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Review

Managing Non-Sewered Human Waste Using Thermochemical Waste Treatment Technologies: A Review

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Abstract: The utilisation of micro-scale thermal treatment technologies for non-sewered applications has been emerging as a prominent route for the safe treatment and disposal of high water content hazardous feedstock. This study provides a comprehensive review of the technological concepts practiced up to date in commercial/pilot and small scales for various types of solid fuels. The respective challenges are critically described and discussed to aid in the selection of promising technology for on-site sanitary applications. Furthermore, the challenges observed with the nominated (pyrolysis) technology are discussed in detail and addressed. This study suggests rapid energy recovery from by-products primarily made up of the highest yield of syngas with a desirable calorific value. The optimum operating ranges are discussed to ensure a reliable thermal conversion of sludge materials considering the application constraints and technology drawbacks. However, further studies are needed to investigate the uncertainties regarding emissions, energy consumption and overall associated costs.

Keywords: sewage sludge; faecal; combustion; gasification; pyrolysis; thermochemical conversion; syngas; bio-oil

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1. Introduction

The human population produces a significant amount of sanitary waste every year, up to 55.1 kg/person/year, which equates to an overall figure of around 385 million tonnes per year for a global population of 7 billion [1]. Human excreta is a hazardous waste that needs to be managed safely. Faecal sludge (FS) is a generic term referring to the mixture of undigested or partially digested slurry/solids resulting from the storage or treatment of black water or excreta with or without grey water [2]. In general, faecal sludge management (FSM) includes storage, collection, transport and treatment in wastewater treatment plants (WWTPs) and the safe end use or disposal of FS [2]. However, FSM also relates to non-sewered sanitation systems such as pit latrines and septic tanks [3]. Several organisations such as the international sanitation community, Water and Sanitation for the Urban Poor (WSUP) and The Bill and Melinda Gates Foundation have supported initiatives with a focus on FSM challenges in low-income countries [2–4]. In contrast to FSM, sewered sanitation is only concerned with wastewater/sewage treatment [5].

A typical wastewater treatment plant (WWTP) receives polluted wastewater from multiple sources, including municipal and commercial sources, in the form of water, human excreta, personal care products, etc. The two products of WWTPs are effluent and sludge, which need to be of adequate quality for disposal according to the Urban Wastewater Treatment European Directive (UWTED) in the EU [6]. Common methods of the disposal of treated sludge are landfilling, land application as a fertiliser and combustion. According to Eurostat [7], two of the commonly used methods in the EU have remained as agricultural use and combustion. However, land disposal and combustion are subject to increasingly strict regulations due to pathogen risks, greenhouse gas emissions from microorganism activities due to inefficient organic removal and a large amount of flue gas emissions, respectively [8]. Details about the European parliament and council directives can be found in [6,9]. Currently, the recycling of sewage sludge through agricultural lands is legal in the UK and accounts for almost 80% [10] of the overall volume. Land spreading is banned in some EU countries, such as the Netherlands, where combustion is favourable due to concerns over the safety of its use in farmlands [11]. These risks include the presence of pathogens such as Escherichia coli and salmonella, persistent organic pollutants, heavy metals and microplastics [12]. Hence, future resilience through the implementation of robust and sustainable treatment processes is of high importance to tackle associated challenges with such waste materials.

Despite several variations of WWTPs, most of them currently follow the same route for the treatment of wastewater/sewage sludge: (1) preliminary treatment, (2) primary treatment and (3) secondary treatment. An inevitable by-product of raw sewage treatment is the sludge generated from the primary and secondary steps. After removing large objects via straining with bar screens (preliminary step), the suspended solids in the water column settle at the bottom of the tank due to gravitational differences in the primary step. The sludge generated is a semi solid/slurry that includes 50–70% suspended solids, which is pumped toward the sludge treatment process. Further on, using biological processes, non-colloidal solids are removed and organic constituents are stabilised, namely 'secondary sludge'. The generated sludge is further treated following the sequence of thickening and dewatering (centrifuge, plate press, belt press, etc.), conditioning (thermal, chemical) and final treatment (composting, combustion, thermal treatment, wet oxidation, etc.), storage (liquid sludge, dry sludge, ash) and transportation for landfilling, agriculture or other uses, as depicted in Figure 1 [9]. All these methods aim for the stabilisation of the biodegradable fraction of the organic matter for reducing the risk of putrefaction, diminishing the concentration of pathogens, reducing weight and volume and odour elimination [13].

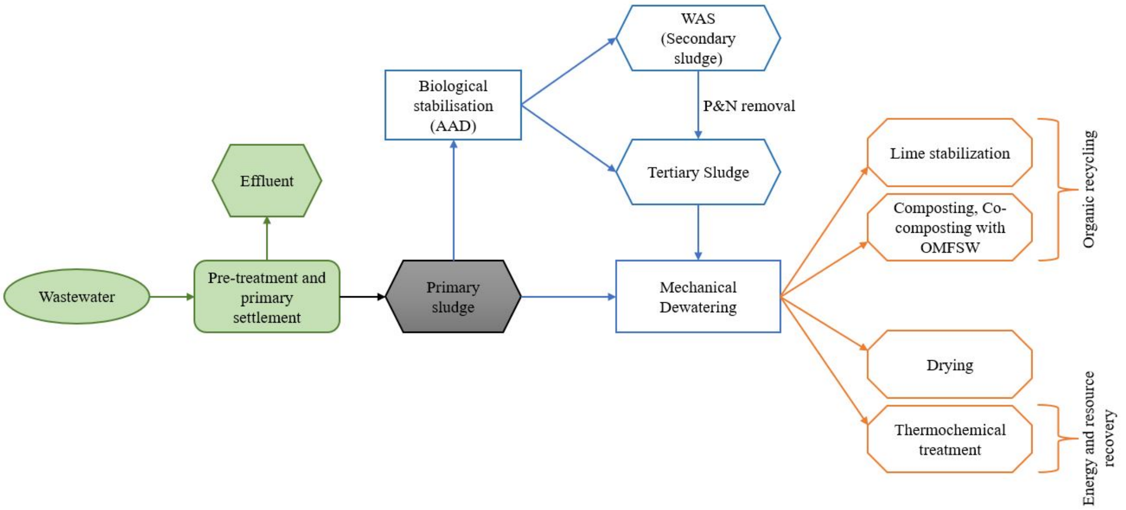

Figure 1. Sewage sludge treatment processes (AAD—Anaerobic digestion, WAS—Waste-activated sludge, OFMSW—Organic fraction of municipal solid waste) [9,14,15].

The characteristics of outputs from wastewater treatment processes depend on the production/treatment route pursued and the origins of the sewage. An example of a stabilisation technique for sewage sludge is anaerobic digestion in the secondary treatment step from which the product can be utilised as fertiliser. In addition, this process can recover energy by harnessing the biogas released from the digester [16].

One objective of this critical review is to discuss the solid waste management/stabilisation technologies and their operational challenges. The state of the art of these thermal treatment technologies for on-site, non-sewered, sanitary applications in small scale is reviewed to clarify the specific operational challenges occurring through their implementation. The aim of this study overall is to outline the challenges for developing a suitable technology for on-site sanitary applications and to address optimum ranges of operating conditions for a reliable performance.

2. Sewage Waste/Biomass Treatment Technologies

2.1. Anaerobic Digestion

Anaerobic digestion is a biological conversion process of organic compounds in an oxygen-free environment, producing biogas using microorganisms. The ability to utilise organic feedstock with a high moisture content without reducing the calorific value of the produced biogas is a major advantage of this technique. However, the reaction time ranges from 7 days to 5 weeks and the conversion efficiency of organic constituents from 30–60%; this is not sufficient for agricultural applications regarding their high organic content and poor biodegradability [17]. Digestate from the anaerobic digestion of sludges is still likely to pose biohazardous and other risks due to microplastics [12]. In addition, the volume of the treated sludges through biological means is observed to reduce only 5% of the original mass of sludge [18]. Dewatered sludge can be directly fed into the digester for biogas recovery; however, the high organic content of the digestate has emphasised the utilisation of a pre-/inter- and/or post-treatment step for maximum energy recovery and volatile organic conversion [19].

