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REVIEW PAPER

Treatment technologies for urban solid biowaste to create value products: a review with focus on low- and middle-income settings

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Abstract Treatment of biowaste, the predominant waste fraction in low- and middle-income settings, offers public health, environmental and economic benefits by converting waste into a hygienic product, diverting it from disposal sites, and providing a source of income. This article presents a comprehensive overview of 13 biowaste treatment technologies, grouped into four categories: (1) direct use (direct land application, direct animal feed, direct combustion), (2) biological treatment (composting, vermicomposting, black soldier fly treatment, anaerobic digestion, fermentation), (3) physico-chemical treatment (transesterification, densification), and (4) thermo-chemical treatment (pyrolysis, liquefaction, gasification). Based on a literature review and expert consultation, the main feedstock requirements, process conditions and treatment products are summarized, and the challenges and trends, particularly regarding the applicability of each technology in the urban low- and middle-income context, are critically discussed. An analysis of the scientific articles published from 2005 to 2015 reveals substantial differences in the amount and type of research published for each technology, a fact that can partly be explained with the development stage of the technologies. Overall, publications from case studies and field research seem disproportionately underrepresented for all technologies. One may argue that this reflects the main task of researchers—to conduct fundamental research for enhanced process understanding—but it may also be a result of the traditional embedding of the waste sector in the discipline of engineering science, where socio-economic and management aspects are seldom object of the research. More unbiased, well-structured and reproducible evidence from case studies at scale could foster the knowledge transfer to practitioners and enhance the exchange between academia, policy and practice.

Keywords Municipal solid waste management · Organic waste · Recycling · Valorization · Developing countries

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1 Introduction

The generation of solid waste has been increasing on a worldwide scale, mainly driven by growing global population, urbanization and economic growth, coupled with changing production and consumption behavior (Karak et al. 2012). Ensuring adequate solid waste management is acknowledged as one of the key challenges of the twenty-first century and considered a fundamental element for sustainable development (Scheinberg et al. 2010; Wilson 2015). Opportunities for improvement remain particularly pronounced in urban low- and middle-income settings, where solid waste management is characterized by low waste collection coverage, lack of treatment and inadequate disposal. Many appropriate solutions are hindered given the fast and unregulated growth of settlements in topographically often challenging areas, lack of financial resources, ineffective organizational structures, lack of viable business models, low political priority setting by governments and minimal enforcement of policy and legislation (Marshall and Farahbakhsh 2013; Zurbrügg 2013). Adverse effects on human health, the environment, and social and economic development are the consequence (Guerrero et al. 2013).

In low- and middle-income settings, a predominant characteristic of municipal solid waste—defined as non-liquid waste from households, small businesses and institutions (Wilson 2015)—is the high fraction of organic, hence biodegradable matter (=biowaste). This fraction often constitutes more than 50% of the total waste generated and can be as high as 80% (Troschinetz and Mihelcic 2009; Wilson et al. 2012). Biowaste is comprised of food and kitchen waste (e.g. from households, restaurants, hotels, schools, hospitals), market waste, yard and park waste, and residues from food and wood processing industries (Hoornweg and Bhada-Tata 2012). Unmanaged biowaste poses a considerable threat to public and environmental health as it impacts through olfactory nuisance, attracts insects, rodents and other disease vectors, and generates leachate that may contaminate surface and groundwater supplies (Reddy and Nandini 2011). Moreover, uncontrolled disposal of biowaste emits methane, a major greenhouse gas (Bogner et al. 2008).

Advancing on biowaste management is an ideal entry point for overall municipal solid waste management improvements (Srivastava et al. 2014; Wilson 2015). Besides reducing public health threats (Ahmad et al. 2007) and environmental burden (Friedrich and Trois 2011), returning resource value of waste into the economy reflects the paradigm shift towards a circular economy focused on 'closing loops' through recovery, while at the same time considering new business opportunities and economic growth (Ghisellini et al. 2016; Witjes and Lozano 2016). Biowaste treatment in a circular economy addresses resource scarcity, for instance the depleting nutrients stocks such as phosphorus (Zabaleta and Rodic 2015). It can also act as driving force for overall waste management when, for instance, the economic value of biowaste-derived-products incentivizes waste collection or the new revenue opportunities enhance financial sustainability of the system (Lohri et al. 2014).

