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Chapter 6

Sanitation biomass recovery and conversion

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Chapter objectives

The aim of this chapter is to present the sanitation biomass recovery and conversion value chain (SBRCVC) activities that show how enterprises offer resources that enhance the emerging low-carbon circular bioeconomy and in turn reduce reliance on virgin raw materials. Furthermore, it intends to explore better understanding of enterprises and businesses that valorise secondary organic resource-materials from excreta, wastewater, sewage and faecal sludge with other blended organic-waste-derived biomass and then those ventures that could convert these bioresources into different valuable products, ranging from high-value amino acids and proteins, short-chain fatty acids, enzymes, biopesticides, bioplastics, bioflocculants, biofertilizer and biosurfactants as well as those that use them to produce other kinds of commodities.

6.1 INTRODUCTION

A value chain that addresses sanitation biomass recovery and conversion (SBRC) could offer resources that enhance the emerging low-carbon circular bioeconomy in developing and developed countries and in turn reduce the reliance on virgin raw materials as a result of being biomass drawn from secondary materials (Panoutsou *et al.*, 2020). This could also mitigate climate change and contribute to local economic growth such as creating skilled employment opportunities (BFG, 2012; Panoutsou *et al.*, 2020). It could focus on recovery and reuse of resources from excreta and wastewater fractions that do not interfere with natural ecosystems or human food chains, but rather on recovered resources such as soil conditioners, compost and effluent for irrigations which are well established end-products. Wastewater treatment for resource recovery is a rational solution to avoid problems derived from droughts and water shortages, especially for countries with water restrictions (Jodar-Abellan *et al.*, 2019; Zarei, 2020a), while wastewater management including safe reuse of water and the recovery of vital resources, could open remarkable opportunities for commercial markets. Recently, nanomaterials gained significant attention for widespread applications in biosensing,

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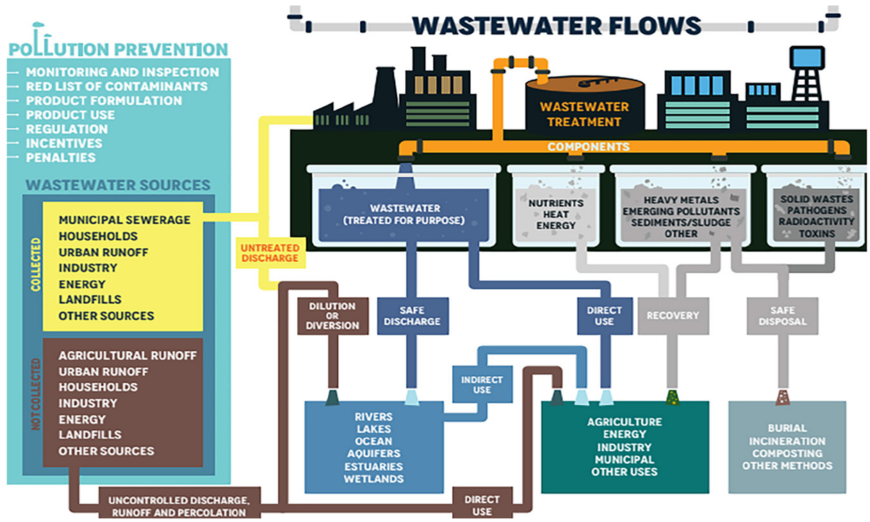

Figure 6.1 Wastewater flows and sources. (Source: WWAP (UN-Water), (2017). CC-BY-SA 3.0 IGO, license © 2017 by the authors)

water splitting, energy recovery, environmental remediation, and wastewater treatment (Kadam *et al.*, 2020; Wang *et al.*, 2020; Zarei, 2020a, 2020b, 2020c; Zarei & Aalaie, 2019). In particular, treated wastewater can be reused for multiple purposes in the industrial sector and for agricultural purposes, irrigation, groundwater recharge for effluent quality improvement; it can also be used for domestic purposes – fire protection, car wash, and toilet flushing (Zarei, 2020a; see Figure 6.1). Other possibilities that are starting to be implemented include sewage sludge and faecal sludge biomass composting used to produce animal feed from black soldier fly larvae or fodder crops, incorporating building materials such as bricks, tiles, cements, concretes, mortar, and so on, and also energy in the form of fuel, electricity and heat (Andriessen *et al.*, 2019; Zarei, 2020a). In addition to these recovered end-products, all of these could also support solutions for coverage and access problems of safely managed sanitation while providing appropriate incentives for faecal sludge management (Diener *et al.*, 2014; Wielemaker *et al.*, 2018). Revenues from resource recovery and reuse after conversion could partially offset operation costs, incentivize proper operation and maintenance, and stimulate regular emptying and delivery of faecal sludge, particularly in developing countries (Andriessen *et al.*, 2019). Studies have confirmed the emergence of viable business models for value chains around sanitation biomass resource recovery and reuse that in turn help ensure sustainable provision of safely managed sanitation (Diener *et al.*, 2014; Murray & Ray, 2010).

This could be viewed as the sanitation biomass recovery and conversion value chain (SBRCVC) and it would deal with enterprises and businesses that valorise secondary organic resource-materials from excreta, wastewater, sewage sludge, and faecal sludge with other blended organic-waste-derived biomass as well as those that could convert these bioresources into different valuable products, ranging from high-value amino acids and proteins, short-chain fatty acids, enzymes, biopesticides, bioplastics, bioflocculants, biofertilizer and biosurfactants (Zhang *et al.*, 2018). Value chains encompass the full range of activities required to bring a product or service from conception, through different phases of production that involve a combination of physical transformation and input from various producers and services to delivery, to the final consumer and final disposal after use (Maaß & Grundmann, 2016). Unlike conventional value chains the SBRCVC is not necessarily made up of sequential and linear activities; rather it is viewed as manifold connections in which value is co-created by a combination of players and enterprises (Maaß & Grundmann, 2016; Peppard & Rylander, 2006) comprising environment, social, economic and governance actors interacting through institutions, technology and other relevant stakeholders to:

- Co-produce product and service offering;
- Exchange product and service offering, and
- Co-create value along the biomass recovery transformation chain (Lusch *et al.*, 2010; Maaß & Grundmann, 2016).

The economic value created from value chains is commonly measured by the added value, that is a success indicator that describes the performance of a firm, business or the increase in value resulting from production, processing, marketing and other economic activities (Haller, 1997; Maaß & Grundmann, 2016). It can also be understood as the difference between the value of goods and/or services delivered from one business to another, and the value of all inputs received by this business from other businesses and/or enterprises for producing that particular good or service. It is a set of interlinked activities that deliver products/services by adding value to bulk materials (feedstock through the process of conversion to high-value products). In such a bio-based sanitation-waste value chain, the feedstocks tend to be biomass drawn from by-products of existing primary production or secondary origins like sanitation-derived biomass (Lokesh *et al.*, 2018; see Figure 6.2). Bioresources value chains that valorise secondary resources are designed to turn available organic materials into different valuable products that range from high-value chemicals, fertilizers, and biochar to secondary-used by-products and renewable energy; and are capable of transforming waste/secondary feedstock

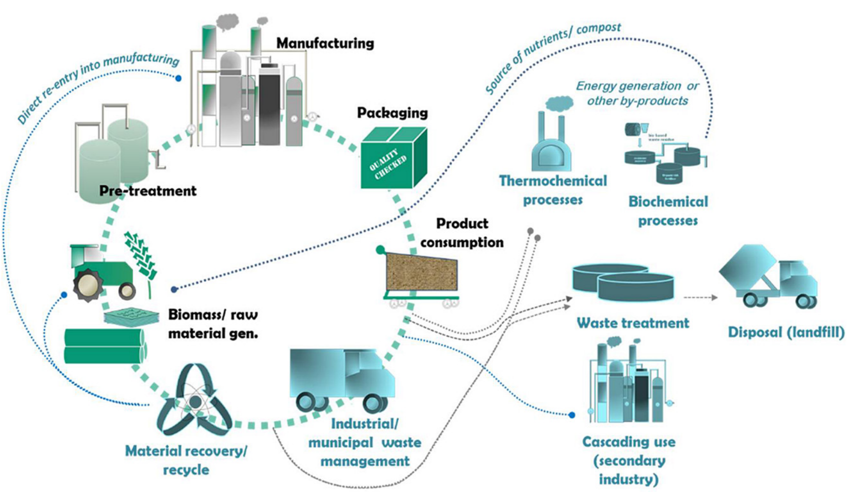

Figure 6.2 A generalised map of a bio-based value chain. (Source: Lokesh *et al.* (2018). Under CCA 4.0 license, © 2018 the authors)

into arrays of high-value products called integrated biorefineries (Lokesh *et al.*, 2018; Pan *et al.*, 2015). Integrated biorefineries contain a pre-treatment plant that prepares the feedstock for biomass conversion/transformation within the value chain before packaging and distribution (Greene, 2014; Lokesh *et al.*, 2018) to the final consumer or end-user.

In addition, biomass recovery value chains contribute to materials recycling, climate mitigation, and greenhouse-gas (GHG) emission reduction as well as the development and implementation of several outstanding technologies like combustion, gasification and anaerobic digestion hinged upon sustainable strategies that could overcome some obvious challenges. Pan *et al.* (2015), for instance, proposed such related strategies with options that cover technology, finance, institutions, public concerns and regulations (Zarei, 2020a). However, in Malaysia Lam *et al.* (2013) developed a two-stage biomass model waste-to-energy (WTE) process with the first stage being a micro-stage waste-biomass optimization and allocation integrated waste-biomass processing hub; and the second stage being a macro-stage designed to handle the synthesis and optimization for the WTE (Zarei, 2020a). These strategies provided both the analysis of economic value and sustainable solutions for the utilization of waste-biomass for resource recovery.

Normally, the value chain theory recognizes the stages and activities of the value chain's competitive advantages or disadvantages, and where cost advantage strategy optimization should focus mostly on activities that contribute the most to cost reduction (Darmawan *et al.*, 2014). Furthermore, types and forms of sanitation biomass resource recovery should always meet local conditions and user acceptance, and, whenever possible, should be decided early in the planning process, so that appropriate treatment objectives can be set to ensure public health protection of the end-users (Reymond, 2014). Also, a market-driven assessment can help to inform which end-product is most marketable in a specific location (Andriessen *et al.*, 2017, 2019). For instance, research indicates that there is a high demand for solid fuels in urban areas of Sub-Saharan Africa, particularly from manufacturing industries like the brick and cement industries (Diener *et al.*, 2014). Also, wastewater sludge is used as fuel in co-combustion with coal or other solid fuels in industrial setups, both in carbonized and dried forms (Fytili & Zabaniotou, 2008; Werther & Ogada, 1999).

In fact, there are nine ways for the recovery of energy from sewage/faecal sludge (Rulkens, 2008):

- anaerobic digestion of sewage/faecal sludge;
- production of biofuels from sewage/faecal sludge;
- direct production of electricity from sewage/faecal sludge in microbial fuel cells;
- incineration of sewage/faecal sludge with energy recovery;
- co-incineration of sewage/faecal sludge in coal-fired power plants;
- gasification and pyrolysis of sewage/faecal sludge;
- use of sludge as energy and raw material source in the production of portland cement and building materials;
- supercritical wet oxidation of sewage/faecal sludge; and
- hydrothermal treatment of sewage/faecal sludge.

The SBRCVC value chain comprises all stages and activities that input a resource flow from sanitation systems (sewered and non-sewered sanitation) such as urine, faeces, excreta, anal cleansing materials (dry and water), flushwater, brown water, black water, greywater, wastewater, sewage, faecal sludge, and so on, (McConville *et al.*, 2020) to recover and reuse products. It can be analysed in such a way that all important connections are balanced in a circular manner to achieve resource efficiency and sustainability from the very beginning (Koottatep *et al*., 2019; Panoutsou *et al*., 2020). The SBRCVC is the sum of the remuneration received from all value-added activities of all stakeholders participating in the primary treatment of excreta and wastewater, pre-treatment of recovered biomass from sewered and non-sewered sanitation systems, biomass conversion and transportation, and biomass products packaging, as well as the biomass end-use market (Haller, 1997; Maaß and Grundmann, 2016). In other words, SBRCVC takes a look at the remunerations of participating businesses and/or enterprises (public and/or private) involved in the treatment, recovery and reuse of excreta, wastewater, sewage sludge and faecal sludge, crop production, bioenergy generation, and so on. The added value also reveals some social distributional implications of the value chain. The parameters differ from the conventional profit calculation because the remunerations paid to employees, creditors, and the State are considered as part of the added-value and not as value-reducing components (Möller, 2006).

6.2 THE SANITATION BIOMASS RECOVERY AND CONVERSION VALUE CHAIN AND CIRCULAR BIOECONOMY

Escalating environmental and economic pressure to use resources responsibly and add value to the used material/products in the commercial sphere has helped the development of technology routes and material circularity in the sanitation and waste biomass sector (Lokesh *et al*., 2018). The aim of such systems thinking is to 'close the loop' by becoming resource efficient through developing and establishing a sanitation symbiosis to reduce the pressure on virgin biomass (Lokesh *et al*., 2018). The SBRCVC aligns with the implementation of a circular bioeconomy and water–food–energy nexus approaches, that is, a coordinated integration approach that cuts across natural-resources-related sectors and sanitation, which is expedient for solving water, energy and food supply security. Conventional sanitation systems often dispose large loads of nutrients into water bodies, and this causes eutrophication (Mallory *et al*., 2020; Wang *et al*., 2017); global wastewater has enough nutrients to replace 50 million tonnes of fertilizer (CGIAR, 2013; Mallory *et al*., 2020), which represents a significant proportion of the estimated 262 million tonnes supplied per year (FAO, 2019; Mallory *et al*., 2020). The core argument of the nexus approach and circular bioeconomy for sanitation is that the multiplicity of feedbacks and interdependencies resulting from linkages among subsystems, such as sanitation, water, food and energy, jointly affect the sustainability of the broader social-ecological systems (Ganter, 2011; Hellegers *et al*., 2008; Hussey & Pittock, 2012; Villamayor-Tomas *et al*., 2015; Waughray, 2011). The integration of the circular bioeconomy, the nexus and sanitation value chain expands the base of sanitation natural resources which is capable of enhancing water, food and energy security on a local and global scale (Maaß & Grundmann, 2016). This extends the water–food–energy nexus approach to take into account not only the linkages between single resources, but also the connections between whole biomass recovery value chains that use these resources. The benefit of the economic impacts of reducing virgin natural-resource utilization and turning sanitation input–inflow materials to generate desirable out-products complies with the core principles of a circular bioeconomy. The added advantage is that these complex linkages and integration resulting from the adoption of the circular economy for sanitation can further enhance the recovery of resources like faecal sludge, wastewater and sewage sludge through products like animal-feed, energy, biogas, compost and recycled water (Ddiba *et al*., 2020; Diener *et al*., 2014; Mallory *et al*., 2020).

The combination of sanitation biomass recovery and a circular bioeconomy has the potential to directly contribute to 12 out of the 17 UN Sustainable Development

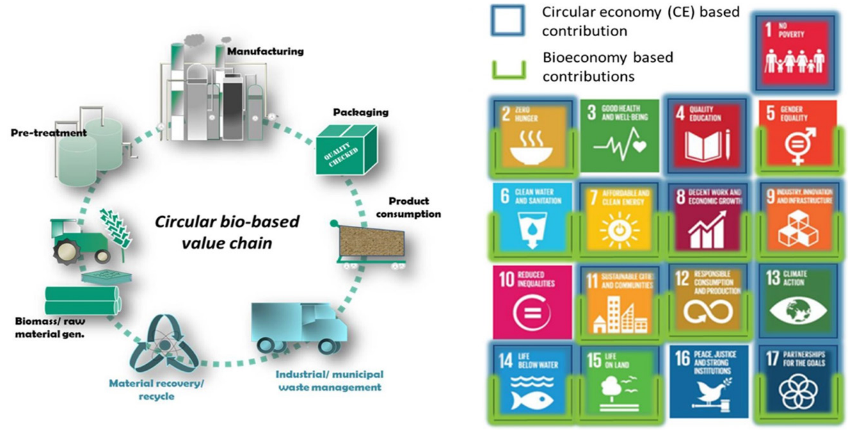

Figure 6.3 Potential for circular biobased value chain to contribute to achieving UN's SDGs and the potential of value chain mapping and analysis in quantifying these goals. (Source: Lokesh *et al.* (2018). Under CCA 4.0 license, © 2018 the authors)

Goals (SDGs) (Figure 6.3). These make a direct contribution to access to water and sanitation for all (SDG 6), sustainable consumption and production (SDG 12), and reducing pressure on the environment, air, water, and land (SDGs 13, 14 and 15) (Blair *et al.*, 2021; Lokesh *et al.*, 2018). There is also a contribution to SDGs related to food security and sustainable agriculture (SDG 2), decent work and economic growth (SDG 8), resilient infrastructure and sustainable industry (SDG 9), climate action (SDG 13), terrestrial ecosystems (SDG 15) and SDG 7 (affordable and clean energy) (Blair *et al.*, 2021). In addition, further contributions can be seen in utilizing the rural knowledge pool and alleviating poverty (SDG 1), good health and well-being (SDG 3), reducing inequalities (SDG 10), guarding the local ecosystem services that encourage sustainable cities and communities (SDG 11), creating jobs and socio-economic opportunities (SDG 8), forging skills among communities through quality education (SDG 4), and working in partnership with rural communities and local biobased biomass recovery infrastructure (SDG 17) (Blair *et al.*, 2021; Lokesh *et al.*, 2018). The use of biomass recovery requires devising smart strategies and value-chain pathways to lock the chains of GHG emissions, either via carbon capture or soil incorporation of high-quality biochar (Blair *et al.*, 2021; Lokesh *et al.*, 2018).