The overall aim of sludge treatment is to achieve the effective elimination of organic matter and a high recoverable energy content of sludge (11.10–22.10%) [20]. Therefore, thermal treatment technologies have proven to be attractive for resource and energy recovery, treatment and disposal of sewage sludge (SS).

2.2. Conventional Combustion

Thermal treatment processes include combustion and the emerging gasification and pyrolysis technologies. In comparison to anaerobic digestion, thermochemical conversion routes provide much shorter reaction times for the treatment of sludge (seconds to minutes). However, these processes require sludge with a lower moisture content where the decomposition of >90% of the organic matter occurs in the presence of a surplus oxygen, partial oxidising or anoxic (minimised oxygen) environment.

Combustion is used for medical and municipal waste [21]. Combustion is currently used for heat recovery from sewage sludge with the incorporation of a heat recovery step in the treatment process, but the traditional practice was only intended for a reduction in the volume and the elimination of harmful elements [22]. Combustion takes place at high temperatures (800–1150 °C) in the presence of surplus oxygen for the complete oxidation of organic matter, which delivers the transformation of carbonaceous materials into a flue gas consisting of oxides of carbon, nitrogen, sulphur and particulate matter, while releasing a substantial amount of heat and other trace gases and H_2O. Multiple hearth furnace (MHF) and fluidised bed (FBF) are the two common reactor types utilised for sewage sludge combustion, of which the MHF is suitable for wet sludge while the FBF is used for both wet and dried sludge. A major barrier for the cost and process efficiency of sludge combustion is the moisture content of sludge with the acceptable limit of <50% [23]. Hence, dewatered sludge undergoes a drying step after the dewatering stage to increase the calorific value of the fuel for thermal processing [20]. A high moisture content results in incomplete combustion as well as heat loss from the evaporation of the moisture content [23]. Additionally, it reduces the energy content of the sludge to 4 MJ/Kg (60–80% moisture content), which is inappropriate for autothermal combustion [24]. Therefore, this process is usually associated with the utilisation of auxiliary fuel and catalysts for the initiation and further reaction stability. This process offers a reduction of up to 90% in the volume of sludge, leaving an inert material (ash) for disposal. This is a potential product and could be used for the production of building materials [15]. A high ash content in SS is also thermally parasitic, which leads to incomplete combustion, thus forming a variety of pollutants such as polycyclic aromatic hydrocarbons and dioxins [25]. The high inorganic constituents in sewage sludge ash such as alkali-induced metals also cause further challenges such as slagging and agglomeration. A major challenge for the combustion of sewage sludge is the elevated amount of NO_x, SO_x, etc., which could be sourced from human activities (e.g., faeces) [26]. Different researchers investigated the pollutant emission of sewage sludge combustion, concluding a reduction in the concentration via lower combustion temperatures [20] and co-blending [27] for NO_x and SO_x, respectively. In a study by Han et al. [23], it was observed that SO_2 could also react with the water in the wet sludge and lead to the formation of H_2SO_3, a corrosive compound for metal surfaces. Although analysis on the concentration of heavy metals in the past studies on SS combustion revealed modest percentages below legal limitations, these studies still implicated the utilisation of efficient gas cleaning systems to capture the heavy metals present in the particulate matter and highly volatile species (e.g., Hg, Cd and Pb) in the vapours [28,29]. To address the problems mentioned above, recently there has been an increasing interest in an emerging method named 'co-combustion' by combining sewage sludge with other high-rank energy fuels such as biomass and coal [25].

2.3. Emerging Methods

Although combustion leads to a major reduction in the volume of sludge, the large amount of flue gas generated through the process incurs a high cost for their treatment as well as high energy consumption for pre-drying. Wand et al. [30] reported that the development of co-combustion with a slight modification in conventional combustion equipment for sludge has taken precedence over pyrolysis, gasification and mono combustion in large scales.

2.3.1. Co-Combustion

Co-combustion has been considered as a new route for net CO_2 reduction in sewage sludge valorisation. The utilisation of co-combustion/blending has mainly aimed for improving combustion reactivity and reducing pollutants and greenhouse gas (GHG) emissions. In a study by Rong et al. [31], a synergetic interaction between the rice husk and sewage sludge co-combustion was observed, while the reactivity between the blends was improved when the SS proportion remained <30 wt.%, resulting in the production of an ash with lesser slagging potentials. Moreover, Wang et al. [30] investigated the combustion behaviour of sewage sludge (SS) and wheat straw (WS) co-blending, where the combustion characteristics of SS were enhanced with the highest synergetic interaction in the presence of 50% WS.

2.3.2. Advanced Thermochemical Treatment (ATT)

The thermochemical conversion of sewage sludge is a promising alternative to biochemical practices due to its ability to decompose almost all organic parts (biodegradable or non-biodegradable) in a short period. In addition, there has been great interest towards the valorisation of sewage sludge and municipal waste into oil and synthetic gas via pyrolysis and gasification [22]. Advanced thermal treatment technologies are also capable of reducing the volume of waste, degrading hazardous organic matter and recovering hydrocarbon compounds from the residues rather than heat only. Additionally, the risk of producing dioxins, furans, SO_x and NO_x could be mitigated via restricting the environment in ATT processes [8].

Pyrolysis

Pyrolysis, together with the evaporation of bound moisture, is an initiating step in all thermochemical conversion processes occurring at moderate temperatures (350–600 °C) in an inert (non-reactive) environment. The decomposition of SS (organic matter) through this process results in the production of liquid pyrolytic oil (condensable volatile fraction), pyrolysis gas (non-condensable volatile fraction) and char (solid residue) [32]. The liquid pyrolytic oil has been upgraded for combustion in boilers or engines as well as electricity production [33]. The biochar derived through pyrolysis has been utilised as a solid fuel, an adsorbent for decontamination, a fertiliser for soil amendment and briquetting [14,34,35]. However, the char from sewage sludge has not been found suitable for heat recovery owing to its low heating value (5 MJ/kg) as well as the presence of a high concentration of heavy metals, which restricted its landfilling [32]. To address the challenges with the utilisation of char, researchers have focused on improving the quality of the char for soil productivity and the remediation of contaminants via feedstock chemical impregnation [36]. The syngas generated through thermal cracking of the tar in high temperatures (secondary reactions) is used in internal and industrial combustion engines [37]. Depending on the various operational parameters such as the heating rate and residence times, pyrolysis is classified into three main categories, namely slow, fast and flash pyrolysis [38]. Slow heating rates (0.1–1 K/s) and long residence times favour the formation of char [34], while lower or higher residence times in high temperatures with high heating rates result in liquid and syngas production, respectively [17]. Table 1 illustrates the process conditions in different pyrolysis modes where the residence times of volatiles for slow/intermediate, fast and flash pyrolysis are 10–30, <2 and 0.5 s, respectively [39]. Conventionally, fast pyrolysis has been used to produce pyrolytic oil, whilst slow/intermediate pyrolysis has favoured the formation of char and non-condensable combustible fractions. High heat influx involved with fast pyrolysis, as well as substantial heating rates for the rapid decomposition of dry matter, faces complexities regarding the pre-processing of the feedstock. Pre-processing includes operations such as particle size reduction and efficient drying to a range of 10% moisture content [40]. Park et al. [41] observed that larger particles in the sewage sludge led to incomplete fast pyrolysis due to a lack of uniformity. The liquid pyrolytic oil, especially the organic fraction, from fast pyrolysis contains a high heating value of ~33 MJ/kg, which makes the fast modes of more interest compared to slow pyrolysis. Hence, most previous research focuses on the production of bio-oil within fast pyrolysis of sewage sludge [22]. The production of pyrolytic oil through this process requires fast vapour removal and quenching to mitigate the chance of secondary reactions, resulting in the breakdown of longer chain species with high molecular weight to light gaseous products [41].

Table 1. Classification of pyrolysis process [38,42].