Biowaste treatment and its benefits has attracted considerable interest of researchers worldwide (e.g. Polprasert 2007; Yang et al. 2015b). Many publications, however, either include liquid biowaste or then emphasize only certain waste treatment options without allowing a comparison among them. A comprehensive overview of a wide range of different biowaste treatment technologies is still lacking. This article attempts to fill this gap by reviewing the state-of-research and research challenges for a wide range of biowaste treatment technologies. It puts a special focus on the applicability of these treatment approaches for low- and middle-income settings where the need for solutions is most evident. The way this review is structured it: (1) provides a systematic, descriptive overview of the main treatment technologies for urban biowaste, (2) compares the state-of-research of these biowaste treatment technologies by examining the type of research published in scientific articles from 2005 to 2015, and (3) investigates if and how scientific publications address the issue of biowaste treatment specific to low- and middle-income settings.

Source-segregated solid biowaste is considered as feedstock of the presented treatment technologies. Thus, the review does not look into treatment options for mixed municipal waste streams, such as mechanical–biological treatment (MBT) with refuse/solid derived fuel (RDF/SDF) production (Di Lonardo et al. 2012; Velis et al. 2010), incineration (Astrup et al. 2009) or landfill treatment (Hashisho and El-Fadel 2014).

2 Methodology

This review of biowaste treatment technologies for low- and middle-income settings is based on a comprehensive scientific literature review and expert consultation. In expert group dialogs a simplified, structured overview of the selected treatment technologies was developed. The technologies reviewed are grouped according to their principal conversion processes and show the corresponding treatment products and their potential end-uses.

Each reviewed biowaste treatment technology is briefly summarized according to the following structure: (1) introduction including a brief historical background, (2) input material (feedstock specifications and pre-treatment requirements), (3) conversion process and main technologies, (4) output (product characteristics, post-processing requirements and end-uses), and (5) critical review of challenges and trends in low- and middle-income settings. Citation of scientific key literature allows access to more detailed information on each technology.

The Scopus search engine and database, an abstract and citation database of peer-reviewed literature, was used for the state-of-research analysis. The search was conducted for the publication period of 2005 until and including 2015, and was performed between 2nd June and 7th July 2016. Three search levels were applied consecutively. At each level a specific set of search terms was adopted as shown in Fig. 1. The search results of each level were then used as a basis to apply the search terms of the next level. The comprehensive listing of all applied search terms at each level with the specific search codes can be found in the supplementary material.

Search level 1 After consultation of waste experts in a focus group discussion, search terms of each specific treatment technology descriptor, process and corresponding treatment as well as their synonyms were defined. These search terms (connected with the Boolean "OR") were used in the search categories "article title" and "keywords" (authors keywords as well as the indexed keywords). Other technologies descriptors were excluded using the Boolean "AND NOT" feature in the "article title" category. This "AND NOT" feature was not applied to the "keywords" category to retain publications that comparatively discuss different treatment technologies. This process was repeated for each technology and the results were analyzed in terms of frequency of publication.

Search level 2 This level then used terms describing the feedstock for treatment—solid waste and its synonyms—to filter the results from search level 1. The "AND NOT" Boolean was used in the "article title" category to exclude articles related to other waste which is not considered relevant for this review.

