisture. This method is applied to dewater sludges with very low concentrations of free water, considering the other methods remove it with a preferable cost to benefit ratio. The sludge can reach values up to 90% TS, being the treatment efficiency highly dependent on climate, with hot and dry weather being beneficial.

Thermal Treatment: Removal of water by application of heat from anthropogenic sources, usually applied to sludges with low free and interstitial water concentrations since the other methods remove them with a preferable cost to benefit ratio. Henceforth, this method is associated with high operational costs and should only be considered when drying beds or solar dryings methods are unviable. The sludge is normally dried to 40-60 TS% but this value can be up to 90% [12, 18]. Additionally, due to the high temperatures of the process, the treated sludge is fully sanitized.

Anaerobic Digestion – Process based on naturally occurring processes, in the absence of oxygen, by the action of microorganisms to produce stabilized matter with fertilizing properties (digestate) and biogas. There are mainly two types of anaerobic digestion, Mesophilic and Thermophilic, differing to the operation temperature, 20-45°C, and 50-80°C, respectively [19]. Mesophilic Digestion is associated with lower costs, making it the most common in low/middle income countries, but the temperatures versus the residence time in the reactor do not guarantee the sanitation of the digestate, while thermophilic digestion does. Generally, the FS feed is liquid, and the system operates in continuous mode. According to [20], FS can be co-digested with other residues, such as agricultural waste and manure, enhancing the biogas quality and quantity produced.

Lime Treatment - Lime is added to liquid or solid FS to raise pH to around 12, for at least 30 minutes, and inducing a petrification state that inactivates pathogens and reduces odors [1]. The treated FS is stabilized/sanitized and has soil conditioning properties.

Co-Composting - Aerobic process based on natural mechanisms by the action of microorganisms to produce a hummus-like product. Composting cycles last around 6 to 8 weeks, which includes a phase that the heat generated by the bacteria reaches thermophilic levels to promote the inactivation of the pathogens. On the other hand, generally, FS does not have the optimum composting required characteristics, especially a low C:N ratio, which may limit pathogen inactivation and final product quality [21]. Hence, FS is usually mixed with high C:N ratio residues such as the organic fraction of municipal solid waste or sawdust. When properly done, the final product is classified as a high-quality organic soil conditioner [21].

Extended Storage - Sludge is stored to reduce its pathogen load, based on natural die-off. The storing site is usually closed to protect FS from rain, where it is stored for at least 6 months, keeping in mind that longer periods are associated with higher inactivation levels. According to [26], hotter climates are optimal for the process.

Pasteurization – Use of heat from anthropogenic origins to inactivate pathogens. According to [22], 50°C and 55°C, during 60 and 5minutes, respectively, were sufficient to reduce helminth egg concentration to below 1egg/g ST. Due to high operation costs, pasteurization should only be applied whenever extended storage is unviable, generally due to high area requirements and/or low processing rate.

Carbonization - Thermochemical transformation of LF into char (carbon-like product), by the action of heat, generally 300-500 °C, in the absence of oxygen, from minutes to days [23]. The

FS feed should have at least 60-70% TS and can be co-carbonized with other organic residues [14]. The final product, char, is fully sanitized and can be used as a solid fuel or organic soil conditioner.

Incineration - Total combustion of FS, generally at temperatures around 850-900 °C, to reduce them into ashes, at around 10% of the original volume, which are normally disposed at a landfill [1]. From the energetic point of view, it is beneficial to reduce FS moisture, to at least 50-70% TS [13].

Briquetting/Pelletizing - Compressing FS into briquettes or pellets to facilitate transportation and commercialization. Other residues/materials can be added to the mixture to act as a binder or to enhance the market value of the product, such as coal dust to produce fuel briquettes. To maintain structural stability, it is recommended that FS feed has around 50-60% TS [24]. Henceforth, it is reported in the literature that briquettes can passively dewater from 40-60% to 90% TS in a week under optimal atmospheric conditions [9, 25].

4. Faecal Sludge Disposal

Final disposal compromises the last stage of FS management, being crucial to ensure the safe handling and disposal of FS, regarding environmental and human health impacts. Furthermore, whenever possible is preferable to apply valorization routes that might offset significant fractions of operational costs of the operation through direct income (commercialization of FS-based products) and/or attraction of external funding considering additional positive impacts on the social-economic and environmental dimensions. The main disposal methods identified were energetic valorization, land application, and landfill disposal.

Legal Context and Regulations

According to [7, 26], the majority of low/middle income countries, especially in Africa, do not have a legal framework regarding FS disposal and the level of monitorization is low or none. In these situations, is preferable to adopt regulations proposed by international organizations and/or other countries, that are suitable regarding the economic and technical context of these countries. One of the examples is the WHO regulations that state that the pathogen concentrations in the final product should be adapted to the expected human contact, with no restrictions applied regarding pathogens at values below 1egg/ gTS [17]. On the other hand, most of the existent regulations are applied to land application methods, while energetic valorization is often neglected.