Pyrolysis Process	**Temperature (°C)**	**Heating Rate (°C/min)**	**Solid Residence Time (s)**	**Particle Size (mm)**	**Product Yield (%)**		
					Oil	Gas	Char
Slow/int	400–500	10	~500	5–50	30	35	35
Fast	400–650	100	0.5–10	<1	50	20	30
Flash	700–1000	>500	<0.5	<0.2	75	12	13

Product diversity and distribution are mainly dependent on process temperature, operational modes, reactor configuration and feedstock characteristics [43]. Different reactor designs have been established for pyrolysis depending on the desired final output (e.g., heat, electricity, liquid, syngas and/or char) as well as feedstock characteristics. For instance, fluidised bed reactors have been found suitable for the fast pyrolysis of biomass in commercial applications regarding their good temperature control and efficient heat transfer [39,42].

The chemical reactions taking place during pyrolysis are endothermic and are pursued in an inert (non-ignition) environment by means of external heat source. Hence, to address the energy intensity of pyrolysis, research on the partial/complete combustion of syngas and pyrolytic oil for the self-sustainability of this process has been carried out [44,45]. Since the desirable product from pyrolysis (mainly fast and flash modes) is the bio-oil, <10% moisture content [18] in the feedstock has been considered suitable for fast pyrolysis, which implies greater energy consumption for pre-drying in comparison to combustion. A high water content has been known to be disadvantageous for the energy content and combustion characteristics of bio-oil [46]. Although the pyrolysis of raw sludge (MC of ~70–80 wt.%) leads to a significant condensed water fraction in the bio-oil, this method has been found to be suitable for the generation of hydrogen-rich non-condensable gases via in situ steam reforming of the volatile compounds and partial gasification of the char [47]. Dominguez et al. (2006) stated that the pyrolysis of wet sewage sludge provides a higher gaseous fraction with significant hydrogen content within the combination of pyrolysis and gasification due to the presence of water in the reaction atmosphere compared to the pyrolysis of dried sludge [48]. To conclude, high water content as a major challenge for the production of bio-oil cooperates with the self-sufficiency issues of pyrolysis for the limitation on the commercialisation of pyrolysis. However, opportunities for the usage of pyrolysis in large resource recovery applications from dried sludge are predicted [32].

An advantage of pyrolysis over combustion and gasification is that the emissions include lesser pollutants (e.g., heavy metals, dioxins, furans). Conesa et al. (2009) investigated the effect of temperature and oxygen on the emission behaviour of different wastes including sewage sludge, where it was observed that the concentration of furans was increased along with an ascending oxygen ratio [49], whereby polyaromatic hydrocarbons (PAHs), which were formed through pyrolytic conditions, followed a negative trend with the oxygen increase. Analysis on the temperature effects also revealed a maximum point at temperatures of about 750–850 °C under pyrolytic conditions. In contrast, the PAH concentration under combustion conditions was also maximised at ~800 °C. This could indicate less pollutant emission because of the lower operating temperature of pyrolysis. Moreover, Jin et al. (2016) analysed the behaviour of heavy metals during the pyrolysis of sewage sludge and concluded the retention of the majority of them in the char, resulting in enhanced bioavailability and thus lower risk to the environment [34].

Gasification

Gasification is an extension to the pyrolysis process in which the resultant gas and solids (char) from pyrolysis undergo further reactions in the presence of 20–40% oxygen needed for combustion. The temperature through this process ranges from 700–1000 °C, where the formation of light combustible gases (syngas), such as H_2 and CO and other gases (i.e., CO_2, CH_4), from the gasification of the carbonaceous content (char) takes place [14]. This process involves two more core stages after drying and pyrolysis, where the partial oxidation of the char and volatiles takes place involving a gasification agent such as air, CO_2 and steam or a combination of these (e.g., air–steam or steam–O_2). These stages result in the gasification/reduction of the char via the heat generated from the exothermic oxidation reactions in ~1100 °C. The resultant heat from the partial oxidation stage also supplies the energy for drying and pyrolysis, which implies the self-sustaining behaviour of the process. However, the acceptable moisture content limit suitable for in situ drying of SS during gasification is less than 20 wt.% [17]. Moreover, due to restrictions on the reaction environment, the formation of SO_x, NO_x, heavy metals and other aromatic compounds is minimised [32]. The syngas obtained from this process is typically used for heating or electricity generation, or further processed for chemical or liquid fuel synthesis [22].

The product yield, quality and the process completion because of complex sequential thermal decomposition reactions in various stages throughout the process are dependent on the gasification medium, gasifier type, reaction conditions and feedstock composition. Among several types of gasifier configurations, fixed-bed downdraft, fixed-bed updraft and fluidised bed reactors have been investigated for sewage sludge [22,50]. The difference in an updraft and downdraft configuration is mainly in the introduction mechanism of the gasification agent into the reactor. In an updraft configuration, the gasification agent enters the reactor from the bottom and the feedstock falls from the top, resulting in rapid oxidation of the char from pyrolysis reactions. Following that, the hot gases exit the reactor from the top, potentially carrying high concentrations of tar. However, in a downdraft configuration, the gasification medium is introduced from the side, which descends within the contact with the pyrolysis products. This configuration facilitates the reduction mechanism of the char via further heat transfer in the char bed. The overall energy efficiency of the updraft design is higher compared to the downdraft design, owing to the efficient heat transfer between hot gases between volatiles, char and sludge in the reduction, pyrolysis and drying zones, while the hot gases exit the reactor in high temperatures. However, the tar content of the syngas (producer gas) as a bulk criterion is lower in comparison to the updraft design [40]. Although keeping moisture content in the range of >20 wt.% is preferable due to heat losses and the energy consumption of water vaporisation during gasification, the two reactor designs can handle higher moisture contents up to 50% in optimum reaction conditions [22]. Moreover, fluidised bed reactors have been utilised to address the challenges regarding uniform heat transfer and temperature distribution in the reactor via introducing the gasification medium in a suspended form fluidising gas.

2.4. Review of Comparative Assessment Studies

Several researchers have published comparative studies on the thermochemical conversion of sewage sludge to aid in the selection of a sustainable technology for sewage sludge management [17,32,51]. The objective of these publications has been to review the literature and compare the thermochemical conversion technologies either qualitatively or by using a comparative method (SWOT, FAHP, etc.). However, the conclusions from these studies differ since various technical criteria are applied in each study. The ranking mechanisms in previous studies are affected by the environmental regulations and technological development corresponding to the geographical zone in which the study was carried out. A critical review of these publications indicated that among combustion, gasification and pyrolysis as the main thermal treatment routes, pyrolysis could potentially provide a more sustainable approach towards sewage sludge management. This finding is a result of reduced pollutant emissions and zero hazardous waste disposal goals achieved through this technology. Nonetheless, the advantage of this technology is offset by intensive energy consumption for pre-treatment/drying that needs to be addressed to fulfil sustainability goals [32].

2.5. Review of Micro-Scale Human Faecal Sludge/Faeces Treatment Studies

Recently, there has been a great shift in interest towards the utilisation of small-scale thermochemical conversion technologies for sanitation [52,53]. The on-site sanitation approach for non-sewered communities (low-income countries) or parts of developed countries where sewage infrastructure is inaccessible/difficult is identified to aid in the promotion of faecal sludge management [54,55]. Some of the features of this approach are restrictions on the finances for storage and transportation, potential energy recovery from natural resources and mitigation of the risk of non-optimal disposal of human faecal waste in the environment. Indeed, the physical and chemical characteristics of the solid waste (mainly faecal matter and/or tissues) generated and stabilised through these decentralised wastewater treatment systems are different from those stabilised in commercial/pilot-scale wastewater treatment plants. Most of the research in this area has been conducted in response to initiatives such as Bill and Melinda Gates' 'Reinvent the Toilet Challenge' (RTTC) [2,3,56]. The innovative sanitary systems built under this initiative are required to operate in a waterless mode, whilst pursuing sustainable operation from the energy intensity point of view by recovering energy from solid waste [52]. Meanwhile, the micro-scale thermal processing systems in these contexts are designed to handle human waste in households of ten people considering the average input rates of 200 g per capita per day [52]. In response to this initiative, researchers at Cranfield University developed a novel sanitary system 'Nano Membrane Toilet' (NMT), for which extensive research on the utilisation of thermal treatment methods for human faeces was undertaken [52,54,55,57].