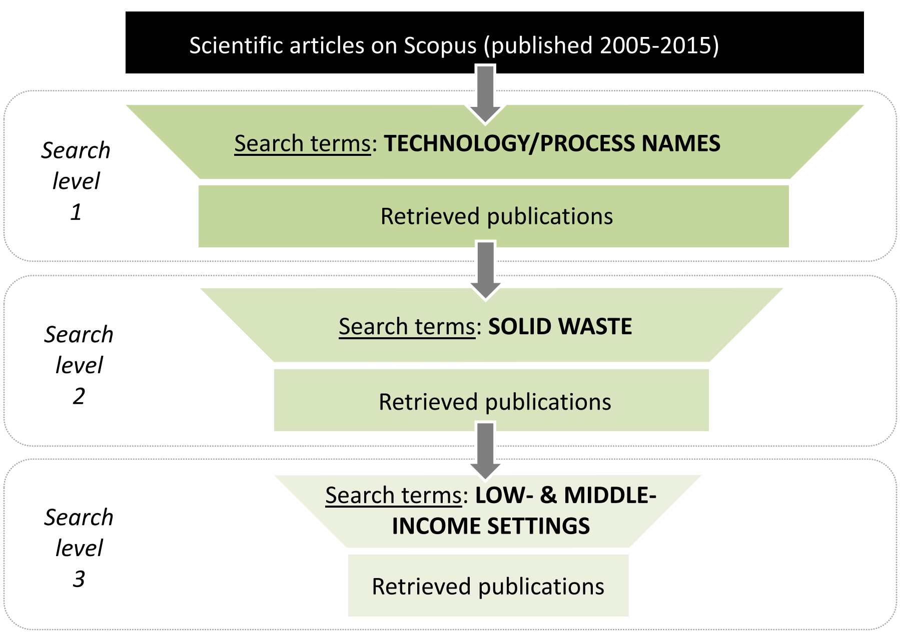

Fig. 1 Levels of scientific literature search and corresponding search term categories

Feedstock terms such as wastewater, sludge, faeces, urine, sewage, manure, livestock waste, dairy waste, tire, e-waste, medical waste, are examples of such exclusion (see supplementary material). Results were analyzed regarding frequency of publication for each technology and then analyzed in more detail to assess the type of research conducted. Three research type categories were established:

1. *Process engineering* Articles of laboratory/bench scale work with a technical focus on the basic fundamentals to understand and optimize the process
2. *Implementation* Pilot/demonstration scale or case studies discussing the field application
3. *Sustainability aspects* Financial, social, environmental aspects, models and simulations, theoretical evaluation, potential analysis, decision support tools

From the search level 2 results for each technology (=population size), a representative sample size was calculated based on an error margin of 5%, a confidence level of 95%, using a conservative response distribution of 50%. Then 20% was added to this calculated sample size to account for potential non-target articles in the selection. The calculated number of publications was then randomly extracted from the results of search level 2. Each author of the present article then individually classified each selected article into the three research type categories, whereby articles could fit in one, two or all three categories. The research type classifications for each treatment technology were then compared to each other.

Search level 3 This level then filtered the results of search level 2 to extract those articles that relate to low- and middle-income settings. Besides using a defined list of search terms to capture this aspect (see supplementary material) all 105 country names which are classified as low-income, lower-middle income, or upper-middle income countries (World Bank 2015) were included. Furthermore, eight countries classified with a low or middle Human Development Index (HDI) (United Nations Development Programme 2015), and two countries with <60% of the population served by waste collection services (UNEP 2011) were added to the list. In total 126 search terms were thus used for the search categories "article title" and "keywords". The results were analyzed in terms of frequency of publication for each technology as well as the trend of publication frequency over 5 year periods.

3 Overview of biowaste treatment technologies/processes

In this context biowaste treatment technologies are defined as processes that convert discarded biowaste into new products with potentially some value. Treatment technologies for urban solid biowaste are grouped into four main categories: (1) direct use, (2) biological treatment, (3) physico-chemical treatment, and (4) thermochemical treatment (Fig. 2).

Sustainable waste recycling requires a supply of adequate waste materials as input, and the market demand for the output products (Vergara and Tchobanoglous 2012). For biowaste such markets will depend on the intended end-use of the outputs, which can roughly be clustered into three end-use groups:

Animal husbandry Biowaste-derived products can be used as animal feed. This will continue being of increasing relevance considering the major global shift towards diets with increased consumption of animal products. The demand for meat and milk is expected to be 58 and 70% higher in 2050 than in 2010, with low- and middle-income countries significantly contributing to this increase (FAO 2011). A growing demand for animal products requires increasing amounts of feed. Rising prices of conventional feed resources such as soy—and fishmeal, the risk of future unavailability and the current associated negative environmental impacts in production of such conventional feed are triggering innovation and alternative feed. Protein products derived from waste, such as insects or worms, are increasingly being considered as possible alternative option (Makkar et al. 2014).