Land Application

Soil additives can either be classified as fertilizers, which consist of high nutrient products that aim to enhance plant growth, or soil conditioners, which consist of the reposition of soil organic matter to improve soil properties, such as water retention and structure.

Due to the capitalistic short-term view of agriculture, globally there is a trend to use inorganic fertilizers (mainly N, P, K based), only intending to enhance the yield of the next crop. According to [19], these intensive agriculture practices are damaging soils worldwide due to the non-reposition of organic matter and secondary and micronutrients, such as S, Ca, Mg, Zn and Fe. The same author estimates that 80% of the agricultural sites suffer from erosion and in the last 40 years 30% became unproductive.

In this context, land application of FS might be relevant in mitigating these impacts considering it aims to recycle the nutrient content and organic matter of FS, to produce organic fertilizers and soil conditioners. Furthermore, unlike nitrogen, phosphorous is a mined substance only available in some countries and [4] states that in a long-term view we might suffer from a phosphorous shortage. Considering that 25% of the global phosphorous ends up in water bodies or landfills [17], the land application of FS might be crucial in mitigating these impacts.

FS land application can be distinguished in the commercialization of FS-based products (generally for agriculture purposes) and land disposal (valorization without commercialization, generally in non-agriculture areas). When applying FS to soil it is important to ensure that the agronomic rates are not exceeded (to avoid nutrient leachate) and the heavy metal concentration is adequate to the soil characteristics. Furthermore, is crucial to ensure that the FS pathogens concentration is suitable with the projected human contact, as recommended by the WHO. E.g. the required level of pathogen reduction in agriculture versus non-agriculture purposes. Additionally, it is recommended that unstable should be applied on the soil surface since it has a potential vector attraction due to odors

Agriculture application is generally associated with the commercialization of FS high-quality products that went through several stages of treatment, either to comply with the pathogens thresholds but also to have a similar or higher quality compared to concurrent market options. The main routes of treatment are co-composting, planted drying beds, lime treatment and carbonization to produce soil conditioners, and anaerobic digestion to produce organic fertilizers. Additionally, depending on the desired final product quality, sanitation or compaction processes may be applied. On the other hand, non-agriculture application (land disposal) is often associated with lower quality FS products that do not comply with the agriculture standards but still have fertilizer and/or soil conditioner value, such as untreated FS or FS from drying beds. To achieve higher quality products, it is necessary to apply further treatments that presuppose an economic return via commercialization that is unlikely to happen in the non-agriculture routes. Since is it likely that the FS is not properly stabilized/sanitized, the public access of the disposal site is generally restricted, while the FS is often buried using the method "deep row entrenchment", to reduce human and animal contact [27]. Trees are then planted above the disposal area, while the sludge is naturally treated over the years, supplying them with nutrients, and improving soil characteristics, making this method relevant for wood production purposes and forest areas rehabilitation. The main constrain of land disposal is to find eligible disposal areas that comply with safe buffering zones from dwellings, surface, and groundwater, and so on, being the restrictions tighter for liquid FS due to the higher possibility of leaching.

Energetic Valorization

Energetic valorization presupposes the use of FS (generally treated) as a fuel, taking advantage of its heating value. Besides the mitigation of sanitation impacts, these methods can be relevant in the low/middle income countries' context, since the use of solid fuels, especially wood (either raw or carbonized), is predominant. One example is Uganda, where, according to [28], 78,6% of the household energy consumption is wood-based. These consumption patterns put tremendous pressure on forests, which is likely to increase due to population growth. According to the World Economic Forum, in 2020, 50% of the wood extracted from nature worldwide is for fuel use. Considering that FS heating value is comparable to other biomass fuels, its use as a fuel can be a sustainable solution to offset significant portions of wood consumption and have positive environmental impacts such as in ecosystems and in CO2 emissions. FS-to-energy can be associated with commercialization routes or internal use in the plant and can be distinguished in both solid fuels and biogas, which can be later transformed into electricity.

The main forms of solid fuels are dewatered FS briquettes (normally dried to around 90% TS) or FS carbonization. To enhance the calorific value of the final product and its market value, other high heating value residues, such as coal dust, can be added to the mixture. This is especially important in FS carbonization considering that the process reduces significantly the volatile solid fraction of FS, thus reducing the final product heating value. FS carbonization is more likely to be a relevant method whenever there is demand specifically for carbon-based fuels, e.g. co-combustion with coal for energy production.