The gasification of dry and moist human faeces via thermodynamic modelling at the optimum equivalence ratio (ER) has been investigated [57]. Authors observed a decline in the content of exergy obtained from moist faeces (max 15 MJ/kg) at the optimum equivalence ratio and temperatures compared to dried samples (24 MJ/kg). The high moisture content of faecal samples was identified as 'parasitic' to gasification since the optimum point for thermal cracking was studied to be near combustion conditions (equivalence ratio of 0.55–0.62). As a result, the heat generated through gasification was absorbed by water vaporisation reactions and the ignition and subsequent conversion processes were delayed. Overall, this study reveals the exergy deficiency of moist faeces' gasification, as the generated heat and the exergy of the syngas were not sufficient for in situ drying, implying the necessity of energy-intensive pre-drying of the feedstock.

In another study, a bench-scale downdraft combustor was used to evaluate the optimum conditions for converting faecal biomass to energy through combustion [55]. The combustion characteristics of dry and moist faeces were evaluated under different conditions (i.e., air-to-fuel ratio, moisture content, etc.). Preliminary results from the combustion of simulant faeces showed a moisture limit handling of 60% with a bed temperature of 600 °C. The optimum combustion conditions for various dried faeces were characterised as (1) a minimum bed temperature of 600 °C and (2) 16 L/min airflow rate. The tests were performed using 50–75 g of wood biomass to ensure the optimum bed temperature followed by an addition of 50 g of faecal samples. However, the results revealed the failure of the tests in the case of moist faecal samples due to the non-definite form of faecal samples. Different shrinkage rates in faecal samples representing different moisture contents were observed to result in the partial drying of faeces without ignition. To confirm, this physical characteristic of human faeces was found to decrease the front combustion velocity dramatically from 2.18 to 0.72 mm min^{-1} where shrinkage was high [58]. Evaluation of the effects of fuel pellet size during combustion by [55] indicated a poor carbon conversion efficiency and a reduction in the process temperature attributed to improper interaction between the biomass material and hot air.

Findings from the study by Onabanjo et al. (2016) were used to successfully commission a novel micro-combustor capable of operating in downdraft and updraft modes under continuous feedstock flow conditions [54]. In contrast to the 2016 study, the continuous mode of operation was followed to limit the energy requirement for ignition and to keep the combustion bed at a sufficient temperature for incoming faecal material. The aim was to convert human faeces with the lowest possible temperature to ensure energy efficiency and to reduce the heat loss through combustion. Ultimately, the heat generated was used for the pre-drying of the feedstock or the other energy consumer with the NMT concept. The optimum temperatures for sustained fuel ignition and steady-state operation of the reactor were estimated as 220–240 °C for dried faeces and were generated using an air igniter. The authors stated that the spark device as a part of the ignition system was not necessary as the temperature reached 400 °C. The dominant challenge with the self-sustainability of combustion was the fuel feeding rate at this small scale, which caused two operational problems:

Incomplete thermal conversion as the interval between each feeding was delayed for longer than 2 min, mainly due to the scale of the process with an optimum 1.2 g/min feed rate;

Blockage in the feeding system due to char production at the reactor's inlet; The authors suggested that further research for the optimisation of the micro-combustor for self-sustained combustion should be carried out [54].

A summary of the reviewed benefits and drawbacks associated with the main sewage waste stabilisation technologies throughout this study is provided in Table 2. The contents aim to highlight the overall performance of each technology, implemented in various scales, to facilitate the selection of a method for the decentralised treatment of human waste in micro-scale sanitary applications.

Table 2. Pros/cons of sewage waste stabilisation methods.

	Main Sewage Sludge Stabilisation Methods			
	Biological	**Thermochemical**		
	Anaerobic Digestion (AAD)	**Combustion**	**Gasification**	**Pyrolysis**
Advantages	• High water content of solid waste has no impact on the calorific value of biogas • Cost efficient technique • Simple by-products for end-use (Methane for energy recovery and stabilised sludge as fertilizer)	• Major reduction in the sludge volume (90%) • Complete pathogen removal and sterilization • Chance of energy recovery	• High efficiency energy recovery • Lower environmental emissions due to production of 'cleaner' syngas • Major volume reduction • Complete pathogen destruction and sterilization	• Takes place under inert environment—no need for auxiliary fuel • Pathogen removal and sterilization • Low sensitivity to the feedstock physical properties • Low emissions due to absence of oxygen • Retention of inorganics and metal content in the char fraction • Lower heat fluxes—robust reactor operation • Chance of energy recovery from products
Disadvantages	• Very long processing timeframes • Limited conversion of organic matter (30-60%) and poor energy recovery • Non-efficient elimination of hazardous fraction in sludge • Limited reduction of sludge volume	• Lack of regulations • Requires ignition with the aid of auxiliary fuel • Needs fuel pre-treatment and moisture reduction • Extensive emission control needed • Operational complexities due to the ash and particulate matter • Very high heat fluxes with reaction area	• Need for moisture content reduction • High sensitivity to the physical properties of the feedstock • Need for ignition—auxiliary fuel • High heat fluxes present in the reactor • Inadequately practiced • Need for gasification agent—constraining implementation • Tar production	• Requires fuel pre-treatment (drying) • Energy intensive process • Inadequately practiced • Delivers by-products to be handled • Lack of regulation

3. Discussion

A critical review of previous work completed on the subject of thermochemical treatment reveals the technical challenges associated with the implementation of 3× main thermochemical processes for various types of biomass and waste materials. Furthermore, a detailed analysis on the research completed for the development of on-site sanitation technologies highlighted the necessity of highly accurate process control and the optimisation of gasification/combustion. This has been due to the need for proper in situ ignition of the fuel, which is highly sensitive to the moisture content, feedstock flow rate, fuel physiochemical characteristics and the design of the reactor. Hence, the suitability of thermal conversion systems for sanitation depends on the capability of the system to handle alternative feedstock flow rates with different shrinkages and moisture contents. In this study, pyrolysis is selected as the promising method for on-site sanitary applications, and further on, a comprehensive discussion on these processes will be conducted. Overall, research on the thermal conversion of human faecal waste is very scarce and a huge gap on the optimisation, emission rates as well as net energy balances of these processes remains in the literature.

3.1. Energy Consumption

The thermochemical conversion routes practiced commercially for sewage sludge as the most similar material to human faecal waste and other biomass types are depicted in Figure 2.

For a combustion process, the chemical reactions corresponding to each step occur sequentially with some overlaps delivering different inputs for the following step with various energy contents. However, these processes are well distinguished from one another owing to the presence of oxidising agents in different concentrations during each stage [59]. Hence, the net energy balance analysis of each thermal treatment process is different and difficult to be compared with others regarding the: (1) complex sequential endothermic and exothermic reactions and (2) the variety in the energy content of the products in the outputs. It is notable that a positive/negative net energy balance for these processes does not consider the drying process. The initiating drying process is a complete endothermic step for the vaporisation of the water content in biomass/waste requiring a substantial amount of energy, such as 3.4 MJ/kg in typical dryers with non-unity efficiency [60].