The circular bioeconomy is, therefore, the intersection of the bioeconomy and the circular eco-economy which is the regenerative system for resource input, waste emission and energy leakage formed by closing material and energy loops (Geissdoerfer *et al.*, 2017; Koottatep *et al.*, 2019; Morone & Imbert, 2020). Thus, the sustainable bioeconomy represents the renewable segment of the circular economy (European Commission, 2018) while the circular bioeconomy focuses on the sustainable, resource-efficient valorization of biomass in integrated multi-output production chains while also making use of residues and wastes and optimizing the value of biomass over time via cascading (Feleke *et al.*, 2021). The key elements of the circular bioeconomy (Feleke *et al.*, 2021; Stegmann *et al.*, 2020) include:

- sustainable biomass sourcing;
- circular and durable product design;

- use of residues and waste;
- integrated, multi-output production chains;
- bioenergy and biofuels;
- biobased products, food, and feed;
- prolong and shared use;
- energy recovery and composting; and
- recycling and cascading

The circular economy (CE) is an economic system that is based on business models that replace the 'end-of-life' concept with reducing, reusing, recycling and recovering materials in production/distribution and consumption processes to accomplish sustainable development (Ddiba *et al.*, 2020). The circular economy aims to promote the maximum use of resources and reduce waste by closing economic and ecological loops of resource flows (Haas *et al.*, 2015) and eliminates waste by design, keeping the added value of a product for as long as possible (Sariatli, 2017). Waste is viewed as a resource in a production process, which suggest less extraction of fresh materials and energy consumption (Feleke *et al.*, 2021). On the other hand, the bioeconomy involves production of renewable biological resources and converting these resources and waste streams into value-added products, such as food, feed, biobased products, and bioenergy (European Commission, 2012a). An important feature of the bioeconomy is extending biomass production and processing beyond food, feed, and fibre to include a range of value-added products with potential applications in many sectors, for example, the food, health and energy sectors (East African Science & Technology Commission, 2019). Therefore, implementing circularity within the sanitation system (sewered and non-sewered) forms a biological materials cycle involving recovering water, nutrients, energy and other materials which are typically managed within different resource management sectors (Ellen MacArthur Foundation, 2017).

An analysis of 56 of the world's largest cities found that closing the nutrient loops in large urban cities is most feasible in Africa, Asia and Europe due to cropland density local to these cities (Moya *et al.*, 2019; Trimmer & Guest, 2018). And so a circular bioeconomy within the context of a sanitation biomass recovery value chain could: create an opportunity for incentivizing and stimulating sustainable sanitation by providing additional income streams and reducing the sanitation service cost to the user (Moya *et al.*, 2019); contribute to keeping the added value in products for as long as possible (Maaß & Grundmann, 2016; Smol *et al.*, 2015); and to ensuring higher regional and domestic competitiveness by increasing the effectiveness of resource allocation, resource utilization and productivity (Maaß & Grundmann, 2016; Su *et al.*, 2013). Other potential benefits of circular approaches to a sanitation biomass recovery marketplace include mitigating greenhouse gas emission, securing water, food and energy resources, and providing employment opportunities in growing cities (Andersson *et al.*, 2016).

However, the main determinants of sanitation biomass recovery and conversion products and services in a circular bioeconomy (CBE) are volume of waste collected, integration of faecal sludge (FS) and sewage sludge (SS) with other waste streams, enabling policies and subsidies, and marketing. Also, a number of technical, social and political transformations would need to take place to make a CBE conducive for sanitation businesses that could drive the sanitation biomass recovery value chain (Mallory *et al.*, 2020). Some studies have revealed that, technically, businesses often struggle to collect sufficient waste to make their model of reuse viable, and large increases in financial viability can be achieved by increased collection (Ddiba, 2016). Furthermore, literature looking at the circular bioeconomy for sanitation biomass recovery mostly focuses solely on sewage or faecal sludge, but business models are often driven by the integration of organic solid waste and other biomass (Moya *et al.*, 2019; Otoo & Drechsel, 2018; Remington *et al.*, 2018; World Bank, 2019). On this basis the Toilet Board Coalition (TBC) argues that FS/SS should be seen as part of a biological waste stream encompassing all biodegradable or organic waste to really enable a CBE for sanitation biomass recovery (TBC, 2017). Thus, when considering the circular bioeconomy for a sanitation biomass recovery value chain, it is essential to assess the contribution of other sources of biomass to the development of intended products and the market for the potential products or they will not provide the additional income stream that is desired (Dumontet *et al.*, 1999). This is because in terms of social transformation, marketing and awareness of products also have a large influence in the ability of enterprises and businesses in the value chain to recover economic benefits from the CBE (Mallory *et al.*, 2020).

6.3 SANITATION BIOMASS RECOVERY AND CONVERSION VALUE CHAIN MAPPING

Value chain mapping describes stages of value creation by enterprises and other organizations as part of the process of designing and delivering goods and services for their end-users (European Commission, 2012b; Lokesh *et al.*, 2018). Value chain maps are a valuable, flexible and convenient tool to develop and analyse the scope and performance potential of a biobased business model by breaking down the various process dynamics into logistics, sectors of application and embedded stakeholders. The strengths, weakness, costs and competition from other value chains in the production of specific commodities can be visualized via a value chain map (Lokesh *et al.*, 2018). In essence, value chain mapping provides a generalized yet visual schematic of the dynamics including the resource flow and actors integrated within the SBRVC that are actively playing crucial roles in the delivery of relevant sanitation-derived products (SDPs) to the end-user markets. They involve a network of technologies and infrastructures to convert low-value biomass raw materials to high-value products; activities that safely recycle excreta and organic waste while minimizing the use of non-renewable resources such as water and chemicals. Safely recycling means that waste flows are managed to ensure that physical, microbial and chemical risks are minimized so that recycled products do not pose any significant health threat or environmental impact when correctly used (McConville *et al.*, 2020; Tapia *et al.*, 2019).

The SBRVC main activities and enterprises are broken down into biomass feedstock, biomass pre-treatment, biomass conversion, ancillary services (transportation, storage, product packaging services) and end-user market; together they make up the entire value chain. As such, the value chain involves physical attributes and needs to be designed with a focus on minimizing physical challenges throughout raw material production and conversion (Panoutsou *et al.*, 2020), which is described as a physically efficient value chain. The market assets refer to the delivery of biobased products to the end-users and this adds an innovative nature to the value chain (Panoutsou *et al.*, 2020). The system design of the SBRCVC integrates other value chain activities and enterprises within the IFSVC such as sanitation service (chapter 5), product design & development (chapter 2), and product and equipment manufacturing (chapter 3) as major contributors to the operationalization of the SBRCVC. There are five competitive priorities that have to be considered to ensure that the value chain delivers the required/expected value-added specific targets. These competitive priorities are: (i) flexibility, (ii) quality, (iii) cost, (iv) innovation, and (v) transparency (Panoutsou *et al.*, 2020) (see Figure 6.4). Meanwhile, the activities associated with these technologies and infrastructure include sourcing raw

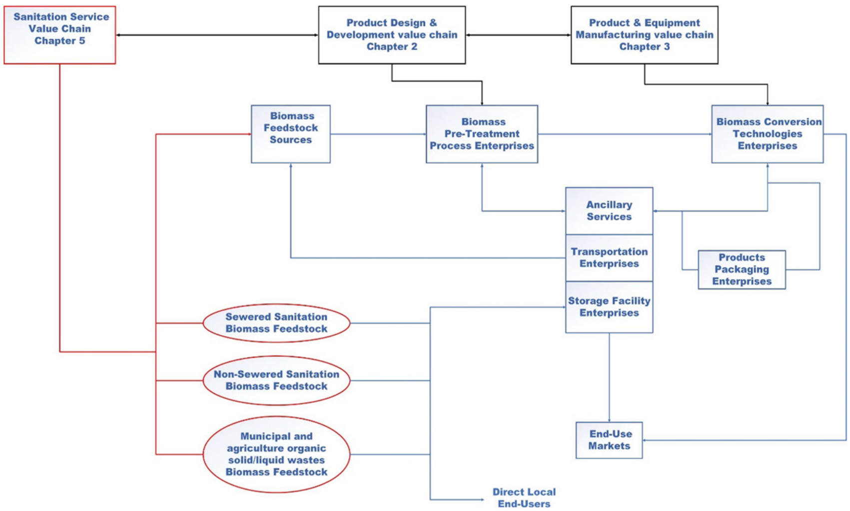

Figure 6.4 Sanitation biomass recovery and conversion value chain enterprises' activities (Source: Authors).

materials, processing, logistics, inventory management and waste management (Jarvis & Samsatli, 2018).

6.3.1 Biomass feedstocks

Waste biomass forms the feedstocks for the sanitation-derived resource recovery value chain. They are heterogeneous and chemically combined renewable-source waste products and/or by-products of either plants and/or animal origin (Siwal *et al.*, 2021). In other words they are any organic materials derived from plants and animals that are classified as biomass feedstock. Biomass can also broadly be classified according to origin and source: biomass generated in rural (agriculture, forestry, and livestock), urban (sewage and municipal solid wastes), and industrial (cellulose and agri-food industries) areas (Ahmed *et al.*, 2019; IREA, 2014; Saxena *et al.*, 2009). Due to the usual abundance, sustainability and low price of biomass, these forms have proved to be possible options for the replacement of non-renewable energy and other useful products (Anukam & Berghel, 2021; Anukam *et al.*, 2016). Sanitation biomass recovery (SBR) feedstocks belong to the non-lignocellulosic biomass (NLB) class of biomass – waste derived from sewage sludge, faecal sludge and organic solid wastes (McConville *et al.*, 2020; Rulkens, 2008; Siwal *et al.*, 2021), see Figure 6.5. The blending of other classes of NLB is to enhance the quality of the raw materials for the production of high-value bioproducts such as biomass derived from municipal organic solid wastes, animal and human wastes, and agricultural waste (Begum *et al.*, 2013).

However, biomass varies owing to a number of factors such as the heterogeneity of biomass, its application and origin (Ahmed *et al.*, 2019). Any organic materials directly or indirectly derived from the process of photosynthesis is considered biomass (Anukam & Berghel, 2021). The chemical composition of biomass depends strongly on it sources (Ahmed *et al.*, 2019; Bajpai, 2016; Popa, 2018).

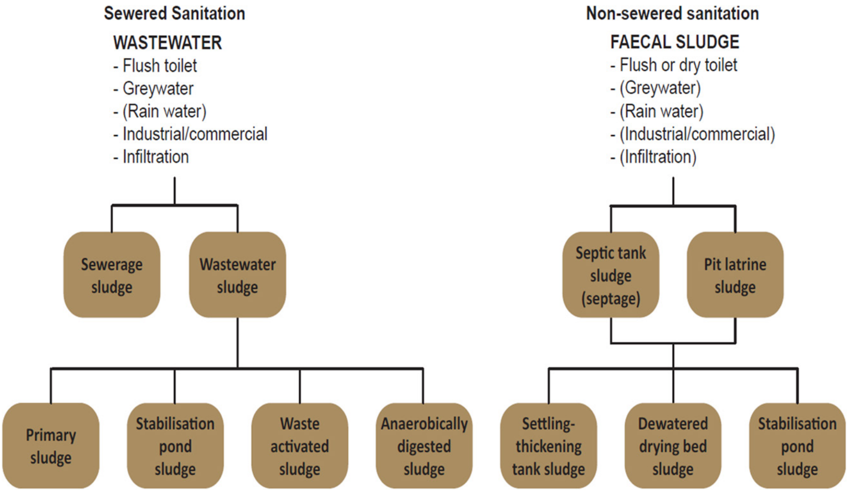

Figure 6.5 Examples of terminology used for different types of sludge relating from sanitation systems. (Adapted from Englund and Strande (2019) by McConville *et al.* (2020). ©Swedish University of Agricultural Sciences (SLU), Department of Energy and Technology. Uppsala, Sweden.)

6.3.1.1 Plant biomass feedstocks

In plants, biomass is formed through conversion of carbon dioxide in the atmosphere into carbohydrates in the presence of the sun's energy.

$$6CO_{2(g)} + 6H_2O_g \rightarrow C_6H_{12}O_{6(s)} + 6O_{2(g)} \quad (6.1)$$

Biological species will then grow by consuming these botanical or other biological species, adding to the biomass chain (Basu, 2018; Mamvura & Danha, 2020). The plant origin biomasses are commonly referred to as lignocellulosic biomass (LB) which is composed of an aromatic polymer (lignin) and carbohydrate polymers (cellulose, hemicellulose) (Anukam & Berghel, 2021; Li & Jiang, 2017).

The internal structure of LB reveals a crystalline fibrous structure of cellulose, which forms the core of the complex structure of biomass. The position between the micro- and microfibrils of the cellulose matrix is occupied by hemicellulose, while lignin plays a structural role that encapsulates both cellulose and hemicellulose. However, their complex structure greatly hinders their utilization due to the high level of crystallinity of cellulose as well as the cross-linking of carbohydrates and lignin (Ahmed *et al.*, 2019; Chang & Holtzapple, 2000) which results in their stable and recalcitrant structure that make them resistant to enzymatic attack (Ahmed *et al.*, 2019; Taherzadeh & Karimi, 2008; Tursi, 2019), see Figure 6.6. To overcome this challenge, pre-treatments of the feedstock become crucial.

(I) ***Cellulose (40–50%)*** is a linear polymer and a complex carbohydrate (or polysaccharide) with a high molecular weight and a maximum of 10 000 monomeric units of D-glucose, linked by β-1,4-glycosidic bonds. The molecular formula of cellulose is $(C_6H_{12}O_6)_n$ (*n* indicates the degree of polymerization) and its structural base is cellobiose (i.e. 4-o-β-D-glucopyranosyl-D-glucopyranose, see Figure 6.7). Cellulose is the most abundant organic compound found in nature and plays a structural function in plant cell walls. The reactivity and

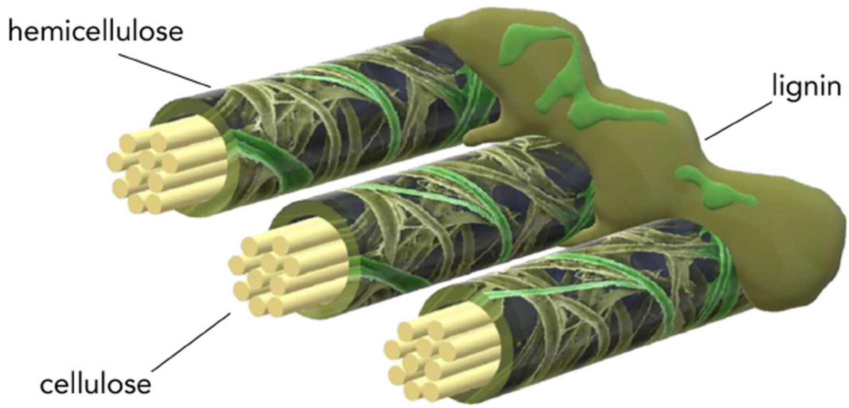

Figure 6.6 Structure of lignocellulose biomass (Source: Tursi, 2019).

morphology of cellulose chains are structurally influenced by the intermolecular hydrogen bond between the hydroxyl group on C-3 carbon and the oxygen of the nearby glycosidic ring. The formation of these bonds makes the molecules more stable and rigid (Ahmed *et al.*, 2019; Bernal *et al.*, 2017; Smith *et al.*, 2010; Tursi, 2019).