Biogas can be produced through FS anaerobic digestion and is considered a high-quality and sustainable energy source. As mentioned, biogas can be converted to energy which can be relevant, considering objective 7.1 of the SDGs – supply of sustainable electricity to all populations in 2030. Generally, the biogas or electricity produced are sold, but there are also reported cases of internal use in the plant.

Landfill Disposal

Landfill disposal can be defined as the planned burial of FS and is a method that does not valorize the residue. Considering that there is a disposal fee, generally, in USD/ton, it is often advantageous to reduce FS moisture content to reduce the disposal costs but also haulage. Additionally, most of the landfills require FS with a TS content above 20%, to minimize the leachate [29]. Another option is FS incineration and the landfilling of the remaining ashes.

Although there are main concerns that properly engineered landfills must have, e.g. proper location, ground impermeabilization, leachate treatment, and cover from rain events, most of these disposal sites in low/middle income countries do not have them, resulting in negative impacts on both ecosystems and human health. The author of [30] studied 31 landfills in 13 countries in Sub-Saharan Africa and concluded that around 80% are not properly designed.

5. Discussion and Additional Relevant Factors

When properly applied, all the disposal methods mentioned in this article ensure the safe disposal of FS. On the other hand, whenever possible it is preferable to apply valorization methods either to enhance the economic viability of FS management but also to promote external positive economic, social, and environmental impacts from a long-term perspective.

It is important to understand that is unlikely, especially in big urban areas, to apply a single disposal method that is capable to support the entire FS generated. Thus, it is relevant to access all the possible options, regarding the local context, compared them including the external impacts, and apply the most beneficial method to the fraction of the FS that they can support. For example, considering a city that generates 100 m^3 FS/day, after an options analysis, it was concluded that the most beneficial disposal scheme is to co-compost 30 m^3 FS/day, 20 m^3 FS/day for fuel briquettes, and the remaining 50 m^3/day are landfilled due to the inexistence of further viable valorization options. Additionally, regarding On-Site Sanitation systems, it is crucial in the planning process to adjust the scale of operation. Bigger scales tend to reduce the operational costs per ton FS treated, but on the other hand increase significantly the haulage costs. Thus, even considering the same disposal method, e.g. commercialization via co-composting, it might be beneficial the implementation of several decentralized FSTP over centralized plants [11, 14].

The option accessing and comparing process is extremely complex due to a large number of impactful variables. Henceforth, it is crucial that the planner analyses in detail the application context, regarding factors such as availability of other residues flows that might be relevant to co-process with FS, municipality plans that could attract subsidies and financing, existing infrastructures that are able to process FS, and so on, to establish the disposal configuration that enhance the benefits regarding environmental and social-economical dimensions at a long-term view.

Commercialization methods viability is strongly dependent on market factors such as market existence, FS-based products acceptability, and quality of the final product versus market competitors.

Land Disposal of FS is an effective valorization method but might be limited, especially in medium to large, mainly due to area restrictions.

FS landfilling should only be considered when valorization methods are not viable, and the planner must ensure that the disposal site is properly engineered to prevent negative impacts. If this condition is not verified, the disposal site should be improved, or a new landfill construction should be considered. Until a proper disposal site exists, efforts should be made to retain FS in compartments or in the FSTP, if bigger negative impacts are projected.

When a disposal method is being applied and more beneficial one exists but is unviable, e.g. landfilling versus valorization methods, the limiting factor should be identified and efforts should be made to apply it, e.g. consumer education in case of product unacceptability and finance of subsidies attraction in case of economic unviability.

6. Conclusions

On-Site Sanitation systems play a relevant role in supplying improved sanitation in low/middle income countries, with an increasing tendency due to population growth and the established objectives of the SDGs. However, FS management chains are linked with several flaws, mainly attributed to economic factors, that result in the absence of proper treatment and illegal dumping of FS. While these practices exist, a population should not be considered open defecation-free, regarding the negative impacts on the environment and public health.

Although FS is often perceived as a valueless residue, it contains several characteristics and compositors that allow valorization routes. The main ones identified were energetic valorization, taking advantage of FS heating value, and land application (either with or without commercialization), taking advantage of FS nutrient content and organic matter recycling on soils. These disposal methods can be a driver to enhance the economic viability of the operation regarding direct revenue of the FS-based products commercialization (circular economy sanitation) and/or attraction of external funding due to the additional positive impacts in the environmental and socio-economic dimensions. Whenever these methods are not viable, proper landfilling should be considered.

Regarding all the disposal options, treatment methods should be applied to FS, with the thickening/dewatering processes assuming especial relevance, considering volume reduction and consequent transport, further treatment, and disposal costs reduction. In the valorization routes, it is important to ensure that the pathogenic load do not pose dangers to human health considering the expected human contact.

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