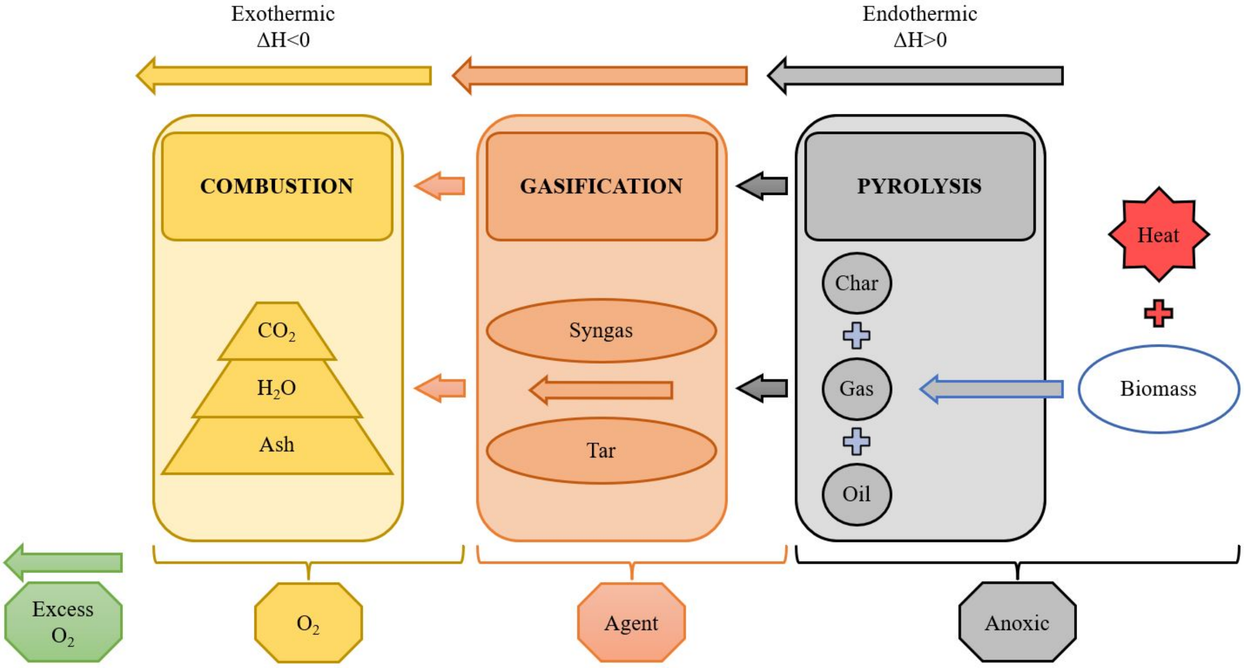

Figure 2. Three common thermal treatment routes [58].

In the context of sanitary applications, for the implementation of a successful thermal conversion system in an application where extraneous energy is available for the completion of treatment, pyrolysis could still be an option. As depicted in Figure 2, pyrolysis is an energy-intensive process in contrast to gasification and combustion since the endothermic non-spontaneous reactions are predominant in this step/process. In the case of sewage sludge, pyrolytic reactions were found to be mostly endothermic in the order of 100 kJ/kg, whereas the exothermicity of oxidative reactions was found to be in the order of 10,000 kJ/kg [61]. To further elaborate, net energy positivity/negativity could be defined as the energy released from the exothermic reactions or available in the energy-rich products of each process, being less than, equal to, or more than the energy needed to complete the endothermic reactions in each process.

For pyrolysis, researchers have explored the sensible heat to bring reactants to pyrolysis temperature, the heat of pyrolysis and the sensible heat for product evolution, all together known as the enthalpy for pyrolysis [62], for different types of biomass and sewage sludge using different methods, shown in Table 3. Daugaard et al. [63] estimated the enthalpy for two types of wood as well as two herbaceous materials ranging from 0.8 ± 0.2 MJ/kg for oat hulls to 1.6 ± 0.3 MJ/kg for pine. The method utilised in this study covered a comprehensive analysis on the energy inputs and outputs within the reactor accompanied by inaccuracies in the estimation of heat loss within the range of 16–17.5%. In another study, the heat for the pyrolysis of birch dowels in dry and moist (55 wt.%) conditions was determined as 2.9–3.5 MJ/kg and 8.1–8.6 MJ/kg [62]. Further studies investigating the enthalpy for the pyrolysis of biomass and waste are summarised in Table 3.

Table 3. Enthalpy values and net energy assumptions for the pyrolysis of various biomasses and sewage sludges.

Waste Type	Enthalpy (MJ/kg)	Moisture Content (%)	Description	Reference
Oak Oat hulls Pine Corn stover	1.46 ± 0.28 0.78 ± 0.20 1.64 ± 0.33 1.35 ± 0.28	8.0 10.2 7.5 8.8	Pilot-scale fluidised bed pyrolysis reactor operating at about 500 °C.	[63]
Birch dowels	2.9–3.5 8.1–8.6	0 55	'Water tracer' technique was applied for the determination of the time of pyrolysis for a dry and an identical moist particle. However, this non-conventional method is known to result in errors within calculation [63].	[62]
Wood chips	0.7	5.9	The analysis of the enthalpy of pyrolysis was performed on a multiple-hearth reactor. An empirical method 'P.D.U.' was used to indicate the difference between electric energy consumption prior and through wood feeding.	[64]
Cedar, Pine, Willow, Bamboo, Sasa bamboo	1.3 ± 0.2 1.5 1.5 1.5 1.6	0	Enthalpy for the pyrolysis of five different types of biomass materials was calculated using a screw feeding reactor. The analysis aimed for the determination of the enthalpy of the formation of products based on their composition. However, the method used for the enthalpy of bio-oil included errors.	[65]
Willow chips	1.17	9.1	Analysis on conventional and MW pyrolysis (required electricity).	[66]

Recently, several studies reported a self-sustainable pyrolysis to be achievable through theoretical combustion of the pyrolytic products. Typically, a low heating value of the non-condensable fraction has made it more suitable for heating the unit [67]. For sewage sludge, McNamara et al. (2019) found the energy content of pyrolytic gas and oil to be always sufficient for the pyrolysis process using the theoretical heat capacities of the constituents [60]. In another study of sewage sludge pyrolysis [68], the available theoretical heat of combustion for domestic sewage sludge was determined as 825 kJ/kg. This suggests higher recoverable energy from the non-condensable fraction of syngas in comparison to the heat required (730 kJ/kg) for the pyrolysis of the same type at 500 °C. For the two other types, excessive energy through the combustion of the bio-oil fraction was suggested for the self-sufficiency of the process. However, the analyses were all performed on dried sludge solids with 5.7% moisture content. Furthermore, analysis on the five different types of dried biomass by [67] indicated a self-sustainable pyrolysis to be feasible. The available enthalpies for pyrolysis in the literature in a range of 6–15% of biomass HHV were used. The authors observed that, considering the upper limit (15% HHV of biomass) as the enthalpy for pyrolysis, the process gas yielded at a high treatment temperature of 650 °C could only surpass the enthalpy in some cases.

Taking the completed analyses on the energy efficiency of pyrolysis into account, the commercialisation of pyrolysis is still criticised by some researchers. Rollinson and Oladejo (2019) stated that a self-sustainable pyrolysis process is practically implausible and thermodynamically unproven. The authors highlight the importance of considering pre/post-treatment energy demands as well as proper thermodynamic considerations repetitively [69].

In the context of sanitary applications, addressing a gap on the heat required for the pyrolysis of human faeces/faecal sludge is necessary. This could be followed by an analysis on the conditions to produce maximum yields with the highest calorific value of py-gas and py-oil to address the net energy balance of this system. In a study on the pyrolysis of human faeces, Yacob et al. (2018) investigated the effects of heating rate and HHT on the yield and energy content of the non-condensable fraction of syngas (py-gas) including CH_4, CO, CO_2 and H_2 as well as ethane. The promising conditions were evaluated as an operating temperature of 450 °C and a heating rate of 2.5 °C/min, which provided 22.8 MJ/Nm^3 and 29.6% gas mass yield, respectively [53]. However, in this study the analysis was performed on dried human faeces. To limit the energy consumption of a system implemented for sanitation, the recoverable exergy of syngas is of concern. An analysis on the total exergy of the syngas from the gasification of human faeces showed that moisture content could increase the exergy from 19 to 22 MJ/kg at an ER of 0.55 [57]. The moisture content limit was also observed to increase within progressive ER but at the expense of total exergy loss of the syngas, up to a point beyond which the exergy potential reached a lower extent than the gasification of dry faeces at the optimum point. Hence, the operating range at which the pyrolysis system can accommodate the highest moisture content is essential to reduce the energy needed for pre-drying.