(II) ***Hemicellulose (25–35%)*** is one of the major constituents of plant cell walls and consists of heterogeneous branched polysaccharides. It is strongly linked to the surface of cellulose microfibrils. The content and structure of hemicellulose are different depending on the type of plant (Bala *et al.*, 2016). The various sugar units are arranged with different substituents and in different proportions. Hemicellulose decomposes thermally between 180 and 350°C, thereby producing non-condensable gas, coal and a variety of ketones, aldehydes, acids and furans (Ahmed *et al.*, 2019; Bernal *et al.*, 2017; Carpenter *et al.*, 2014; Smith *et al.*, 2010; Tursi, 2019). In nature, hemicellulose is amorphous and has adhesive properties, with a high tendency to toughen when it is dehydrated. Hemicellulose almost entirely consists of sugars with five carbon atoms (xylose and arabinose) and six carbon atoms (glucose, galactose, mannose and rhamnose) with an average molecular weight of <30 000 (Bonechi *et al.*, 2017; Jindal & Jha, 2016; McKendry, 2002; Tursi, 2019). The different groups of molecules making hemicellulose include xylans, mannans and arabinogalactan (Tursi, 2019), see Figure 6.8).

(III) ***Lignin (15–20%)*** is also contained in plant cell walls, with the function of binding, cementing, and putting the fibres together in order to enhance the compactness and resistance of the plant structure. Lignin is also recognized for

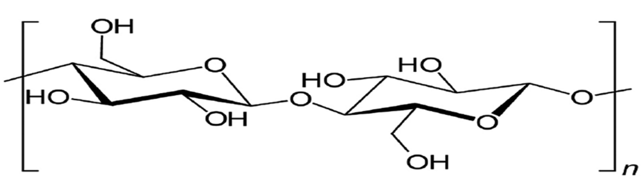

Figure 6.7 The structural formula of cellulose (Source: Tursi, 2019).

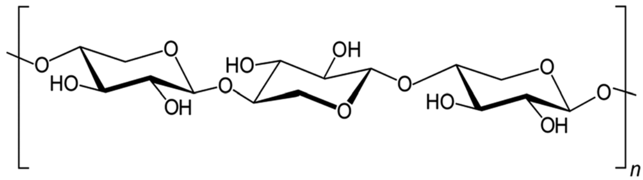

Figure 6.8 The structural formula of hemicellulose (Source: Tursi, 2019).

its encrusting effect as it protects fibres and prevents degradation (Tursi, 2019). Its elemental composition is approximately 61–65% carbon, 5–6% hydrogen and the remainder is oxygen (Fromm *et al.*, 2003). Structurally, it is a complex amorphous aromatic polymer with a three-dimensional network composed of phenylpropane units linked together. The monomeric units are held together in different ways: through oxygen bridges between two propyl and phenyl groups, between a phenyl and a propyl group, or through carbon–carbon bonds between the same groups. In particular, this macromolecule is formed through the radical oxidative polymerization of three hydroxycinnamyl alcohols representing the basic structural monomers: p-phenyl monomer (type H), guaiacyl monomer (type G) and siringyl monomer (type S), deriving from coumarinic, coniferyl and synapyl alcohol respectively (Ahmed *et al.*, 2019; Bernal *et al.*, 2017; Smith *et al.*, 2010; Tursi, 2019), see Figure 6.9. These compounds differ from each other due to the different degrees of methoxylation. Overall, given the considerably high global availability of lignin, that is 300 billion tons, with an annual increase of about 20 billion tons (Hodásová *et al.*, 2015), development of innovative technologies for lignin valorization is essential.

The two main components of biomass are lignocellulosic biomass (LB) and non-lignocellulosic biomass (NLB) which can be in the form of cellulose, hemicellulose and lignin (Ahmed *et al.*, 2019; Bernal *et al.*, 2017; Smith *et al.*, 2010; Tursi, 2019). Other minor components of biomass are extractives, proteins, water and inorganic

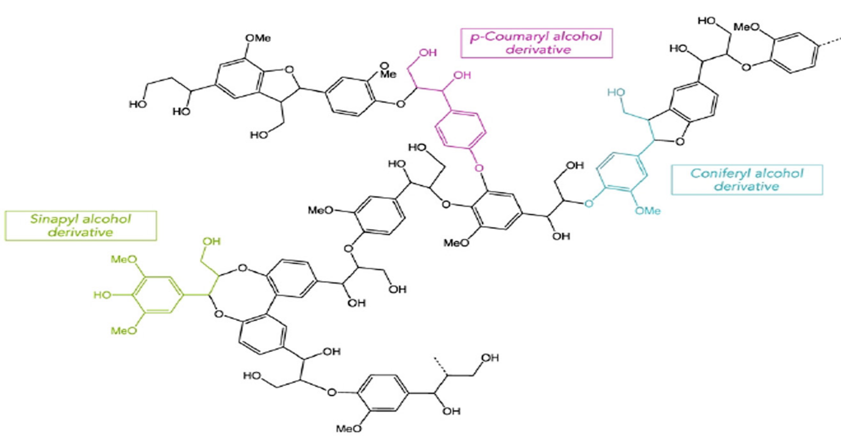

Figure 6.9 The structural formula of lignin and its precursors (Source: Tursi, 2019).

components such as silicon (Si), sodium (Na), potassium (K), calcium (Ca), magnesium (Mg) and aluminium (Al). These minor constituents do not significantly contribute to the formation of the total structure of the biomass (Anukam & Berghel, 2021; Raven *et al.*, 1992; Tursi, 2019).

6.3.1.2 Animal biomass feedstocks

Besides the plants and their derivatives, biomass also contain animals, microorganisms, and a portion of plants and materials derived from them, which are defined as non-lignocellulosic biomass (NLB) (Li & Jiang, 2017); the components mainly include lipids, proteins, saccharides, inorganics, minerals as well as a fraction of lignin and cellulose (Anukam & Berghel, 2021; Li & Jiang, 2017). NLB also includes resources such as sewage sludge, faecal sludge, plants and animal organic wastes, manure, algae, animal hair and bone and so on (Anukam *et al.*, 2016; Li & Jiang, 2017). It is chemically composed of C, H, O and N, comparable to non-renewable resources (Rana *et al.*, 2021; Siwal *et al.*, 2021; Thakur *et al.*, 2012). NLB is an excellent architectural material, arranging various atoms in an orderly manner to build units. Compared with LB, the NLB usually contains more miscellaneous elements such as N, P, S and metals, which are embedded in the skeleton of its structural unit. During heat treatment, the heteroatom of its structural unit can act as an activator or catalyst for biomass pyrogenic decomposition (Li & Jiang, 2017). Also, different compositions of NLB can lead to different thermochemical conversion behaviour in comparison with LB; understanding NLB behaviour during heat treatment and its physicochemical properties is essential to optimizing the conversion process for efficient waste disposal, resource recovery, and preparation of functional NLB materials (Li & Jiang, 2017; Liu *et al.*, 2015a; Yoshida & Antal, 2009).

(I) ***Sewage sludge (SS),*** a product of sewered sanitation can be described as any solid, semi-solid or liquid waste generated from a wastewater treatment facility. This wastewater can be sourced from municipal, commercial or industrial processes. The physical properties (low ratio of solid to liquid matter) of sewage mean it requires thickening and mechanical dewatering to help increase the solid particles to about 10–25 wt% from the original predominantly liquid (<3 wt% solid) state (Cieslik *et al.*, 2015; Li & Jiang, 2017; Magdziarz *et al.*, 2016; Oladejo *et al.*, 2019; Seiple *et al.*, 2017; Syed-Hassan *et al.*, 2017). The solid phase in sludge is made up of an inhomogeneous mix of proteins, carbohydrates, oils, inorganic matter and micro-organisms. This mixture of organic, inorganic and living organisms results in an unstable, volatile and putrid matter with toxic elements (Cieslik *et al.*, 2015; Li & Jiang, 2017; McConville *et al.*, 2020; Oladejo *et al.*, 2019; Rulkens, 2008; Siwal *et al.*, 2021; Wang *et al.*, 2016). Sewage treatment or stabilization involves biological (composting or digestion), physical (e.g., pressure, heat, vibration, microwaves) or chemical (oxidation, alkalinity adjustment) methods to stabilize the organic matter (including destruction of pathogens, odour elimination and reduction of volatile contents) contained in the primary sludge in order to improve the quality of effluent, maximize nutrient recovery and/or for safer disposal. The product of this stabilization process can be referred to as secondary sludge if it undergoes further biological processes (Chan & Wang, 2016; Mulchandani & Westerhoff, 2016; Oladejo *et al.*, 2019; Seiple *et al.*, 2017; Vaxelaire & Cézac, 2004). Anaerobic digestion is one example of such stabilization techniques: its secondary sludge can be used as fertilizer while the biogas produced from the digester can form part of the energy recovery capabilities of the process (Oladejo *et al.*, 2019; Winkler *et al.*, 2013). The elemental composition of sewage sludge differs greatly from case to case despite the common elements like C, O, H and

N. The C content varies between 25% and 70%, caused by the high ash content varying from 15% to 50%. The high ash content in sewage sludge is usually linked with the significant levels of other elements such as P, Ca, K, Mg, Fe, Si, Na, and so on (Li & Jiang, 2017). On the other hand, sewage sludge contains many easily available plant nutrients such as N, P, K and organic matter, which raises wide interest in its use as a fertilizer in agriculture or as a regenerator for soil (Khan *et al*., 2013; Li & Jiang, 2017). Furthermore, it also can be used to produce renewable biofuel owing to its high decomposable organic content (Li & Jiang, 2017; Xie *et al*., 2014). Sustainability measures have increased focus on the recovery and reuse of sludge after treatment to reduce landfill requirements and environmental footprints, and to lessen impacts on the land, groundwater and food supply (Li & Jiang, 2017; Oladejo *et al*., 2019).

(II) ***Faecal sludge (FS),*** a product of non-sewered sanitation, is the raw or partially digested semisolid material that is produced primarily from human excreta and blackwater, but also includes anything else that goes into onsite sanitation systems such as flush-water, cleansing materials, menstrual hygiene products, greywater (i.e. bathing or kitchen water, including fats, oils, and grease), and solid wastes, and which needs to be removed periodically and transported to a faecal sludge treatment plant, followed by safe disposal or end-use (Barani *et al*., 2020; Strande, 2021). Faecal sludge is grouped by consistency according to Strande (2021) and Velkushanova (2021) as:

- *liquid (TS <5%):* which is relatively diluted with the consistency of water or domestic wastewater, is readily pumpable and usually collected from wet containments such as leach pits, septic tanks or wet pit latrines;
- *slurry (TS 5–15%):* normally thicker than liquid, but still watery with a wet mud consistency, pumpable in lower ranges and thus difficult to shovel; it is common in pit latrines (improved or unimproved) with a frequent input of greywater or subject to infiltration;
- *semi-solid (TS, 15–25%):* soft paste-like materials, not pumpable, but can be spadable at the higher end of the range; it is collected from onsite containments such as pit latrines, composting toilets and leach pits, or from dewatering treatment technologies; and
- *solid (TS >25%):* the majority of free water has been removed; it can come from dry toilet systems or dewatering treatment technologies.

FS recovery may support the development of viable business models for sustainable sanitation (Barani *et al*., 2020; Diener *et al*., 2014). The most common form of resource recovery from faecal sludge solids has been that of soil conditioning. However, more promising options have recently emerged including the use of faecal sludge as a component of building materials, as source of protein for animal feed and as industrial fuel (Barani *et al*., 2020; Diener *et al*., 2014). Other approaches for energy recovery from non-sewered sanitation systems are combustion (Sellgren *et al*., 2017), gasification (Onabanjo *et al*., 2016), smouldering (Yermán *et al*., 2015), hydrothermal oxidation (Miller *et al*., 2015) and hydrothermal carbonization (Afolabi *et al*., 2017).

Other notable contributions of NLB feedstock for the SBRCVC as biomass include:

(III) ***Livestock manure (LM)***, a predictable side-product of animal husbandry that adds to greenhouse gases through the release of CH_4 to the environment if not regularly captured (Siwal *et al*., 2021);

(IV) ***Food waste (FW)***, valorisation through AD, fermentation and composting processes can create high-value products such as biofuels, biomass, and biofertilizers (Siwal *et al*., 2021);

(V) ***Agricultural waste (AW)***, which is a standard classification of carbon-rich biomass overflowing with cellulose, hemicellulose and lignin as lignocellulose (Siwal *et al*., 2021; Thakur *et al*., 2012; Zielinska *et al*., 2021);

(VI) ***Forestry residue (FR)*** is an essential lignocellulose raw material for bioenergy generation; pyrolysis of FR has been used to generate bio-oil and biochar (Demirbas & Balat, 2006; Singh *et al*., 2018; Siwal *et al*., 2021);

(VII) ***Marine processing waste*** **(MPW)**, includes fish production trash such as scales, skin, visceral mass, air bladders, gonads, head, tails and fins, crab shells and shellfish waste, head, and body carapace, and much more;

(VIII) ***Manure*** is an important nutrients source containing abundant organic matters, N, P, K and other trace elements; manure from humans and animals is widely used as plant fertilizer. The proportions of C, O, H and N in manure are usually 40–50%, 30–35%, 5–7%, and 2–5% respectively; and

(IX) ***Fermentation processing waste (FPW)***, which includes lipids, proteins, and carbohydrates that can be converted into products such as fatty acids (acetic, propionic and butyric acid) and alcohols (ethanol and butanol) by the fermentation process (Chohan *et al*., 2020); and food processing waste (Siwal *et al*., 2021).

Other sources of feedstock are organic wastes derived from municipal activities such as restaurant and kitchen wastes, food processing industry waste, and agricultural and crop processing (crop and garden waste, sawdust, fruit, chicken and other animal manure and abattoir waste) (Polprasert & Koottatep, 2017).These classes of waste can either be reduced, recycled or transformed through the application of new and innovative approaches and technologies into energy, organic fertilizers, and animal feed as well as other useful products (Polprasert & Koottatep, 2017).

As noted earlier, although feedstock sourcing seems a simple process, technically, businesses still find it difficult to access enough of the right quality waste biomass to achieve a viable reuse business model; stronger financial viability improved feedstock collection (Ddiba, 2016; Koottatep *et al*., 2019; Polprasert & Koottatep, 2017). It is crucial that the SBRCVC is flexible enough to use variety of feedstock to produce high-value goods (Hennig *et al*., 2016; Lokesh *et al*., 2018). Feedstock end-of-life characteristics play a prominent role at any given stage of a value chain because of the capability of utilizing waste biomass for raw feedstock (also called 'cascading use'), which makes it a sustainable business model as there will be a regular influx of low-cost feedstock that promises a continuous product supply to the market (Budzinski *et al*., 2017; Lokesh *et al*., 2018). This strategic management and utilization of sanitation-derived feedstocks and organic waste could deliver three-fold benefits: environmentally through reduction of waste treatment and disposal; economically by enabling resource efficiency and through transformation of waste (as low-cost raw materials for a secondary industry); and socially through creation of jobs, new value chains and social equity (Lokesh *et al*., 2018; Pagotto & Halog, 2016).

6.3.2 Biomass Pre-treatment processes

There are various options for enterprises in the value chain to be involved in pre-treatment of biomass; and the most appropriate one or the most appropriate combination mainly depends on the subsequent conversion and utilization of that biomass, that is for thermochemical or biochemical conversion technologies (Papadokonstantakis & Johnsson, 2020). Collected biomass is subjected to pre-treatment and/or pre-processing to increase its resource value as well as enhance its conversion to high-quality and high-value bioproducts. Some common pre-processing/pre-treatment steps are mainly related to removing moisture by drying and decreasing the size of biomass particle, typically by grinding, milling, balling and pelletizing. These steps may also influence the efficiency of the subsequent biomass utilization processes (Papadokonstantakis & Johnsson, 2020). Such processes make subsequent biomass conversion more economical and environmentally friendly for transportation and storage (Tapia *et al.*, 2019).

Pre-treatment is a necessary process step for both biochemical and thermochemical conversion of biomass and involves structural alteration aimed at overcoming the recalcitrant nature of biomass. It is required to improve biomass characteristics in order to enhance their efficient utilization for production of high-value bioproducts (Anukam & Berghel, 2021; Anukam *et al.*, 2016; Chiang *et al.*, 2012). The main goal of biomass pre-treatment is to facilitate microbial digestion by removing barriers and making the organic content of the substrate easily accessible and usable for producing high-value bioproducts (Kasinath *et al.*, 2021). Thus, complex organic matter (e.g., cellulose, hemicellulose, and lignin, proteins, polysaccharides and lipids) need to be solubilized and hydrolysed into simple components such as long-chain fatty acids, sugars and alcohols (Kasinath *et al.*, 2021; Zhen *et al.*, 2017). Pre-treatment processes (also known as conditioning) are used to speed up and enhance digestion as well as improve dewatering and the quality of the digestate (Kasinath *et al.*, 2021). For example, in pre-treatment processes requiring the use of heat, the degradation ability of lignocellulosic biomass (LB) is controlled by its polymeric and aromatic constituents (cellulose, hemicellulose and lignin), while the heteroatoms and inorganic elemental components of non-lignocellulosic biomass (NLB) could act as catalysts to facilitate decomposition. This then forms a product that has a carbon framework with a change in the original structure that increases the performance of the pre-treated material during bioconversion processes (Anukam & Berghel, 2021; Anukam *et al.*, 2017; Liu *et al.*, 2015a; Yoshida & Antal, 2009).

Pre-treatment technologies can be classified into physical, chemical, physicochemical and biological pre-treatment methods (E4tech (UK) Ltd *et al.*, 2015; Papadokonstantakis & Johnsson, 2020):

(I) ***Physical pre-treatment*** aims to increase the accessible surface area and pole volume and decrease the degree of polymerisation of cellulose and its crystallinity.

(II) ***Chemical pre-treatment*** mostly uses alkalis, acids, ozonation, Fenton or Fe (II)-activated persulfate oxidation to delignify the biomass and decrease the polymerisation and crystallinity of cellulose (Kasinath *et al.*, 2021; Patinvoh *et al.*, 2017). The most commonly used acid is H_2SO_4 (Morales *et al.*, 2017; Papadokonstantakis & Johnsson, 2020) and the most common alkali is NaOH. These are applied to solubilise the hemicellulose fraction of biomass and make the cellulose accessible to enzymes. Organic acids can also be used to enhance cellulose hydrolysis and reduce production of inhibitors (Papadokonstantakis & Johnsson, 2020).

(III) ***Physicochemical pre-treatment*** affects both physical and chemical properties of the biomass; among such techniques are steam explosion, ammonia fiber explosion (AFEX), wet explosion, CO_2 explosion, and so on.

(IV) ***Biological pre-treatment*** is carried out using microorganisms (temperature-phased anaerobic digestion and microbial electrolysis cells) such as white rot fungi (Kasinath *et al.*, 2021; Papadokonstantakis & Johnsson, 2020; Patinvoh *et al.*, 2017; Sarkar *et al.*, 2012). This alters the structure of lignin and cellulose, separating them from the lignocellulosic matrix.

Although biological pre-treatment is typically carried out under mild conditions, the rates of hydrolysis are low and current efforts focus on combining this technology with other pre-treatment methods and developing new microorganisms for rapid hydrolysis (Kasinath *et al.*, 2021; Papadokonstantakis & Johnsson, 2020; Patinvoh *et al.*, 2017). Other pre-treatment methods can make use of mechanical techniques such as ultrasonic, microwave, electrokinetic and high-pressure homogenization (Kasinath *et al.*, 2021; Patinvoh *et al.*, 2017).

Pre-treating sewage sludge and faecal sludge (being the main feedstock for the SBR) is usually characterized by high concentrations of solid and organic matter and a significant presence of pathogens, nutrients, and organic and inorganic pollutants, and involves single or combined physical, chemical and biological means to disrupt the floc structure of sludge and hydrolyse organic matter, as well as provide significant enhancements in terms of solid reduction to produce the required high-value bioproducts (Neumann *et al.*, 2016). Pre-treatment can be applied to primary, secondary and/or mixed sludges and has been known to significantly improve pathogen deactivation and sludge quality. Therefore, its application to mixed and primary sludge can be attractive depending on the main objective (Wilson & Novak, 2009). Pre-treatment of sludge is expected to rupture the floc structure as well as some bacterial cell walls, resulting in the release of intercellular matter in the aqueous phase (Kasinath *et al.*, 2021), and so helps to reduce its high resistance to both dewatering and biodegradation. The increase in nutrient accessible to microbes enhance the digestion rates and reduces the retention time of conversion of biomass to high-value bioproducts (Kasinath *et al.*, 2021; Khanal *et al.*, 2007; Pilli *et al.*, 2011). The first commercially used thermal pre-treatments for SS were Porteous and Zimpro which were implemented in the 1960s and the early 1970s; a modified lower temperature was subsequently used to enhance the dewaterability of SS (Camacho *et al.*, 2008). During the 1980s, however, various combinations of thermal and pH-based (acid and alkaline) technologies were tested (e.g. Synox and Protox), but none were successfully commercialized owing to insufficient cost-effectiveness. In 1996 the CambiTHP™ process, a combination of thermal hydrolysis and high pressure, was implemented to increase biogas production and digester loading (Neyens & Baeyens, 2003). Then in 2006 Veolia, following their batch process Biothelys®, introduced a continuous-flow process called Exelys – a pre-treatment thermal hydrolysis process for municipal and industrial sludge, as well as for sludges containing fats, oils and grease (Kasinath *et al.*, 2021).

A successful SBRCVC depends on a business model often driven by blending agricultural waste, food waste and organic (biodegradable) fractions of municipal solid waste biomass and sanitation-derived biomass (Moya *et al.*, 2019; Otoo & Drechsel, 2018; Remington *et al.*, 2018; World Bank, 2019). It should also be noted that any type of agricultural, food or organic fraction of municipal-waste biomass that consists of lignocellulose fibres will require pre-treatment (Kasinath *et al.*, 2021). This pre-treatment is most frequently a combination of elevated temperature and chemical treatment, while thermal and other mechanical pretreatment methods are also considered (Fernandes *et al.*, 2009; Kasinath *et al.*, 2021). The pretreatment efficiency with respect to lignocellulose biomass depends mainly on the lignin content of the treated materials (Fernandes *et al.*, 2009; Kasinath *et al.*, 2021).

The detrimental effects of pretreatment for these classes of biomass include the formation of refractory compounds, mainly from high-thermal pretreatment. Thermoacid pretreatment may also generate biomass conversion inhibitors such as furans and phenolic compounds, which may hinder microbial activity (Taherzadeh & Karimi, 2008; Vavouraki *et al.*, 2013).

6.3.3 Biomass conversion technologies

The enterprises and actors in the conversion processes generate the needed revenue for the SBRVC by transforming biomass resources such as collected and/or pre-processed biomass into valuable products (Papadokonstantakis & Johnsson, 2020; Tapia *et al.*, 2019). The conversion pathways that transfer sanitation biomass to high-value biobased products include biochemical (photobiological hydrogen production, anaerobic digestion, and fermentation); thermochemical (combustion, pyrolysis, gasification, and liquefaction); mechanical extraction; and physical or chemical (Panoutsou *et al.*, 2020; Papadokonstantakis & Johnsson, 2020). All of these allow low-value biomass resources to gain economic value when transformed into high-value products such as biofuels (biogas, biohydrogen, biodiesel), power, heat, oleochemicals that serve as substitutes for petroleum-based products known as petrochemicals (Papadokonstantakis & Johnsson, 2020; Wikipedia contributors, 2022), single-cell proteins, animal proteins, building materials, soil conditioners, biofertilizers, short-chain fatty acids, enzymes, biopesticides, bioplastics, bioflocculants and biosurfactants (Diener *et al.*, 2014; Eze, 2004; Koottatep *et al.*, 2019; Mafakheri & Nasiri, 2014; Otoo & Drechsel, 2018; Papadokonstantakis & Johnsson, 2020; Polprasert & Koottatep, 2017; Puyol *et al.*, 2017; Zhang *et al.*, 2018).

The two most important physical properties of biomass, regardless of conversion process, are particle size and moisture content. Practically all conversion methods require some degree of size reduction (Williams *et al.*, 2017). For instance, biochemical conversion processes can accept a greater range of particle sizes, and the final size needed tends to be dependent on the processing system utilized (Dibble *et al.*, 2011; Van-Walsum *et al.*, 1996; Williams *et al.*, 2017). Hydrothermal liquefaction is much more insensitive to particle size owing to high heating rates in the liquid media (Akhtar & Amin, 2011; Williams *et al.*, 2017), but a significant amount of size reduction is needed to pump biomass sludges in a continuous system (Jazrawi *et al.*, 2013; Williams *et al.*, 2017). On the other hand, moisture increases heating rates during steam pre-treatment for biological conversion (Brownell *et al.*, 1986; Williams *et al.*, 2017) and also reduces bio-oil quality and thermochemical conversion (Bridgwater *et al.*, 1999; Williams *et al.*, 2017) and causes low thermal efficiency in combustion processes (Jenkins *et al.*, 1998; Williams *et al.*, 2017). Aside from particle size and moisture content, other physical properties of interest include bulk density, elastic properties, and microstructure. Bulk density has a strong effect on transportation and handling costs because lower densities greatly increase transportation cost. Biomass chemical properties also have a large influence on the best conversion process and the quality of the final product. The three primary compounds of interest in biomass conversion are ash content, volatiles and lignin. High ash content generally has a negative effect on biomass conversion across the board by reducing the effectiveness of dilute acid pre-treatment for biological processes (Weiss *et al.*, 2010; Williams *et al.*, 2017) and increasing char yields and fouling in thermochemical processes such as hydrothermal liquefaction (HTL) (Toor *et al.*, 2011; Williams *et al.*, 2017), pyrolysis (Tumuluru *et al.*, 2012; Williams *et al.*, 2017), and combustion (Jenkins *et al.*, 1996; Williams *et al.*, 2017). Conversion technologies covered in this chapter with reference to the SBRCVC are presented below:

6.3.3.1 Thermochemical conversion technologies

The shortage of conventional energy resources, as well as environmental issues related to landfilling the considerable amount of excess sewage sludge and faecal sludge, raised interest in developing methods for the utilization of sludge for energy purposes (Smoliński *et al.*, 2018). Thermochemical technology involves a high-temperature chemical reformation process that requires bond breaking and reforming of organic matter into biochar (solid), synthesis gas and highly oxygenated bio-oil (liquid). Within thermochemical conversion, there are three main process alternatives available:

gasification, pyrolysis and liquefaction (Lee *et al*., 2019). This conversion involves the complete oxidative ignition of sanitation-derived (i.e. faecal sludge) and other organic-waste biomass with the primary aim being to produce high-temperature energy. (Siwal *et al*., 2021). Also, attention is given to thermochemical co-processing of SS and/or FS with fossil fuels and biomass (Garrido-Baserba *et al*., 2015; Kokalj *et al*., 2017) and pyrolysis of SS and/or FS then blended with organic solid waste as well as with biomass from other sources (Deng *et al*., 2017; Ma *et al*., 2017; Zhang *et al*., 2015). The selection of conversion type can be influenced by the nature and quantity of biomass feedstock, and the preferred type of energy, for example end-use conditions, environmental principles, financial circumstances and the precise nature of the project (Siwal *et al*., 2021). Thermal conversion technologies have gained extra attention due to the availability of industrial infrastructure to supply thermochemical transformation equipment that is highly developed, short processing times, reduced water usage and the added advantage of producing energy from other forms of waste that cannot be digested by microbial activity (Uzoejinwa *et al*., 2018). The main business activities are the construction and operation of conversion installations, ensuring conversion processes' efficiencies and optimization of conversion technologies (Panoutsou *et al*., 2020; Tapia *et al*., 2019). The challenges with regards to construction include site selection and access to technology, and for operations, low emission performance, handling mixed volumes of feedstocks and improving synergies for valorisation of residues and co-products (Panoutsou *et al*., 2020).

6.3.3.1.1 Combustion technology

The combustion of all solid fuels is similar to that of sewage sludge and faecal sludge biomass. In the combustion process, biomass and oxygen are combined in a high-temperature environment to form carbon dioxide, water vapour, heat and trace gases (Oladejo *et al*., 2019), see equations (2) and (3). This process is known to produce approximately 90% of the total renewable energy from biomass. The use of combustion technology for waste materials such as sewage sludge and faecal sludge can be used primarily to reduce the volume of sanitation-waste materials, and later heat generation as well as electric generation was added as a resource recovery strategy.

$$\text{Biomass} + \text{Oxygen} \rightarrow \text{Carbon Dioxide} + \text{Water} + \text{Heat} \tag{6.2}$$

The approximate chemical equation for biomass combustion is:

$$CH_{1.44}O_{0.66} + 1.0\ 3O_2 \rightarrow CO_2 + 0.72\ H_2O + \text{Heat} \tag{6.3}$$

The amount of generated heat depends on many factors, but mainly on the types and quality of biomass used in the process, although the average thermal energy produced is 20 MJ/kg of biomass (Nussbaumer, 2003). As shown by equations (2) and (3), the combustion process is an exothermic reaction, that is, the biomass is burnt in the presence of air with subsequent release of chemical energy that could be converted into mechanical and electrical energy (Kaushika *et al*., 2016; Lebaka, 2013).

The principle of solid fuel combustion involves drying, pyrolysis, volatiles combustion, char combustion, ash melting and agglomeration. These stages occur sequentially or simultaneously depending on the configuration, reactor conditions and fuel properties. For example, some sludge and biomass could start pyrolysis at low temperatures (~150°C) typical for fuel drying (Ogada & Werther, 1996; Oladejo *et al*., 2019; Urciuolo *et al*., 2012), see Figure 6.10.

The release and burning of volatiles from this stage generate heat, CO, H_2O, CO_2, NO_x and SO_x, which further interact with the solid char particles in the fuel and increase

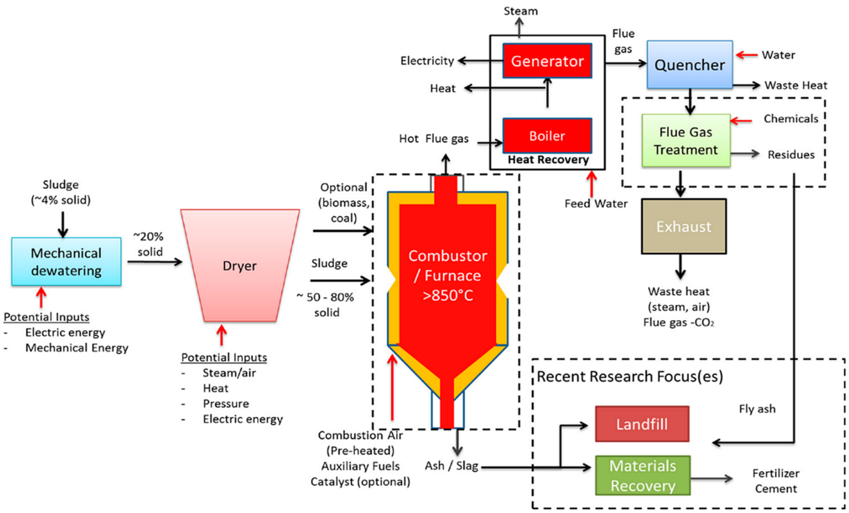

Figure 6.10 Schematic representation of the combustion of sludge. (Source: Oladejo *et al.* (2019) under CCA 4.0 license, ©, 2018 by the authors)

surface temperature (Oladejo *et al.*, 2019). The furnace operates at temperature >850°C for the complete oxidation of sludge which may be done separately or blended with other solid fuels (coal or biomass) (Chen *et al.*, 2018; Rong *et al.*, 2017). This process would require excess air for completion while auxiliary fuel and catalyst might be needed for initiation and maintaining reactor stability for operational efficiency. Ash and flue gas are the main output from this reactor. The flue gas is made up primarily of oxides of carbon, nitrogen, sulphur and particulate matter which act as the thermal store that allows heat transfer from itself to feed water. This aids heat generation for direct use (industrial or residential heating) or electricity generation via steam turbines and generators. After the heat recovery process the flue gas has to undergo treatment for elimination of pollutants before releasing exhaust gas (mostly CO_2 and water vapour) into the atmosphere. The ash generated from this process can be reused in agricultural or construction applications. However, this depends primarily on its chemical contents, particularly the heavy metal content of the ash (Oladejo *et al.*, 2019).

Combustion reactors use various technologies such as multiple hearth, rotary kiln and cyclone and fluidized bed furnace with different fuel needs and operating mode. The major challenge with combustion of sewage/faecal sludge is mostly moisture and ash content that influences the thermal characteristic of the fuel and the design requirements of the combustor. High moisture content is not only a deterrent for increasing the bulk density of the fuel, oxidant and energy for drying the sludge and has the potential of forming erosive sulphuric compounds (Han *et al.*, 2012). The use of ash and slags for other applications contributes to high phosphorus contents and negligible toxic compounds such as heavy metals or polycyclic aromatic hydrocarbons (PAHs) make it suitable for agricultural purposes or raw materials for the construction industry. Co-use of sludge with other fuel such as coal, biomass, other solid waste, fuel oil or gas has been investigated as a means of avoiding the high cost associated with dedicated reactors and also an avenue for reducing net carbon emissions (Oladejo *et al.*, 2019).

6.3.3.1.2 Gasification technology

The thermochemical conversion of sewage sludge/faecal sludge's organic content into high value gases such as H_2 and CO known as synthesis gas as well as CO_2, CH_4, H_2O and other hydrocarbon is the main basis for gasification (Oladejo *et al.*, 2019). The gasification technique comprises chemical reactions in an environment that is oxygen deficient. This process involves biomass heating at extreme temperatures (500–1400°C), from atmospheric pressure up to 33 bar and with low/absent oxygen content to yield combustible gas mixtures. Often described as an incomplete anodic process of organic materials at a high temperature (500–1800°C) to generate synthetic gas (Siwal *et al.*, 2019, 2021), biomass gasification happens to be where the char acts including CO_2 and water stream to create CO and H_2. Also, the volumes of CO, steam, CO_2 and H_2 are compared very quickly on temperatures inside a reactor. Produced gas may be applied as fuel towards the adequate generation of power and/or heat (Colmenares *et al.*, 2016; Siwal *et al.*, 2021). The gasification process transforms carbonaceous constituents into syngas comprising hydrogen, carbon monoxides, carbon dioxide, methane, higher hydrocarbons and nitrogen with the presence of gasification agent and catalyst. By utilizing this syngas, various types of energy or energy carriers are supplied, for example, biofuel, hydrogen gas, biomethane gas, heat, power and chemicals (Lee *et al.*, 2019).