Lastly, the pyrolytic char produced from such a system could also be used for energy recovery through combustion. To maximise the yield of the non-condensable fraction, high heating temperatures are required. Analysis on the product distribution of different biomass types showed a higher yield of combustible species such as H_2 and CH_4 occurring at temperatures $x > 550$ °C in most cases with a lower heating rate [67]. In the case of human faeces, this operating range was at ~550 °C [53]. Though at this HHT, the yield and energy content of the char reduce to half [67]. Ward et al. (2014) observed the faecal chars made at 750 °C having 13.8 ± 0.48 MJ/kg, which was much lower than those made at 350 °C with 25.6 ± 0.08 MJ/kg [70].

3.2. Technology Development

Prioritising a solution to address the issues observed with the energy intensity of a pyrolysis system, the operational reliability of the system needs to be considered carefully to ensure a safe and continuous functionality. This would then allow the transfer of such a system, not only for on-site processing in non-sewered applications, but also for mobile applications where the least maintenance is desirable. To achieve this, a novel design for the pyrolysis system should be proposed to meet the expectations regarding the energy intensity, technology robustness, application constraints and the safe disposal/emission of its by-products. The innovative design of such a pyrolysis system should include an immediate energy recovery step from the by-products, overly controlled by various factors such as the fuel properties, the process conditions and the mechanical design. These factors are interrelated where the immature selection/planning of each could lead to the improper processing of waste, malfunctioning of the reactor, mechanical fatigue or ultimately the infeasibility of the technology for the application.

For a proper energy recovery sub-system, the production of non-condensable fractions would be of more interest to facilitate the product's (non-condensable and condensable fractions) combustion in the afterburner/atomiser. Researchers have reported many more constraints for the combustion of bio-oil in comparison to syngas, where the high water content in the vapour phase has been found to reduce the energy density, the adiabatic flame temperature, local combustion temperature and combustion reaction rates [46]. In addition to the water content, the presence of solid particles (ash, etc.) and other physical properties could complicate the atomisation and lead to erosion in the pipeline. A previous study reported that sustainable combustion could not be achieved through bio-oil since the slight flash in the compound is suppressed by the evaporated water [71]. Furthermore, refractory behaviour observed with the long-chain molecular hydrocarbons complicates the thermal processing of them as well as the high oxygenate content leading to instability and higher viscosity [72]. Overall, through a novel chemical process design, the production of more syngas through pyrolysis followed by immediate energy recovery could provide the potential high temperatures for the ignition of bio-oil in the vapour phase. Some of the core parameters affecting the product distribution and properties will be discussed further to provide an insight on the optimum operating conditions of such a system.

To further elaborate, the term 'operational reliability' of such a system points out the production of a suitable gaseous fraction (both non-condensable and condensable) for rapid combustion and energy recovery. For syngas, as the focus of this study, delivering the highest reactivity for ignition and laminar flame speeds is vital for a reliable combustion performance in the after burner/atomiser. Research on the ignition and combustion properties of various blends of gaseous fuels indicate that the higher the H_2 content, the more O, H and OH radicals are released, enhancing the chain branching, propagation and termination reactions [73]. The presence of these radicals promotes the consumption of hydrogen, C_1 and C_2–C_3 fractions, and overall the reaction rates which lead to lesser ignition delays of the fuel. Trials were conducted in high pressures where lower rates of radical production were observed at H_2/CH_4 concentrations of 40/60% [74].

Similarly, in a modelling study using Digital Analysis of Reactive System software (DARS), it was observed that the more CH_4/H_2 there is, the longer the ignition delay time, with the temperature playing a significant role where the change in reactivity was more sensible at lower temperatures [75]. Moreover, the laminar flame speed was reduced as the CH_4 with lower reactivity was increased in correlation with the reduction of H_2.

Typically, another substantial fraction in syngas is carbon monoxide (CO), which results in the poor ignition of the fuel due to its low combustion rates. Analysis on the thermal efficiency of dual fuel operation of an engine shows that through an increase in the ratio of H_2/CO, an improved thermal efficiency was achieved [76]. However, this was limited to 75:25 as CO oxidation was optimum at this ratio. In addition, the higher H_2 content was observed to increase the flame travel and lower the auto-ignition temperature of the fuel.

Overall, a review of these papers reveals the improved combustion characteristics of syngas within an increase in the H_2 content. However, this would be at the cost of higher generation of NOx fumes in the exhaust gas due to the presence of higher reactive radical species such as O and OH.

In the further steps, the effects of various consecutive process parameters specifying the evolution of different gas species will be discussed to select an optimum processing condition for such a system. Other than the combustion performance of the syngas, criteria to be considered in the further steps are:

(1) Limiting energy consumption as much as possible;
(2) Lesser chances of fatigue, particularly when the least maintenance is feasible;
(3) Accommodating any incoming feedstock volumes with different physical characteristics;
(4) Delivering emissions below regulating limits for both solid and gaseous by-products, and;
(5) Reducing the solid waste volumes in considerable amounts.

3.3. Syngas Yield and Energy Content—A Trade-Off with Combustion Performance, Emissions and Bio-Oil Properties

3.3.1. Temperature vs. Yield

Numerous studies have investigated the effects of various process parameters on pyrolysis products. It is well known that the high heating temperature performs a dominant role on the yield and distribution of pyrolytic fractions [76,77]. Higher temperatures provide sufficient energy for the bonds in biomass to break and achieve a better conversion efficiency [76]. Figure 3 illustrates the trends observed through the pyrolysis of various feedstocks in a few studies.