This process is very similar to combustion with the exception of the lower moisture tolerance in the reactor (<15 wt%) and the deficit in stoichiometric oxidants required for complete combustion. The main outputs from the reactor are gases and ash. Depending on the chemical and mechanical properties, as well as heavy metal contents, the ash generated from the process can be reused in agricultural or in construction applications. The product gases require further processing and clean-up for either use in heat and electricity generation or upgrading of synthesis gas for liquid fuels and chemical synthesis (Oladejo *et al.*, 2019), see Figure 6.11. Gasification reactions can be

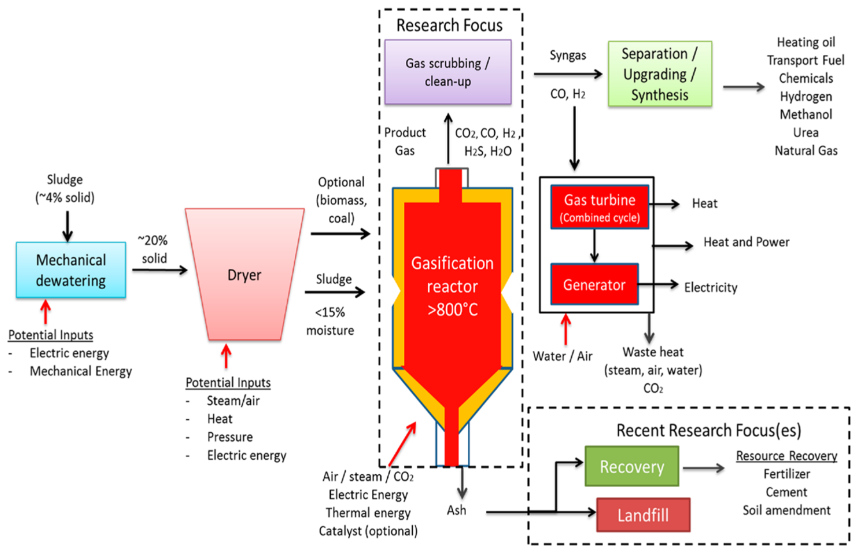

Figure 6.11 Schematic representation of the gasification of sludge (Source: Oladejo *et al.* (2019) under CCA 4.0 license, ©, 2018 by the authors).

divided into sub-stages which are drying of sample (70–200°C), devolatilization (350–600°C), oxidation of volatiles and char gasification. Hence, it can also be termed as an incomplete combustion or extended pyrolysis reaction in which gas–solid, gas–gas and liquid cracking reactions are required to maximise the gaseous product yield.

There are essentially two types of gasification technologies: autothermal (direct) and allothermal (indirect) gasification. In direct gasification, the heat required by the process is only internally generated by the partial combustion of the feedstock, whereas in indirect gasification, energy is also delivered to the process via the gasification agent (steam). Furthermore, in direct gasification all reactions occur in the same device while in indirect gasification, combustion reactions occur in a separate chamber that communicates with the gasification chamber both with mass streams (bed material, char, ashes and feedstock to be combusted) and energy streams (heat carried by the thermal inertia of the bed material itself) (Papadokonstantakis & Johnsson, 2020; Sette *et al.*, 2015). Several types of equipment are usually used for gasification: fixed bed, fluidized bed, including entrained flow gasifier (Papadokonstantakis & Johnsson, 2020; Siwal *et al.*, 2021).

The raw material NLB substance must be well granulated for applications in reactors. Therefore, a trial is required, particularly for sewage/faecal sludges, municipal solid waste (MSW), and so on. (Siwal *et al.*, 2021). Depending on the technology and biomass used, impurities may include dust, ash, bed material, sulphur and chloride compounds. Various types of filters (e.g. textile bag filters such as GoBiGas, Gothenburg) (Papadokonstantakis & Johnsson, 2020; Thunman *et al.*, 2018) can be used to remove the particles from the product gas; the maximum allowable temperature of the filter is an important parameter for avoiding fouling in the heat exchangers cooling the raw product gas. Also, gas composition produced from the gasification process varies according to the type of gasifier, gasification agent, catalyst type and size of particle (Lee *et al.*, 2019) and the technique is considered to be independent autothermic route based on energy balance. It is revealed that biomass gasification is able to recover more energy and higher heat capacity compared to combustion and pyrolysis, probably due to optimal exploitation of existing biomass feedstock for heat and power production (Lee *et al.*, 2019).

6.3.3.1.3 Pyrolysis technology

Pyrolysis is one of the thermochemical technologies for converting biomass in the absence of oxygen into energy and chemical products consisting of liquid bio-oil (also referred to as pyrolysis oil, pyrolysis tar, biocrude, wood liquid, wood oil or wood distillate), solid biochar (also referred to as charcoal), and pyrolytic gas (Papadokonstantakis & Johnsson, 2020). It involves the conversion of sewage sludge/faecal sludge without air at moderate operating temperature (350–600°C), although some pyrolysis reactors that operate at higher temperature up to 900°C exist (Oladejo *et al.*, 2019; Ruiz *et al.*, 2013; Zhang *et al.*, 2010). The output product of this process depends on the process temperature where char yield decreases with an increase in temperature (Oladejo *et al.*, 2019). There are three types of pyrolysis process that differ according to their operational conditions, namely slow, fast and flash pyrolysis (Lee *et al.*, 2019), see Figure 6.12.

It should be noted that high residence time of the fuel in the reactor at low temperature with low heating rates promotes char production, while low or high residence time at high temperature promotes liquid and gas production respectively (Oladejo *et al.*, 2019). The application of this technology is mostly used to maximise liquid fuel yield and energy recovery from sludge. The drying requirements here are greater than for combustion with <10% moisture tolerance in the input sludge fed into the reactor. The pyrolysis of sludge takes place in an inert environment at high temperature, hence an external heat source

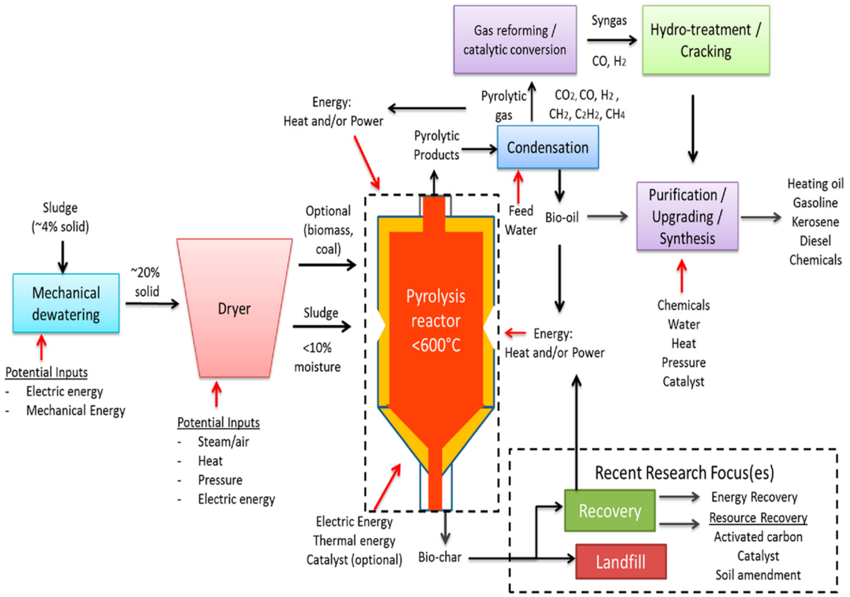

Figure 6.12 Schematic representation of the pyrolysis of sludge (Source: Oladejo *et al.* (2019) under CCA 4.0 license, ©, 2018 by the authors).

(electric or thermal) would be required to supply heat for initiation of the reaction. The utilization of heat sourced from the partial combustion of biogas, or bio-oil derived from the process itself has been critically explored for ensuring self-sustainability of pyrolysis, particularly in waste-to-energy applications (Oladejo *et al.*, 2019).

Pyrolysis technology can be classified based on heating rate and residence time, whether fast or slow pyrolysis. Fast pyrolysis generally uses a high heating rate above 300°C/s and a short vapour residence time below 10 s, while slow pyrolysis adopts a relatively low heating rate (Liu *et al.*, 2015b) and a long vapour residence time and is a promising technology to efficiently treat and sanitize faecal sludge from dry toilets (Mašek *et al.*, 2016). Compared with slow pyrolysis, fast pyrolysis with medium temperatures in the range 400–600°C usually has a higher bio-oil yield (Li & Jiang, 2017). Inside the pyrolysis zone, biomass is exposed to an ideal heat of 700°C during a deficiency of O_2 appearing with the production of bio-oil, char, and syngas. Synthetic gas is a hybrid mainly of CO, CO_2, H_2, CH_4. These may be applied as a subsequent fuel to produce power. Bio-oil yields can be as high as 50–70% wt% of the dry biomass (Lee *et al.*, 2019). Even higher heating rates of 1000–10 000°C/s can achieve bio-oil yields of up to 80 wt% (Amutio *et al.*, 2012). Gas and biochar yields amount to 13–25% and 12–15% of dry biomass feed, respectively (Papadokonstantakis & Johnsson, 2020). In a standard method, the biomass is converted fuel-efficiently without producing slag or transmitting massive amounts of flue gas. The necessary methods and steps of biomass pyrolysis are presented below (Siwal *et al.*, 2021):

(I) crushing to improve the exterior area to enhance heat transmission effect;
(II) dehydrating to improve the effectiveness of gas–solid resources inside the reactor;

(III) anoxic thermal degeneration of organics to produce pyrolysis outcomes (syngas, bio-oil, and char); and
(IV) final subsequent processing of syngas and char.

Biomass pyrolysis reactors can be fixed bed, fluidised bed, heated kiln, rotating cone, screw feeder/auger and vacuum pyrolysis (Bridgwater, 2012). From these reactor types, bubbling and circulating fluidised beds, heated kiln and rotating cone have been commercialized, while others remain at the demonstration or pilot stages. Typical capacities for commercial scale are in the range of 0.2–20 tonnes/hours, at feed moisture less than 10 wt%, feed size of 0.2–50 mm and bio-oil yields of 70–75% wt% (Papadokonstantakis & Johnsson, 2020). Pyrolysis processes decompose organic matter into a solid, liquid and gas mixture. Pokorna *et al.* (2009) classified the condensable pyrolysis products of sewage and faecal sludge into five groups:

(I) mainly containing oxygenated compounds (fatty acids, alcohols, phenols, etc,);
(II) nitrogenated compounds;
(III) sulphur compounds;
(IV) hydrocarbons; and
(V) steroids.

The gas products principally consist of carbon dioxide, carbon monoxide, methane, hydrogen and some volatile liquids like small fractions of phenols, 1H-indols and fatty carboxylic acids (Tsai *et al.*, 2009). The difference between gasification and pyrolysis is that gasification produces fuel gas that can be combusted for heat generation, whereas pyrolysis produces liquid fuel known as pyrolysis oil (py-oil) or bio-oil that can be an alternative to fuel oil in static heating or in the generation of electricity (Lee *et al.*, 2019). Py-oil is dark brown, with high viscosity and low calorific value and is comprised of several chemical components that include acids, alcohols, aldehydes, phenols, and oligomers that originate from lignin (Lee *et al.*, 2019).

Converting sewage and faecal sludge to biochar addresses the stigma of fertilizer obtained from human excreta, since pyrolysis guarantees 100% elimination of pathogens with enriched nutrients in faecal-sludge biochar (Nuagah *et al.*, 2020). Biochar is a rich material obtained by a thermal process (pyrolysis of biomass) in an environment low in oxygen, mostly for the purpose of a soil enhancer. The addition of biochar to soils enhances its properties and filters and retains nutrients from permeating soil water (Crombie *et al.*, 2013; Nuagah *et al.*, 2020). The biochar from sewage and faecal sludge decreases plant accessibility to heavy metals and the danger associated with the probable filtering of heavy metals into the soil that is linked with raw sewage and faecal sludge (Marshall & Eng, 2013; Nuagah *et al.*, 2020).

Pyrolysis has been proven to be an effective technology for treating heavy-metal-polluted biomass, keeping most of the metals inherently. Studies focusing on metal behaviour during pyrolysis of sewage sludge and/or faecal sludge demonstrated that most of the common heavy metals (e.g. Cr, Ni, Cu, Zn and Pb) are retained in the biochar with pyrolysis temperature below 800°C (Jin *et al.*, 2017; Van Wesenbeeck *et al.*, 2014). If the faecal sludge is not dry, the initial energy input will go toward volatilizing the water in the sludge before pyrolysis proceeds (Andriessen *et al.*, 2019). Also, the NLB's biochar mainly contains C, O, H, N, P, and minerals, with percentage ratios highly affected by the mineral contents (Li & Jiang, 2017; Marshall & Eng, 2013; Nuagah *et al.*, 2020). Compared with the thermochemical conversion of LB, an important difference in the pyrolysis process of NLB is attributed to the massive existence of heteroatoms and metals (Li & Jiang, 2017).

In recent years, improvements to py-oil properties have become a major concern. The enhancement of py-oil is desired so that it could be utilized as a substitute for crude oil. There are several routes for upgrading the py-oil that include physical, chemical and catalytical approaches (Lee *et al.*, 2019). Hot vapour filtration is the most frequent method for physical upgrading of py-oil to get better bio-oil. It enables a reduction in the initial molecular weight of the oil and slows down the rate of bio-oil aging. Hot gas filtration eliminates char and inorganic materials from the oil, which is initiated due to the removal of highly unstable compounds of ring-conjugated olefinic substituents and the conversion of guaiacol-type compounds to catechol- and phenol-type compounds (Case *et al.*, 2014).

Hydrodeoxygenation upgradation (HDO), also known as hydrotreatment, is another strategy that offers enhanced oil yield, high oil quality and higher carbon recovery. This process involves the removal of oxygen from oxygenated hydrocarbons via catalytic reactions at high pressure (up to 200 bar (20 MPa)), hydrogen supply and moderate temperature (up to 400°C) (Lee *et al.*, 2019; Zhang *et al.*, 2013). It is stated that the HDO process is able to improve the py-oil quality by refining oil stability and increases energy density (Furimsky, 2000; Huber *et al.*, 2006; Lee *et al.*, 2019; Li *et al.*, 2010). According to Lee *et al.* (2019), there are four main reactions that affect the HDO of py-oil:

- hydrogenation of C-O, C=O and C=C bonds;
- dehydration of C-OH group;
- condensation and decarbonylation of C-C bond cleavage using retro-aldol
- hydrogenolysis of C–O–C bonds.

The main challenge in HDO of py-oil is deactivation of the catalyst which is necessary for effective synthesis for the HDO process (Lee *et al.*, 2019). An alternative method in upgrading py-oil is the use of catalysts and involves the use of methods for enhancing pyrolysis oil quality: (i) the use of downstream process by means of metallic or bi-functional (hydrogenating and acidic) catalysts; and (ii) *in situ* upgrading by integrated catalytic pyrolysis (Dhyani & Bhaskar, 2018). In a catalytic process, the vapour that is produced by pyrolysis will go through extra cracking within the catalyst pores for formation of desirable low-molecular weight compounds (Lee *et al.*, 2019).

6.3.3.1.4 Hydrothermal liquefaction technology

Hydrothermal liquefaction (HTL), also known as hydrothermal carbonization (HTC), involves chemical and physical transformations of carbohydrates into a carbonaceous residue under conditions of wet, high temperature (180–350°C) and autogenous pressure (Li & Jiang, 2017). In the hydrothermal system, water that exists in a subcritical or supercritical state simultaneously acts as medium, reactant and catalyst at a medium temperature range of 250–374°C for 1–12 hours and operating pressure of 40 to 220 bar (4–22 MPa) to convert biomass into bio-oil and biochar (Lee *et al.*, 2019). The HTL process comprises decomposition and repolymerization reactions for bio-oil conversion, aqueous dissolved chemicals, solid deposits and gas. The high pressure in the HTL process helps to maintain water in a liquid state, whilst the blending of elevated pressure and temperature leads to a decrease in the electric constant and density, which influence the hydrocarbons to be water soluble (Pambudi *et al.*, 2017; Tursi, 2019), see Figure 6.13.

This process has shown more advantages and potential than dry carbonization processes (e.g. pyrolysis) for feedstocks containing high moisture. It could be a viable way to dispose of waste streams and realize the value-added utilization (Berge *et al.*, 2011). For example, the process of dehydrating sewage sludge/faecal sludge is time-consuming and costly, owing to the high moisture content. In order to solve this problem, the hydrothermal treatment method was employed to change the physical and chemical properties of SS/FS to yield bio-oil and biochar (Andriessen *et al.*, 2019; Vardon *et al.*, 2011, 2012). A variety of feedstock can be converted to biochar with carbon content

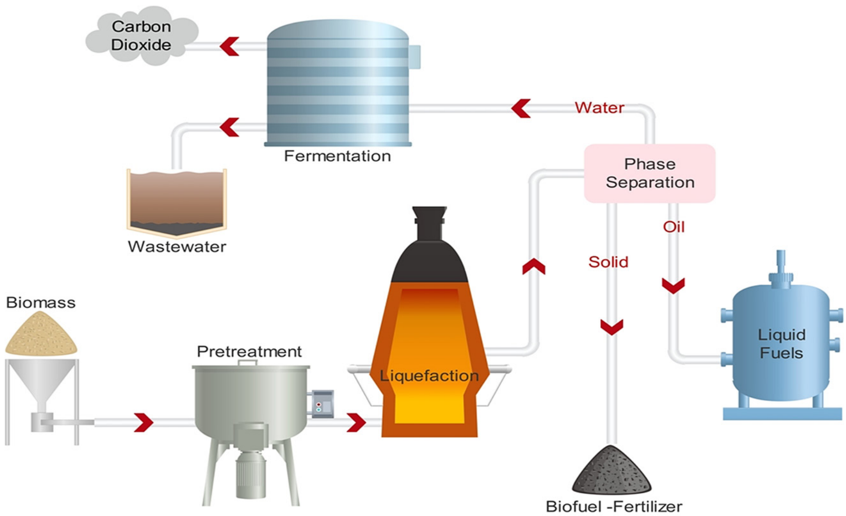

Figure 6.13 Biomass liquefaction scheme. (Source: Tursi, 2019)

similar to lignite with a mass yield of 35–60% via HTL/HTC processes (Kruse *et al.*, 2013; Vardon *et al.*, 2012). A biochar yield of 50–80% was observed with faecal sludge, and higher-value products were obtained even at a lower temperature (Afolabi *et al.*, 2017). The HTC process was found to improve the calorific value of faecal sludge fuel from 16 to 19 MJ/kg as well as to eliminate long drying times on drying beds (Fakkaew *et al.*, 2015a, 2015b; Koottatep *et al.*, 2016). More HTC reactors exist at a pilot scale, but few full-scale examples exist at present (Román *et al.*, 2018). Sewage and faecal sludge are promising feedstocks for HTL/HTC processes as they are readily available in large volumes. In addition, compared to dry sludge, exploiting wet sludge is able to decrease the consumption of energy by 30% (Li *et al.*, 2009).

6.3.3.1.5 Torrefaction technology

Torrefaction can be described as the thermal treatment of biomass to create an output that can be densified by palletization to produce a more energy-dense output called torrefied pellets (TOPs) or pieces, sharing related features to coal (Batidzirai *et al.*, 2013; Siwal *et al.*, 2021). Torrefaction is usually a first stage that is followed by pyrolysis and finally gasification during biomass heat treatment or biomass decomposition (Lange, 2007). It is a low-temperature biomass thermal decomposition process that produces carbon-rich biochar (Mimmo *et al.*, 2014). Biomass partly decomposes during this process generating both condensable and non-condensable gases; the resulting product is a solid substance rich in carbon that is referred to as biochar, torrefied biomass or biocarbon (Lehmann *et al.*, 2011). The torrefaction process is also referred to as roasting, slow and mild pyrolysis, wood-cooking and high-temperature drying (Bergman & Kiel, 2005). As reported in several studies (Agar & Wihersaari, 2012; Bridgeman *et al.*, 2010; Chew & Doshi, 2011; Mamvura & Danha, 2020; Nunes, 2020; Prins *et al.*, 2006), and as shown in Figure 6.14, torrefaction leads to:

(I) Improved energy density;
(II) Better ignition;

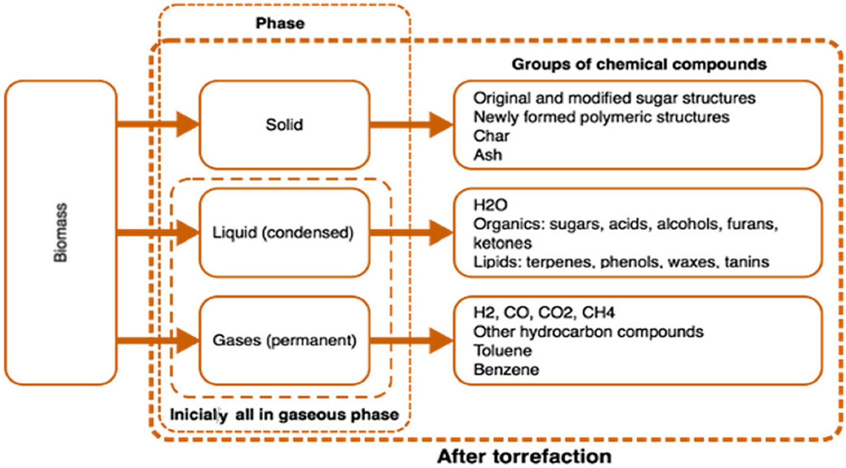

Figure 6.14 Main constituent compounds of each of the fractions formed during the torrefaction process. Nunes, L.J.R. (2020) A case study about biomass torrefaction on an industrial scale: solutions to problems related to self-heating, difficulties in pelletizing, and excessive wear of production equipment. *Applied Sciences* by MDPI under CCA 4.0 license, ©, 2020 by the authors.

(III) Less moisture;
(IV) Higher C/O and C/H ratio;
(V) Improved grind-ability thereby reducing energy required for grinding;
(VI) Biomass that is hydrophobic that is that has less affinity for water;
(VII) More homogenized biomass that is torrefaction devolatilizes, depolymerizes and carbonizes the biomass; and
(VIII) Reduces microbial activity.

This technology enhances combustion performance, particularly in boilers for energy production and for pyrolysis and gasification applications (Basu, 2018), and also leads to better storability of the treated biomass (Mamvura & Danha, 2020). Temperature and retention time are two main parameters that influence torrefaction process efficiency (Wannapeera *et al.*, 2011). Torrefaction is usually conducted at temperatures between 200 and 300°C (Eseltine *et al.*, 2013), and the process temperature is maintained for 15–60 minutes (Verhoeff *et al.*, 2011). Choosing the specific value of those two key parameters for different types of biomass is essential to develop cost-effective biomass treatment (Pulka *et al.*, 2019). Sewage sludge (SS) and faecal sludge (FS) can be valorised via a torrefaction also known as low-temperature pyrolysis. SS/FS are suitable substrates for the torrefaction process in the production of low-quality fuel and/or a source of nutrients essential for plant growth (Nunes, 2020; Pulka *et al.*, 2020). Torrefaction of SS/FS increases the C density and produced biochar that contains a smaller amount of O and H in its structure (Nunes, 2020; Poudel *et al.*, 2015; Pulka *et al.*, 2020). It could also be used as pre-treatment for SS/FS by easing its grindability and improving some of its fuel properties (Atienza-Martínez *et al.*, 2015; Nunes, 2020). The method involves cutting down the biomass to achieve sufficient drying and over 20% humidity, and then a tiny portion of the raw biomass is applied as fuel to the humid content during aeration and torrefaction. The torrefied biomass can then be used as a replacement for charcoal since it is hydrophobic and resistant to degeneration. (Agar & Wihersaari, 2012; Nunes, 2020; Siwal *et al.*, 2021).

6.3.3.1.6 Plasma gasification technology

Plasma gasification of waste biomass is a technologically advanced non-incineration thermal process that uses extremely high temperatures in an oxygen-starved environment to decompose input waste materials completely into very simple molecules (Mountouris *et al.*, 2008). Plasma which consists of free electrons, ions, and neutral particles is defined as the fourth state of matter. Also, the presence of electrons and charged particles is what allows plasma to be considered as neutral. Plasma is thermally and electrically conductive due to the charged particles and can be described as an ionized gas (Roth, 1994). Plasma can be partially ionized as well as fully ionized (Bogaerts *et al.*, 2002). It can occur at different temperatures and densities and there should be sufficient energy in the medium to form plasma from the gas. Also, energy in the medium should be continuous to sustain the plasma, as without sufficient energy to form plasma, the particles will turn to neutral gases. The energy used here can be electrical, thermal, or ultraviolet light, and so on (Sanlisoy & Carpinlioglu, 2017). The unconventional method found in plasma gasification system can be used to convert sanitation-biomass such as SS/FS into synthesis gas and an inert vitreous by-product material known as slag, an efficient energy form (Imris *et al.*, 2005; Sanlisoy & Carpinlioglu, 2017).

This technology utilizes the conversion of a variety of fuels such as sewage sludge, faecal sludge, industrial, medical or municipal wastes and low-grade coals into syngas that mainly include CO, H_2, and CO_2. The produced syngas can be used as fuel in combustion systems, for the generation of electricity and for the production of hydrogen as well as slag and ash (Sanlisoy & Carpinlioglu, 2017). A standard plasma gasification technology reactor is operated within the range of 400–850°C and does not use any external heat source, relying on the process itself to sustain the reaction (Littlewood, 1977; Mountouris *et al.*, 2008). Normal gasifiers are really partial combustors, and a substantial portion of carbon is combusted just to support the reaction (Mountouris *et al.*, 2008). Plasma at high temperature breaks down nearly all the materials to their elemental form excluding the radioactive materials (Lemmens *et al.*, 2007; Mountouris *et al.*, 2008), see Figure 6.15. As a result of the high temperature, toxic compounds decompose to harmless chemical elements. In fact, this is the advantage it offers in comparison with conventional methods of gasification.

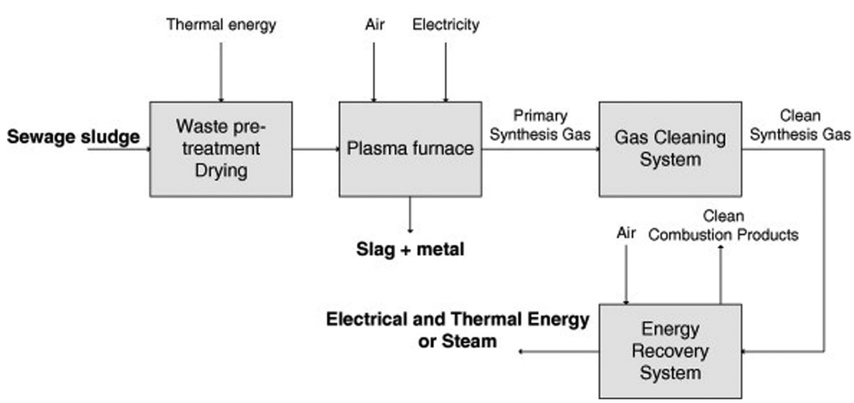

Figure 6.15 Block diagram of plasma gasification process. Mountouris, A., Voutsas, E., and Tassios, D. (2008) Plasma gasification of sewage sludge: process development and energy optimization. Energy Conversion and Management ©, 2008 Elsevier Ltd.

The plasma furnace is the central component of the system where the gasification/vitrification process takes place. Two graphite electrodes, as a part of two transferred arc torches, extend into the plasma furnace. An electric current is passed through the electrodes and the conducting receiver, that is the slag in the furnace bottom. The gas introduced between the electrode and the slag that becomes plasma can be oxygen, helium or other, but the use of air is very common due to its low cost (Mountouris *et al*., 2008). As the temperature is maintained within the plasma furnace, the organic molecules contained in the sewage sludge begin to break down and react with air to form carbon monoxide, hydrogen and carbon dioxide. Water contained in the sludge feed also dissociates and reacts with other organic molecules. As a result of these reactions, all organic constituents and water are transformed into a synthesis gas containing mostly hydrogen, carbon monoxide and nitrogen (Mountouris *et al*., 2008). The basic types of plasma reactors are:

- plasma fixed bed reactor;
- plasma moving bed reactor;
- plasma entrained bed reactor or plasma spout bed reactor (Sanlisoy & Carpinlioglu, 2017; Tang *et al*., 2013).

6.3.3.2 Biochemical conversion processes

Biochemical conversion processes allow the decomposition of biomass to available carbohydrates, which could be converted into liquid fuels and biogas, as well as different types of bioproducts, using biological agents such as bacteria, enzymes, and so on (Mahalaxmi & Williford, 2014; Tursi, 2019). Biochemical transformation is mainly the process of enzyme secretion released by microorganisms to control energy production and conversion into solid fuel (Siwal *et al*., 2021). They can also be referred to as biological pre-treatments aimed to turn biomass into a number of products and intermediates through selection of different microorganisms or enzymes. The process provides a platform to obtain fuels and chemicals such as biogas, hydrogen, ethanol, butanol, acetone and a wide range of organic acids (Chen & Qiu, 2010; Garba, 2020). This process is used when the intention is to make products that could replace petroleum-based products and those obtained from grain. Biomass biochemical conversion technologies are clean, pure and efficient when compared with other conversion technologies (Chen & Wang, 2016; Garba, 2020); classical options are composting and other sanitation-derived nutrients for agriculture, and anaerobic digestion.

6.3.3.2.1 Composting and other sanitation-derived nutrients

Compost is a soil-like substance resulting from controlled aerobic degradation of the organic material in sewage sludge, faecal sludge and/or co-combined with some other biomass conversion composting facility to support agricultural productivity (McConville *et al*., 2020; Nikiema *et al*., 2020; Otoo & Drechsel, 2018; Otoo *et al*., 2018). It is a fertilizing process that can be described as the natural breakdown of biomass through the process of biodegradation with the aid of a microbial population in an aerobic environment to CO_2, H_2O, heat and a further stable output named fertilizer (Siwal *et al*., 2021). The fertilizer is trouble-less, simple to manage and may be harmlessly employed in farming to improve the soil (Irvine *et al*., 2010; Kalyani & Pandey, 2014). Compost is a soil conditioner that contains nutrients and organic matter and it contributes to the formation of humus in the soil, thus improving soil structure and water retention capacity. By adding carbon to soil, compost also contributes to soil carbon storage capacity, which supports climate change mitigation (McConville *et al*., 2020; Nikiema *et al*., 2020). The composting prices provides significant amounts of the three main

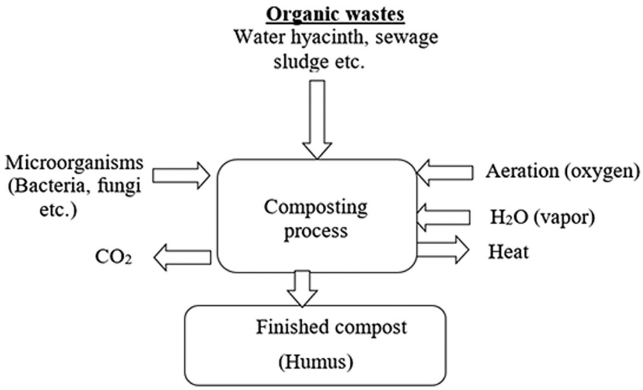

Figure 6.16 Outline of composting process. Singh, J., Kalamdhad, A.S., and Lee, B.K., 2016: published in effects of natural zeolites on bioavailability and leachability of heavy metals in the composting process of biodegradable wastes. Useful Minerals by IntechOpen under CCA 3.0 license, ©, 2016 by the authors.

components of agricultural fertilizer: nitrogen (N), potassium (K), and phosphorus (P; in the form of phosphate), and when sanitation materials are processed along with other organic waste even more N, P, and K can be recovered. Sanitation materials also contain micronutrients such as iron, chlorine, boron, copper and zinc, which are vital for plant and human or animal nutrition, but not generally found in synthetic fertilizer (Andersson *et al.*, 2020; Singh *et al.*, 2016- Figure 6.16).