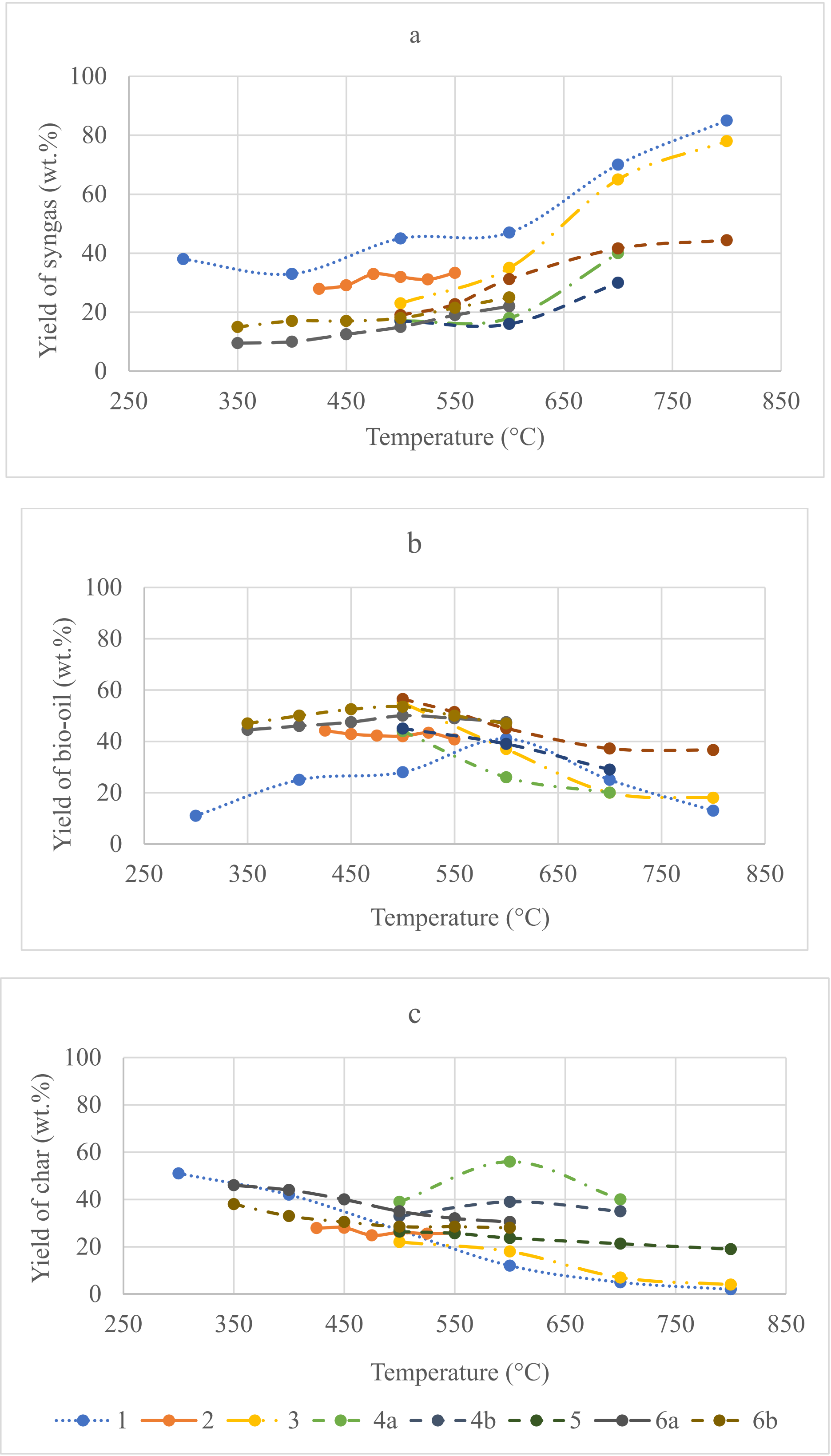

Figure 3. Effects of pyrolysis temperature on the yield of pyrolytic fractions: (**a**) non-condensable fraction, (**b**) condensable fraction, (**c**) residual char: (1) Anaerobically digested sewage sludge [78], (2) Milkweed [79], (3) Legume straw [80], (4a) Corn cob and (4b) Corn stalk [81], (5) Pine woodchips [82], (6a) Rice husk and (6b) Corn stalk [83].

Although the variety of feedstock compositions differentiates the yield of products, a common observation has been the increase in the yield of syngas at temperatures higher than 400 °C with drastic behaviour at 550 °C and further. In contrast, the yield of bio-oil follows the same trend after 400 °C but declines drastically at 500–600 °C and after. This shows the significant gas phase secondary reaction occurring at these temperatures, which is associated with the consistent decrease in the yield of char.

3.3.2. Heating Rate vs. Yield

Analysing the effects of heating rate on the yield, it is well known that the higher the heating rates (fast and flash pyrolysis), the more liquid oil could be produced through rapid extraction of the vapour [84]. However, research shows that for the syngas fraction, the heating rate plays a major role in the progressive generation of syngas during slow/intermediate pyrolysis limited approximately up to 200 °C/min [85]. Research on forestry residues shows that applying higher heating rates yields more syngas up to the point where heat and mass transfer limitations within the reaction area are overcome [86]. The product producer gas will be further discussed in later sections.

3.3.3. Temperature vs. Syngas Calorific Value

To suggest an optimum range of temperatures for such a system to operate at, the energy content of the syngas fraction should also be analysed. Figure 4 shows the calorific values (HHV) of the syngas obtained through temperature variations during the pyrolysis of various types of feedstock in different reactor configurations and operating conditions.

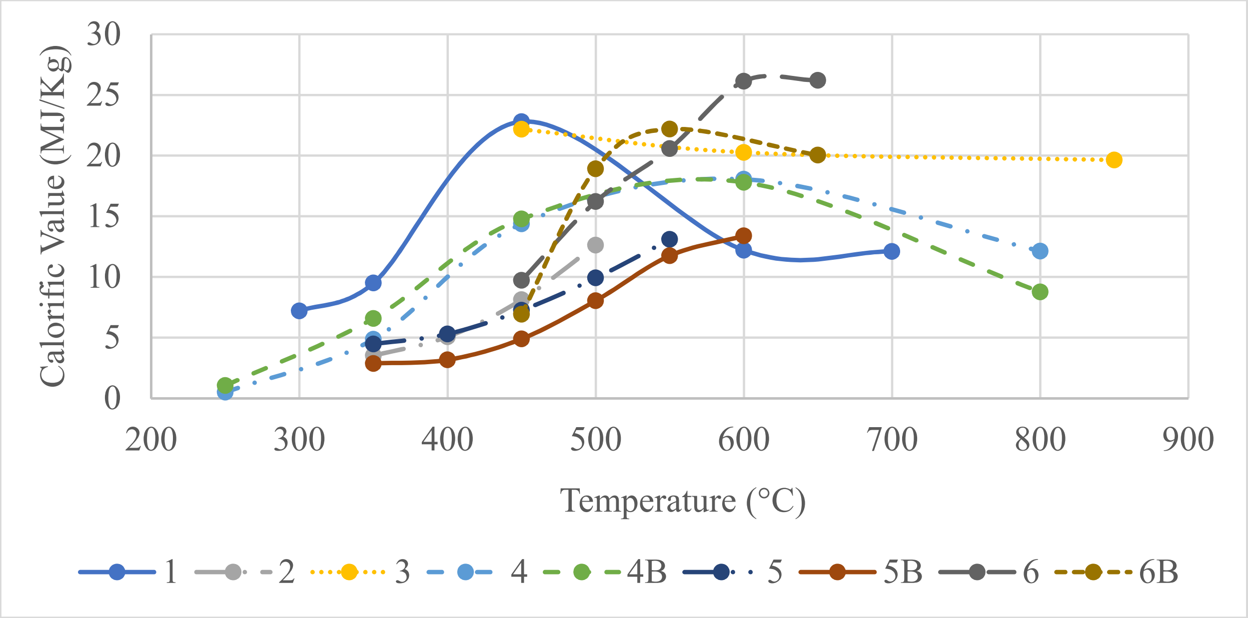

Figure 4. Effects of pyrolysis temperature on the calorific value (HHV) of the syngas: (1) Human faeces [52], (2) Sewage sludge [87], (3) Sewage sludge [43], (4 and 4B) Sewage sludge at 60 and 5 °C/min [88], (5 and 5B) Rice husk and corn stalk [83], (6 and 6B) Dried sewage sludge at 100 and 5 °C/min [89].

The theoretical calorific values in MJ/Kg were calculated using the data on the energy content of each gaseous species reported by NREL [90]. CO, CH_4, H_2, C_2 and C_3 were the only combustible species considered for the comparison commonly reported in all studies, while an average energy content of 65 MJ/Kg was assumed for the last two.

Typically, the most abundant species in the syngas fraction detected in various studies are mainly CO_2, CO, CH_4, C_2–C_3 and H_2 depending on the type of feedstock and process conditions. Clues from pyrolysis practices reveal evidence on the notable increase in the yield of CO and CH_4 at temperatures up to 600 °C and dominant H_2 at further temperatures [91,92]. The production of more hydrogen can deliver zero carbon emissions upon the combustion of syngas, but the operating temperature should be considered carefully with regard to the mechanical design of a system for sanitation where higher chances of fatigue are foreseen at higher temperatures in the structure of the reactor. Moreover, the higher yield of hydrogen leads to the conversion of primary tar from pyrolysis into polycyclic aromatic hydrocarbons (PAHs) such as pyrene and phenanthrene due to decarboxylation and dehydration [84,91].

Highlighted in Figure 4, a temperature between 400 and 600 °C during pyrolysis can trigger an upwards trajectory or a peak for syngas energy content for various waste materials. A reason for this is the generation of an energy-rich fraction such as C_2 at 450 °C and maximum CH_4 up to 600 °C [88]. Notably, the trends for the evolution of these gas species in this range of temperatures could be different based on the process conditions, feedstock compositions and reactor configurations [53,93]. Furthermore, the progressive complex consecutive reactions for the generation of each species through pyrolysis and the consequent partial/complete gasification can be found elsewhere [92,94,95].