There has been enhanced consideration provided to heat healing through aerobic composting operations as a process to develop their commercial feasibility (Siwal *et al.*, 2021; Smith & Aber, 2017). The composting progression is driven by the C/N proportion of the biomass, pile wetness, oxygen stages and heat which are strictly observed (Fan *et al.*, 1981; Siwal *et al.*, 2021). Three classes of microorganisms called bacteria, actinomycetes and fungi are extravagant during the fertilizing method (Polprasert & Koottatep, 2017; Siwal *et al.*, 2021). Other composting conversion technologies that provide nutrients for agriculture are:

(I) *Vermicomposting and vermifiltration* are two low-cost options for human and organic biomass treatment in which earthworms are used as biofilters under aerobic conditions. The end product is worm cast or compost that is a nutrient-rich organic fertilizer and soil conditioner. Also the worms can be harvested from the system, depending on the processes and earthworms can reduce the volume of the faecal sludge by 60 to 90%. The two important parameters are moisture content and the carbon to nitrogen (C:N) ratio. The most commonly used method of vermicomposting is the in-vessel method in which the compost is held in an open vessel. Vermifiltration happens in a watertight container that can receive more liquid inputs such as blackwater or water sludge (McConville *et al.*, 2020);

(II) *Black soldier fly composting and/or black soldier fly larvae (BSFL)* treatment technology is a biological process that relies on the natural growing cycle of the black soldier fly (*Hermetia illucens* (L.), Diptera Stratiomyidae. The BSFL feed only during the larvae stage, then migrate for pupation and do not feed any more, even during the adult stage. The treatment residue, comprised of the larval droppings and undegraded material appears as a compost-like material that can be used as soil conditioner. The larvae can be harvested as a source of protein for animal feed (McConville *et al.*, 2020; Polprasert & Koottatep, 2017);

(III) *Composting toilet conversion technology* is also known as composting based-sanitation systems, dry toilets, biological toilets, biotoilets or waterless toilets (Anand & Apul, 2014; Del Porto & Steinfeld, 1998; Polprasert & Koottatep, 2017). A composting toilet has two primary components, the toilet and the composting tank. The other parts of a composting system often include a fan and vent pipe to remove any odour. The toilet in composting is a waste collector whereby the waste is collected into the composting tank and digested aerobically. Some systems may use earthworms (vermicomposting) as an alternative to aerobic composting (Hill & Baldwin, 2012; Polprasert & Koottatep, 2017; Yadav *et al.*, 2010). Bulking agent or amendments (e.g. sawdust, leaves, and food waste) are often added to help co-manage different types of waste, adjust carbon to nitrogen ratio, and increase porosity of the compost. These toilets are often equipped with mechanical mixers that homogenizes the compost matrix to maintain conditions favourable to aerobic digestion where organic matter is oxidized into ammonia, carbon dioxide, and humus. The end product from these toilets contain stable, high molecular weight dissolved organic matter (Narita *et al.*, 2005; Polprasert & Koottatep, 2017) that can be recycled as soil fertilizers (Anand & Apul, 2014; Polprasert & Koottatep, 2017).

The practice of composting has the ultimate objective of a closed-loop approach that promotes the circular bioeconomy paradigm through the collection, transportation, treatment and recovery of bioresources from sanitation materials using technologies such as urine deviated vacuum toilets, anaerobic digesters, struvite ($Mg(NH_3)PO_4$) precipitation to recover high-value products like water, nutrients, organic matter, energy, and so on; and offers sustainable solutions to sanitation management (Kujawa-Roeleveld & Zeeman, 2006; Lens *et al.*, 2001; Maurer *et al.*, 2012; Polprasert & Koottatep, 2017; Wielemaker *et al.*, 2018; Zeeman, 2012). Also, the organic matter in wastewater and excreta mainly consist of proteins, carbohydrates and fats, that is captured and processed through composting or fermentation process, it could be used as a potent soil conditioner and source of energy when supplemented with food waste and agricultural residues (Lal, 2008; Polprasert & Koottatep, 2017). Increasing soil organic matter (SOM) supports soil functions such as retaining nitrogen and other nutrients, retaining water, protecting roots from diseases and parasites, and making retained nutrients available to the plants (Bot & Benites, 2005; Polprasert & Koottatep, 2017).

Other sanitation-derived biomass nutrients bioproducts include:

(I) *Stored urine from urine-diverting sanitation systems* – primarily made of nitrogen and phosphorus in their mineralized forms and are directly accessible to plants. It can be applied as a liquid fertilizer in agriculture or as an additive to enrich compost (McConville *et al.*, 2020; Polprasert & Koottatep, 2017);

(II) *Concentrated urine* – a nutrient solution obtained by removing water from urine. Water removal is achieved through evaporation, distillation or reverse/forward osmosis of urine. The finished product is between 3–7% of the initial volume. In order to ensure that nitrogen is not lost in the process, nitrification or acidification of the urine is done prior to volume reduction. Depending on the pretreatment process, the majority of the nutrients are retained (McConville *et al.*, 2020; Polprasert & Koottatep, 2017);

(III) *Dry urine* – a nutrient-rich solid fertilizer produced by dehydrating and concentrating human urine in an alkaline substrate (pH $>$, 10). Dry urine's treatment technology (i.e. alkaline urine dehydration) can be implemented using different alkaline substrates, which will determine the composition and physicochemical properties of the dried product. The dried urine captures nearly all of the fertilizing nutrients in urine (McConville *et al.*, 2020);

(IV) *Sanitised blackwater* – refers to blackwater that has been treated in order to reduce microbial risks. Since black water is toilet waste collected with flush water, the water content is rather high since excreta have a low volume of total solid (TS) (∼4%) even without flushwater. Lime treatment can be done by the addition of quick lime (CaO) or slaked lime [$Ca(OH)_2$]. Ammonia sanitization is done by adding urea or aqueous ammonia (NH_3) solution to increase the NH_3 concentration so that it inactivates pathogens. The addition of urea or ammonia also increases the nitrogen concentration of the blackwater (McConville *et al.*, 2020; Polprasert & Koottatep, 2017);

(V) *Digestate* – material remaining after the anaerobic digestion of any feedstock. The feedstock can consist of foodwaste, agricultural or industrial organic waste, sludge or wastewater fractions. The digestate in this context is the liquid, non-dewatered digestate from wet fermentation of sludge, possibly mixed with other feedstocks. Digestate in this form is a mixture of liquid and particles/solids and can also be called 'slurry'. It is often applied as fertilizer or soil conditioner in agriculture. To be a soil conditioner, it should contain organic material to increase the organic carbon (McConville *et al.*, 2020);

(VI) Struvite – often referred to as magnesium ammonium phosphate hexa-hydrate (MAP), is a phosphate mineral that occurs naturally in sanitation systems. It is a common precipitate in pipes and heat exchangers and can also be purposefully extracted from waste streams through the addition of magnesium to urine. Struvite precipitation can be applied to reduce phosphorus concentrations in effluents while at the same time generating a product that can be applied as a fertilizer or industrial raw material (McConville *et al.*, 2020); and so on.

Consequently, composting could be an attractive solution for treating faecal/sewage sludge and other organic waste when blended together. It provides an opportunity to sanitize the sludge, recover nutrients from sanitation biomass and then return them back to soil especially in areas where soil organic matter is depleted due to poor agricultural practices or a lack of fertilizer use (Cofie *et al.*, 2009; Moya *et al.*, 2019). Also, several container-based sanitation companies successfully produce sanitation-derived fertilizer and sell their full production in the local market (Moya *et al.*, 2019). As a result of the high nutrient value of the compost and/or co-compost as well as other sanitation-derived nutrients, many farmers in Africa, Asia and Latin America are very eager to use it in crop production because it also offers a cheaper alternative source to nutrients and is much more readily available (Cofie & Adamtey, 2009; Nikiema *et al.*, 2013). The World Health Organization (WHO) has developed guidelines to promote the safe use of human excreta in agriculture, realizing its resource value and nutrient content for crop production. This has resulted in recent developments of technology and pre-agricultural use of sanitation materials such as composting of dried, faecal sludge, sewage sludge, co-composting with other organic matter and enriched with inorganic fertilizer (Nikiema *et al.*, 2013, 2014).

6.3.3.2.2 Anaerobic digestion (AD)

Anaerobic digestion (AD) is one of the most sustainable and cost-effective technology for sanitation-derived biomass and other organic waste biomass as well as other form of waste treatment for energy in the form of biofuels. This process does not only minimize the amount of waste, but also transforms such waste into bioenergy. Also, the digestates produced during the process are rich in nutrients and can serve as fertilizers for agricultural

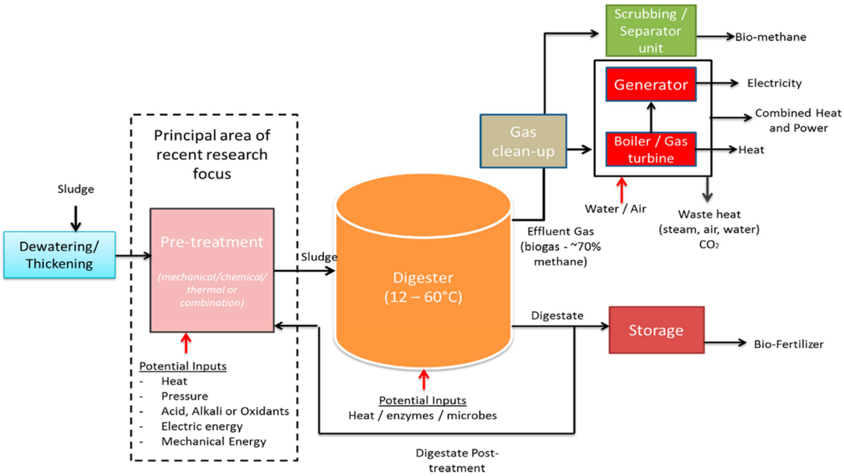

Figure 6.17 Schematic representation of the anaerobic digestion of sludge. Oladejo J, Shi K, Luo X, Yang G, Wu T., 2019: published in A review of sludge-to-energy recovery methods. *Energies* by MDPI under CCA 4.0 license, ©, 2018 by the authors.

purposes (Garba, 2020; Li *et al.*, 2019; Polprasert & Koottatep, 2017). AD is a common profitable process owing to its vast energy improvement into the formation of CH_4 and its inadequate ecological influences; and is additionally capable of deactivating pathogens and stabilizing solid fuel production (Polprasert & Koottatep, 2017; Sawatdeenarunat *et al.*, 2015; Siwal *et al.*, 2021; Zhen *et al.*, 2017). This is a biological process that occurs in an inert environment that converts organic compounds into biogas by using microorganisms. The use of naturally occurring bacteria for biodegradation involves a series of biochemical stages, for example, hydrolysis, acidogenesis (fermentation), acetogenesis and methanogenesis (Lee *et al.*, 2019; Oladejo *et al.*, 2019; Polprasert & Koottatep, 2017; Rulkens, 2008; Siwal *et al.*, 2021 – Figure 6.17).

The metabolic stages is used for mass and volume reduction of the sludge while the organic contents are converted to biogas by the pathogens. The hydrolysis stage involves the conversion of the non-toxic organics into simple sugars, fatty acid and amino acids. Afterwards, the acidogenesis and acetogenesis stages aid the fermentation of the hydrolysis products into acetate, carbon dioxide and hydrogen gas, which are further converted to methane through methanogenesis (Lee *et al.*, 2011; Polprasert & Koottatep, 2017). Each stage of the process affects the performance of the digester. The dewatered sludge can be used directly for energy recovery and aids the conversion of volatile organic solids in the digester. Parameters that affect the yield and energy content of the biogas include nutrient profile of biomass, operating temperature, operating pH, biomass loading rate, as well as hydraulic and solid retention time. The hydraulic and solid retention time must be optimized so that the hydrolysis process (rate-determining step) is not limited by slow loading rate and the methanogenesis process is not bounded by rapid loading rate (Lee *et al.*, 2019; Sialve *et al.*, 2009).

The digester is an air-tight tank where micro-organisms are aided by physical, biological or chemical catalysts (heat, enzymes and/or solvents) for the decomposition of organic matter (Oladejo *et al.*, 2019; Polprasert & Koottatep, 2017). Chemical pre-treatment mainly involves the use of strong reagents such as acid and alkali and oxidants for adjusting the pH of the sludge such that the yield of biogas is maximised by increasing the soluble organic fraction (Devlin *et al.*, 2011; Oladejo *et al.*, 2019; Polprasert & Koottatep, 2017; Valo *et al.*, 2004). Mechanical pre-treatments involve the use of mechanical vibrations such as ultra-sonication to disrupt of the organic solid in the sewage sludge (Devlin *et al.*, 2011; Oladejo *et al.*, 2019; Polprasert & Koottatep, 2017; Valo *et al.*, 2004). Physicochemical pre-treatment such as microwave radiation quickens biological, chemical and physical processes due to heat and/or pressure treatment for improving sludge digestibility and is currently commercially available (Nielsen *et al.*, 2011; Oladejo *et al.*, 2019; Polprasert & Koottatep, 2017).

The effluent gas is biogas which is made up of 60–70% methane, 30–40% carbon dioxide and trace elements of other gases (H_2S) with total calorific value of up to, 28.03–38.92 MJ/Nm^3 (Aryal & Kvist, 2018; Oladejo *et al.*, 2019; Polprasert & Koottatep, 2017; Sivagurunathan *et al.*, 2017; Syed-Hassan *et al.*, 2017). The biogas with its high methane content can be recovered for heat and electricity production using boilers, turbines and generators or alternatively upgraded for use as biomethane. There is also the potential of upgrading biogas to 97.55% methane through the use of water scrubbers. These increases the calorific value of the biogas from, 28.03 to 51.31 MJ/Nm^3 (Aryal & Kvist, 2018; Polprasert & Koottatep, 2017). The remnant, after the digestion process, has high nutritional contents (phosphorus, potassium and nitrogen) that could be used as compost and/or fertilizers for agricultural and soil reclamation purposes (Oladejo *et al.*, 2019; Polprasert & Koottatep, 2017). Biogas energy can offset about 50% of the operational energy used in wastewater treatment facilities. The energy can be used at other sources or sold to the grid. The utilization of this biogas contributes to the reduction of greenhouse gases emissions (Mills *et al.*, 2014; Oladejo *et al.*, 2019; Xu *et al.*, 2014).

6.3.4 Ancillary services

Ancillary services are support activities provided by the enterprises in the SBRVC to ensure operational reliability and maintenance of the value chain. They also create the conditions within which the main activities of the operators are carried out. These services are storage, transportation, and product packaging services.

(I) ***Storage facilities***: Storage ensures that the pre-processed biomass is either transported to conversion processes or stored for future demand (Tapia *et al.*, 2019). The SBRCVC enterprises require blended feedstock with other organic waste materials and this becomes a challenge as more types of feedstock are introduced into the systems. Practically, storage facility stocking is required to align with the biomass conversion plan. Therefore, storage facilities are essential to the smooth operations of the SBRVC (Tapia *et al.*, 2019). They include simple stacks in the biomass generation plants or sites and in centralised storage sites. These activities also require energy for preservation of feedstock (Tapia *et al.*, 2019).

(II) ***Transportation services:*** Transportation infrastructure enable demand satisfaction of one or many resources through its movement from one geographic region to another. In the SBRCVC pre-processed biomass is transported to storage sites and to conversion plants as well as to end-users' market (Tapia *et al.*, 2019). This is done through any means of adequate transportation infrastructure and services available such as road, rail, waterways or any combination of them, but must be based on the type of biomass, path shape and distance of distribution as well as the demand of customers (Tapia *et al.*, 2019).

(III) ***Product packaging services:*** Product packaging is the act of containing, protecting and presenting the contents through the long chain of production, handling and transportation to their destination as good as they were, at the time of production (Adebisi & Akinruwa, 2019). It is the overall feature that underlines the uniqueness and originality of the product and becomes an ultimate selling proposition, which stimulates the impulse buying behaviour (Adebisi & Akinruwa, 2019; Silayoi & Speece, 2005) Packaging provides physical protection, information transmission, convenience, barrier protection, security and marketing to biomass products after conversion (Pongrácz, 2007). In addition to the above, packaging provides protection and preservation to products while at the same time supporting distribution and sales of the products (Pongrácz, 2007). Indicators of safety and usage instructions that describe how end-users should use the product are provided on packages along with information about the contents, the products, as more or less a message from the manufacturer to the customer (Pongrácz, 2007; Selke, 1990). Being biobased products requires packaging that assure preservation and helps in loading, collection, and product stabilization during transportation and storage. This keeps products from shifting and falling as well as reduces damages, breakage and keeping waste as well as related cost to a minimum (Alexander, 1997; Pongrácz, 2007). Distributing bulk and liquid biobased products is virtually impossible without packaging; and packaging should help make a favourable impression, aid identification, and stimulate purchase as well as provide visual pleasing that attracts attention, which is important in an increasingly competitive environment (Pongrácz, 2007; Young, 2002). Also, a wide range of materials are used for packaging applications, including metal, glass, wood, paper or pulp-based material, plastics, ceramics, or a combination of more than one materials as composites (Pongrácz, 2007).

6.3.5 End-Use markets/direct local End-users

The end-use of biomass-based products include activities related to distribution and final consumers' use. Products should be compatible with existing infrastrcture, standards and distribution channels (Panoutsou *et al.*, 2020). Customer acceptance and successful market uptake will be subjected to their fitness as substitute for existing products and commodities in sectors (e.g., chemical, food, energy etc.) (Panoutsou *et al.*, 2020). Thus, end-use market depends on social feasibility because technology and product for sanitation-derived biomass products should meet social acceptance to ensure that such products find a place in the market (Tyagi & Lo, 2013). The biomass market includes farmers who make use of the biofertilizers and other soil amendment organic matters. Others are the industrial markets of refined biomass finished products such as biofuels, which may include the chemical industry, pharmaceutical industry, fertilizer manufacturers and food producers (Ruamsook & Thomchick, 2014; Tyagi & Lo, 2013), as well as the biobased industrial products which are the end-markets' customers of biobased products, such as building materials, animal protein, biogas, and so on (Ruamsook & Thomchick, 2014).

6.4 SBRVC COMPETITIVE PERFORMANCE PRIORITIES

The five competitive performance priorities of (i) flexibility, (ii) quality, (iii) cost, (iv) innovation, and (v) transparency are factors that the SBRCVC requires to operate well to achieve performance-based competitive advantages in a sustainable and resource efficient manner (Panoutsou *et al.*, 2020):

(I) ***Flexibility*** – refers to how the SBRCVC operations responds to external factors, and adjust capacity and product design to meet end-users expectations (Henshall, 2018; Panoutsou *et al.*, 2020). Flexibility is essentially to reduce the cost of the impacts of external factors that may negatively affect the value chain. It also ensures that there is all year-round supply of feedstock to meet the requirement of the conversion pathway for quality production and timely delivery of high-value products (Panoutsou *et al.*, 2020).

(II) ***Quality*** – deals with maintenance and commitment to best standards of systems' and products' performance that ensures the delivery of high-value bioproducts to the consumer. It also focuses on continuous improvement of processes and products performance as well as adherence to quality standards (Díaz-Garrido *et al.*, 2011; Panoutsou *et al.*, 2020). Therefore, quality of feedstocks, practices and end-products are important for successful establishment and uninterrupted operations throughout the value chain (Fritsche & Iriarte, 2014; Panoutsou *et al.*, 2020).

(III) ***Cost*** – addresses the reduction of production costs of goods sold as well as generating added-value (Panoutsou *et al.*, 2020; Saarijarvi *et al.*, 2012). The competitiveness of the SBRCVC relies on the cost of each stage and biomass conversion accounting for almost half of the total (Fritsche & Iriarte, 2014; Panoutsou *et al.*, 2020). Creating value with innovation and reducing cost along the chain is important for commercial viability of the enterprises and actors within the value chain (Lee, 2002; Panoutsou *et al.*, 2020).

(IV) ***Innovation*** – addresses new and improved processes and products as well as equipment in each stage of the chain and among enterprises and actors within the value chain (Panoutsou *et al.*, 2020; Torjai *et al.*, 2015). With sanitation and organic-waste biomass being major resource for the sustainability of the value chain, innovation becomes the key in defining which value chain configurations perform best and is resource efficient as well as effective (Fritsche & Iriarte, 2014; Panoutsou *et al.*, 2020); and

(V) **Transparency** – provide current information about the status of the system to avoidance of displacing other activities or product sectors as this is of great importance for the development of the sanitation and organic-waste biomass sector (Panoutsou *et al.*, 2020; Torjai *et al.*, 2015). There is, therefore, the need to provide clarity and awareness of the benefits from the implementation of the value chain as well as create trust among the society's members (Panoutsou *et al.*, 2020).

6.5 CASE STUDIES

6.5.1 Reusing wastewater and sludge in crop production in Braunschweig, Germany

The city of Braunschweig, located in the Federal State of Lower Saxony, Germany has a wastewater reuse scheme managed by the Wastewater Association of Braunschweig since 1954. The members of this association are drawn from the city of Braunschweig, the water association of the neighbouring city of Gifhorn, and 430 owners of land cultivated and/or leased to farmers. The physical and natural conditions in Braunschweig are rather favourable to the reuse of wastewater for agricultural production, since agricultural soils in the region are sandy and poor in nutrients limited water and nutrient retention capacity (Maaß & Grundmann, 2016; Ternes *et al.*, 2007); this means that a continuous

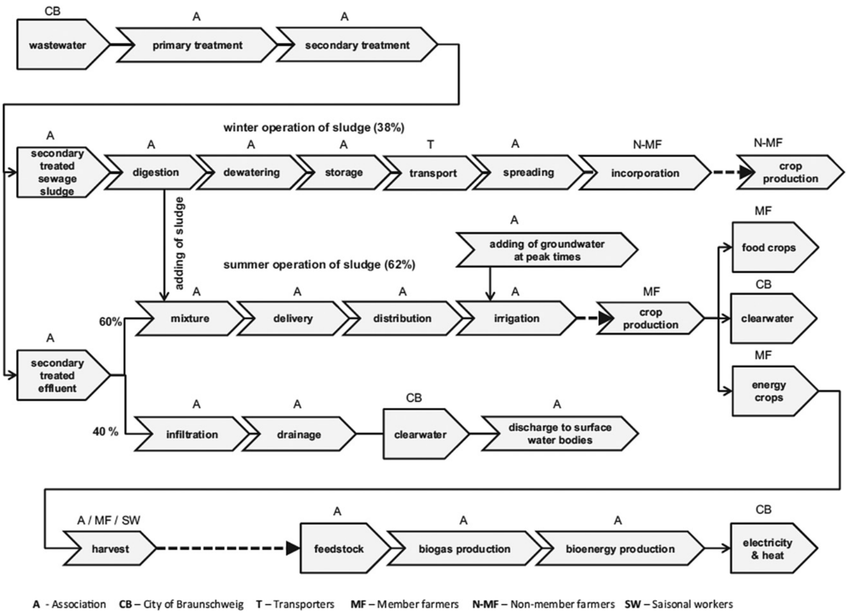

Figure 6.18 Linkages between the value chains of the wastewater reuse scheme in Braunschweig. Reprinted from Maaß, O. and Grundmann, P. (2016) Added-value from linking the value chains of wastewater treatment, crop production and bioenergy production: a case study on reusing wastewater and sludge in crop production in Braunschweig (Germany). *Resources, Conservation and Recycling*, **107**, 195–211, with permission from Elsevier.

additional supply of water and nutrients is essential for crop production. The value chains of wastewater treatment in the city linked crop production and bioenergy production (which are organized by the Braunschweig Wastewater Association), see Figure 6.18. The outputs resulting from the primary and secondary treatment of wastewater, including secondary treated effluent and sewage sludge, are further processed in the value chains of wastewater treatment and reused water as inputs for crop production in the value chains of food and energy. The energy crops are inputs for the anaerobic digestion step in the bioenergy value chain. In this way, the material flows of value chains (including wastewater treatment, crop production and bioenergy production) are linked, based on the agricultural reuse of treated wastewater and sludge. The wastewater of Braunschweig and the surrounding communities is delivered for primary purification to a wastewater treatment plant with a capacity of 60 000 $m^3 d^{-1}$ and a population equivalent of 350 000.

The current treatment process includes mechanical treatment, biological phosphate removal, in combination with nitrification and denitrification, and anaerobic stabilization of sludge (Maaß & Grundmann, 2016; Ternes *et al.*, 2007). In addition, a downstream system of irrigation and infiltration fields is used for the final treatment of the secondary effluent. The largest part of the effluent (60%) is used directly for irrigation on croplands of the member farmers (about 2700 ha). The remaining part (40%) is discharged to infiltration fields (about 220 ha) near the treatment plant. These infiltration areas serve as a natural treatment step by using a meandering system and soil passage before the drained water is discharged to the surface water bodies.

The sewage sludge produced is stabilized via anaerobic digestion and utilized in two different value chains. In the winter period, the sewage sludge is dewatered and stored on-site before it is transported in the summer time to croplands (700 ha) of farmers who are not members of the association in the greater Braunschweig area. Subsequently, the sludge is spread by the association's staff and the farmers incorporate the sludge into the croplands. During the vegetation period, the sewage sludge is added to the effluent prior to irrigation. The mix of effluent and sewage sludge is discharged to a gravity sewer system that brings the mixture to the irrigation fields. The mixture is then spread by the association's staff on the croplands of the member farmers. However, due to precautionary hygienic restrictions, farmers are not allowed to produce fruit or vegetables in the association territory for direct consumption (Bezirksregierung Braunschweig, 2001; Maaß & Grundmann, 2016). Therefore, the main crops cultivated in the irrigation area are maize, grain and sugarbeet. The wastewater reuse scheme was enhanced in 2007 by the installation of a biogas plant operated by the association's members.

6.5.2 Commercialization of human excreta derived fertilizer in Haiti and Kenya

6.5.2.1 Sustainable organic integrated livelihoods (SOIL) – Haiti

SOIL started as a not-for-profit organization in Northern Haiti in 2006 with the approach that access to safe sanitation was a human right; their aim was to provide dignified and safe sanitation to deprived communities that were not served by municipal sanitation in two cities of Haiti, Cap Haitian and Port au Prince. SOIL provides household dry toilets on a lease basis with a service fee directly collected from customers. They provide their 6000 customers with urine-diverting toilets at a cost of $3.20 per month, and six collectors collect the faeces weekly (about 350 tonnes per year) and transform it into compost. Faeces are contained in sealed buckets and then collected in carts and transferred to the waste treatment site by truck. Toilet customers add a cover material after each toilet use – sugar cane bagasse or peanut husks, included in the service fee charged by SOIL – to obtain the optimal carbon to nitrogen ratio for composting. The buckets are emptied into large composting bins with walls made up of pallets filled with carbon-rich material such as straw to allow for air to flow through and provide sufficient aeration in the bin. The bin is sealed when full and left untouched for 2–3 months depending on the temperature and pathogen concentration evolution in the compost bins. The compost bin is then emptied, and the material arranged into windrows where further degradation of the material occurs. The piles are turned once a month for about six more months until the compost properties fulfil the quality criteria set internally. Temperature, moisture, pH and *E.coli* concentration are monitored throughout the process to ensure compliance with WHO standards for thermophilic composting and the safety of the final product. SOIL has chosen to sell its fertilizer to NGOs because they can buy it in large quantities and have greater purchasing power than farmers.

6.5.2.2 Sanergy – Kenya

Sanergy is a social enterprise that has provided safe sanitation in urban slums of Nairobi through shared dry toilets since 2011. They use urine-diverting dry toilets as part of a franchise system (called Fresh Life Initiative) which local entrepreneurs join. They invest in a toilet and operate it as a pay-per-use public toilet, at a cost of $0.05 per use. Another model exists where toilets are installed in accommodation compounds and leased to landlords as an extra service provided to tenants. The toilet entrepreneur or tenants (depending on the model) are responsible for the maintenance and cleaning of the toilet, and for sourcing cover material (usually sawdust) and adding it to the faeces. A third model exists for toilets installed in schools, where toilets are sold to head teachers at a subsidized price to ensure adequate sanitation coverage. About 30 000 people are being

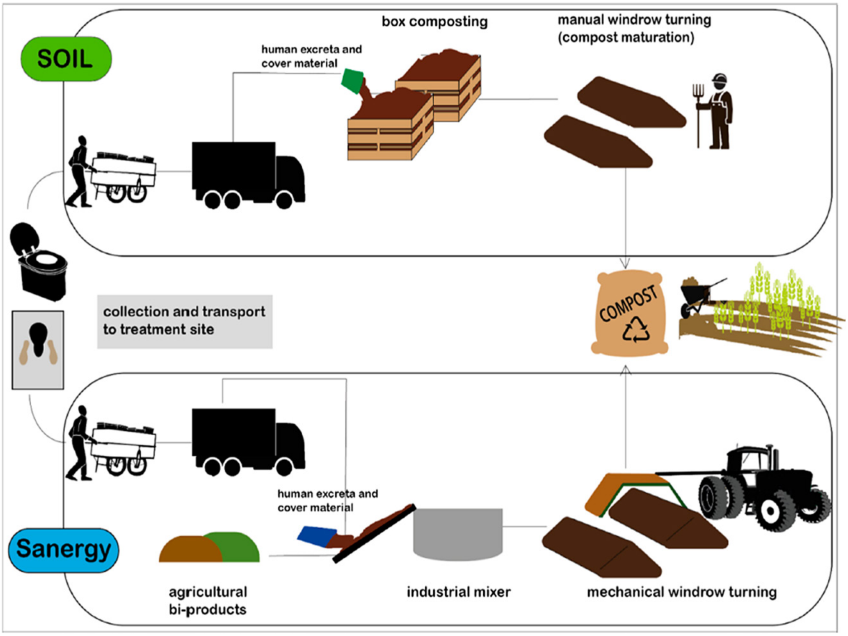

Figure 6.19 Visual summary of SOIL and Sanergy's compost production processes. Moya, B., Sakrabani, R., and Parker, A. (2019) Realizing the circular economy for sanitation: assessing enabling conditions and barriers to the commercialization of human excreta derived fertilizer in Haiti and Kenya. *Sustainability* by MDPI under CCA 4.0 license, ©, 2019 by the authors.

served at the time of reporting, and 60 people are employed in composting and collection. The sanitation and waste management arm of Sanergy are separate: the toilet business, Fresh Life Initiative, being not-for-profit and the waste management arm, Sanergy, is a social enterprise, which collects and treats toilet waste. Similarly to the SOIL system, the waste is collected in sealed containers and transported by truck to the waste treatment facility, about 400 tonnes per month. There the containers are emptied into a mixing tank where additional organic wastes are added, such as agricultural residues. After the mixing phase, the material is laid out in windrows, which are mechanically turned and watered. Process performance is periodically monitored by measuring process parameters (temperature, moisture, pH, CO_2, pathogen concentration, germination tests). The resulting compost is sieved, bagged and sold for agricultural use once the piles meet the WHO guideline standards, which permits their sale to vegetable growers, who receive a good return on investment from the use of fertilizer. The fertilizer production processes are different between the two ventures, as illustrated in Figure 6.19.

6.6 CONCLUSION

Viable business models could emerge from designing SS/FS management systems around resource recovery as this could in turn help ensure sustainable provision of adequate sanitation (Brands, 2014; Murray & Ray, 2010; Puyol *et al.*, 2017; Tyagi & Lo, 2013; Zhang *et al.*, 2018), as sustainable sanitation management involves the recovery and reuse of valuable products and the minimisation of the possible adverse impact of SS/FS on both environmental health and human health (Zhang *et al.*, 2018). Thus, there are two components in SS/FS that are technically and economically feasible to recycle: nutrients (primarily nitrogen and phosphorus) and energy (carbon) (Campbell, 2000). There are several options available for energy recovery from sanitation-waste biomass. The outstanding routes are anaerobic digestion of sludge with biogas recovery; co-digestion, incineration and co-incineration with energy recovery; pyrolysis; gasification; supercritical (wet) oxidation; use in the production of construction materials; production of biofuels (hydrogen, syngas, bio-oil); electricity generation by using specific microbes; and beneficial recovery of heavy metals, nutrients (nitrogen and phosphorus), protein and enzymes (Brands, 2014; Koottatep *et al.*, 2019; Polprasert & Koottatep, 2017; Puyol *et al.*, 2017; Tyagi & Lo, 2013; Zhang *et al.*, 2018). There are global examples of beneficial reuse of resources recovered from SS/FS. The major factors behind this concept are sustainability and environmental concerns, especially those due to resource depletion, soil pollution and global warming. Also, hikes in energy prices, stringent directives for sludge disposal, and increasing protest from environmental authorities and from the public domain (Kalogo & Monteith, 2008; Tyagi & Lo, 2013) contribute effectively. However, the technical feasibility, risks, costs and benefits of the SBRCVC activities and products all need to be assessed to determine viability of each of the value chain pathways and products. The quality of sanitation-biomass-derived products and their market values are important factors with respect to the future feasibility of these processes (Zhang *et al.*, 2018).

6.7 Take action

(I) Identify sanitation biomass recovery and conversion business enterprises and other actors in your local area and country

(II) Conduct an informal survey to determine the operational and financial viability of such ventures

6.8 Journal entry

(I) Find out the level of sanitation biomass recovery and conversion activities between non-governmental organizations (NGOs) and private business enterprises in your area and indicate their differences and similarities.

(II) What SDGs does the sanitation biomass recovery and conversion value chain (SBRCVC) have the potential to enhance?

6.9 Reflection

What is your perspective on the sanitation biomass recovery and conversion value chain at global, national and local levels and what can be done to improve and strengthen the value chain?

6.10 Guiding questions

(I) What is the sanitation biomass recovery and conversion value chain (SBRCVC)?
(II) What are the main activities on the SBRCVC?
(III) What is the relationship between the sanitation biomass recovery and conversion value chain (SBRCVC) and the circular bioeconomy (CBE)?
(IV) How does the sanitation biomass recovery and conversion value chain (SBRCVC) mitigate climate change hazards?
(V) What are the major nine ways of recovering energy from sewage/faecal sludge?
(VI) Mention the key elements of the circular bioeconomy.
(VII) What are the conversion pathways that transfer sanitation-biomass to high-value biobased products?
(VIII) What are the major ancillary services in the sanitation biomass recovery and conversion value chain (SBRCVC)?

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