3.3.4. Heating Rate vs. Syngas Calorific Value

Analysis on the heating rate shows that the evolution of CH_4 and C_2–C_3 species increases through slow/intermediate pyrolysis, resulting in the peak calorific value at lower temperatures [89]. However, the concentration of these species stays almost constant at temperatures of about 450 °C and after [79,82]. Focusing on the generation of energy-rich fractions such as CH_4 and C_2–C_3 fractions at temperatures ranging from 400–600 °C, Gao et al. [89] achieved a higher yield for these species through slow pyrolysis, whilst CO and H_2 evolution showed a peak through fast pyrolysis. In a study of chicken litter pyrolysis, the concentration of CO and H_2 increased at the expense of CH_4 and C_2 due to decarbonylation and steam reforming reactions through fast pyrolysis [85]. As discussed earlier, the increased yield of syngas in a range of heating rates limited between 0 and 200 °C/min could be attributed to the rapid decomposition of tar into gas, where a substantial increase in the concentration of CO and H_2 is observed [96].

3.3.5. Effects of Residence Time (RT)

Considering the residence time as another core parameter affecting pyrolytic product properties and distribution, an almost 50% breakdown of CO_2 is achieved through higher residence times in addition to the reverse impact of high heating temperature as a common observation in almost all studies on pyrolysis [97]. Moreover, prolonging residence times could generate a higher H_2 fraction through the following reaction:

$$CO + H_2O = CO_2 + H_2$$

Additionally, Jaramillo-Arango et al. (2016) suggested that enough residence times lead to thermodynamic equilibrium, resulting in H_2 overtaking CO_2 concentrations [78]. A review of multiple studies outlined significant changes in the yield of products achievable through RT variation. This is where the maximum liquid yield is obtained with a lower RT and rapid vapour extraction, whilst prolonging RT leads to the formation of syngas through secondary cracking; both are associated with char breakdown to different contents [82,98]. However, the effects of RT are known to be insignificant on the overall syngas and liquid oil properties but are associated with a progressive decrease in the yield of char limited to the completion of reactions [82,99].

3.3.6. Effects of Feedstock Flow Rate

The throughput of a system implemented for on-site sanitation is highly variable depending on the application, where a high/low frequency of toilet usage might lead to the system's malfunctioning due to a blockage, the improper conversion of waste materials or immature moisture handling within the processing timeframe. Results from an analysis on the feed flow rate show that depending on the design of the system, the vapour residence times start to decline as the flow rates increase, and consequently a higher bio-oil yield could be generated as the chances for secondary reactions diminish [100]. Detrimental impacts of this parameter in the case of improper design could be the accumulation of tar and particles in the downstream pipeline or a disruption in the operation of the afterburner. A similar phenomenon to the previous citation was observed in a study on the pyrolysis of forestry waste, where insignificant impacts on the surface functionality of bio-oil were recorded [82]. Moreover, the hyphenation of the gas fraction showed that at a constant residence time of 5 min, the CO_2 concentration was decreased as the chances for primary decarboxylation in the reaction area decreased with higher flow rates.

3.3.7. Effects of Initial Moisture Content

Moisture content has a direct impact on the maximum recoverable energy in such a system where excessive water contents could perform a thermally parasitic role during thermal conversion, which must be considered.

Results from multiple studies confirm that the generation of higher yields of syngas to the detriment of the yield of bio-oil was achieved in most of the cases [78,80,101]. This has been associated with the reduction of char in the system mainly when higher residence times (to conduct reforming) were applied during the process. The governing reactions occurring through the pyrolysis of wet waste materials leading to the partial gasification of organics are [48,59]:

Steam gasification reaction:

$$\mathrm{C\ (s) + H_2O\ (g) \leftrightarrow CO + \ H_2, +131\ MJ/kmol}$$

Steam reforming reaction:

$$\mathrm{CH_4 + H_2O\ (g) \rightarrow CO + 3H_2, +206\ MJ/kmol}$$

$$\mathrm{CH_4 + 2H_2O\ \rightarrow 4H_2 + CO_2, +165\ MJ/kmol}$$

Water gas shift reaction:

$$\mathrm{CO + \ H_2O\ \leftrightarrow CO_2 + \ H_2, -41.5\ MJ/kmol}$$

Mei et al. (2020) observed that the steam-rich atmosphere within the reaction area enhanced water gas shift and steam reforming reactions. This resulted in the conversion of pyrolysis intermediate products (liquid oil) to hydrogen, specifically with the catalytic effects of char at higher temperatures of 600 °C [102]. However, temperatures were found to have an insignificant effect on the yields of by-products below 700 °C [47]. This phenomenon was likely due to the difference in the composition of raw materials [48]. Because of the above equations, the concentrations of H_2 and CO_2 have shown elevation, while CH_4 and CO have decreased where the water gas shift reactions were dominant. Consequently, the calorific value of the gas fractions has declined due to the generation of more hydrogen with a lesser energy content compared to CH_4 and C_2 fractions, and so H_2/CO and H_2/CO_2 ratios increased gradually. Further analysis on bio-oil shows that a higher initial moisture content is conducive in the reduction of longer chain hydrocarbons with higher boiling points in the tar fraction (bio-oil) to form lower weight gas species [102]. However, the associated effects of temperature should be disregarded since the production of two or more ring aromatic PHAs is significantly affected at temperatures higher than 600 °C [47].

Finally, the pyrolysis of wet waste materials could enable higher chemical energy stored in the syngas through gasification reactions of the char and steam reforming of the oil [102]. However, an important factor to be considered is the energy recovery efficiency of syngas with alternative moisture contents. The authors observed the suppression of the total recoverable energy from the by-products due to the loss of sensible heat of the products and latent heat of residue steam vapour [102]. This study investigated the syngas properties within a separate reforming section where the authors demonstrated that a moisture content of 40% delivered the highest energy recovery efficiency of 44.18% from the syngas. The heat consumption for the evaporation of the water content, which does not take part in thermochemical reactions, was found as a possible reason for this.

4. Conclusions

This review followed two comprehensive objectives, further mentioned below, with an aim to address a suitable technology for the proper on-site conversion of solid waste materials generated in non-sewered applications:

1. To provide an overview on the existing solid waste management/stabilisation methods and their associated implementation challenges in commercial/pilot, laboratory and small scales;
2. To select the most promising method and further address the drawbacks.

Nonetheless, the primary aim for these applications is to reduce the waste volumes in sensible amounts and ensure the safe discharge of the products. Typically, the systems implemented for such applications must deal with limitations on regular maintenance and process control for the efficient conversion of sewage-type material in alternative volumes. These additional problems further complicate the design and optimisation of such a system.

Throughout this study, pyrolysis was observed as the most promising method among the existing technologies due to its lower emission rates in large scales and lesser operational challenges both in commercial and small scales. Lower heat fluxes within the reaction area enable the accommodation of alternative feedstocks with lesser necessary optimisation and enhance the handling of moisture content. A major technical challenge observed with this technology is the energy intensity in addition to the pre-treatment (drying), which was addressed through the addition of an on-site rapid energy recovery step from the by-products. A pyrolysis temperature of 400–600 °C and the heating rates pursued at low ranks could result in a sustainable thermal conversion range for moist waste materials. These conditions would aim to produce the maximum yield of syngas with the highest calorific value, which facilitates the combustion performance of the vapour fuel in the afterburner/atomiser. Excessive heat upon the complete combustion of syngas and liquid fuel can potentially limit the energy consumption of pyrolysis or the inevitable drying stage in the system. This study does not take heat waste and ramp up steps into consideration. However, if the overall costs due to energy consumption or pre/post-treatment remain less than the current methods for management or disposal, this solution could be explored through further research. Using a novel design, the detrimental effects of particle size and alternative flow rates on both the conversion efficiency and operational performance could be alleviated through the maximisation of residence times and fuel fluidisation. All of these would aim to produce the highest H_2 and C_1–C_3 fractions in such a range of temperatures while producing an energy-rich gaseous fraction for energy recovery.

For future studies, extensive research on the novel design, useful contents of moisture, potential emissions from such a system and ignition mechanisms of bio-oil in the vapour phase would be suggested.

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