Agriculture Biowaste, a source of carbon and plant nutrients, can be processed into different type of soil amendments with benefit for both crops and soils. These biowaste-derived soil amendments (e.g. compost, digestate) are by many customer groups perceived as low value products (Gilbert 2015). However, with increasingly intense agricultural practices, soils are progressively vulnerable, especially in the tropics. Rapid carbon turnover (3–5 times faster than in

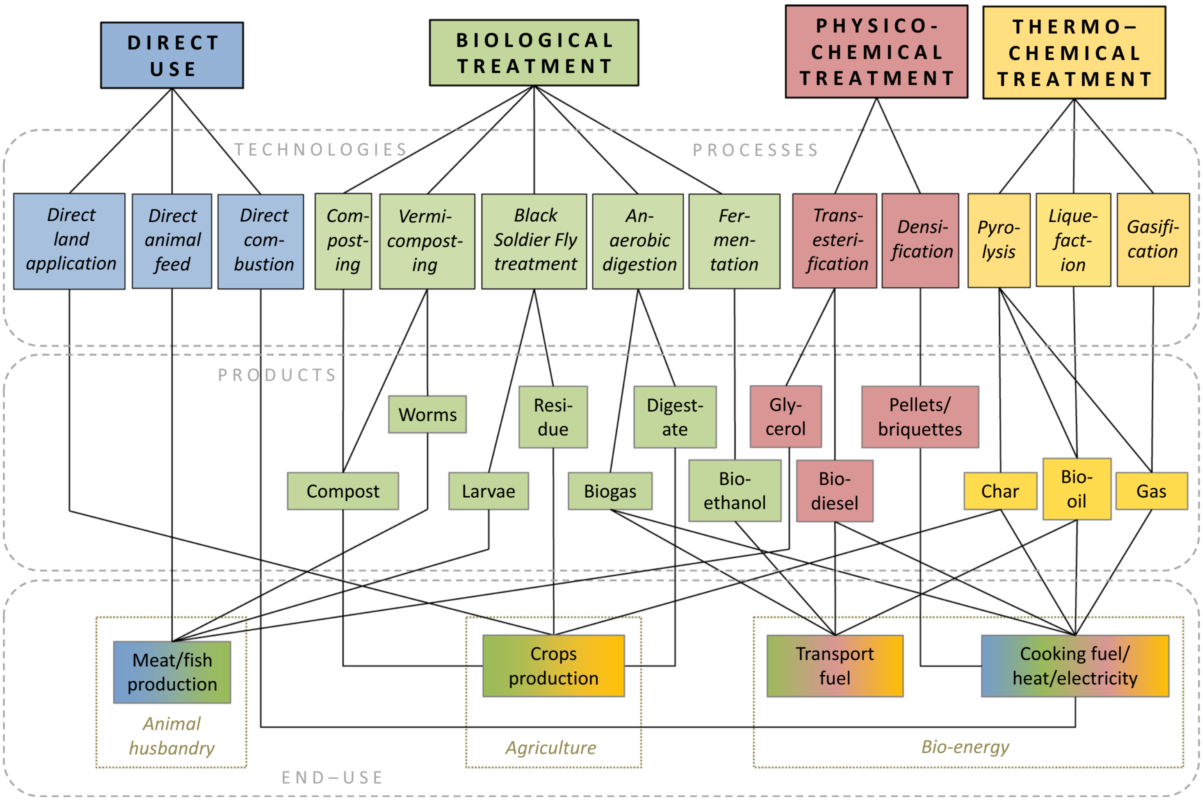

Fig. 2 Overview of biowaste treatment technologies as presented in this review with the respective products generated from waste and their end-use

temperate regions) and extraction, decreasing nutrient retention and water storage capacity, and decreasing erosion resistance are highlighting the need of carbon and plant nutrient replenishment. This can be achieved by recycling organic waste into agriculture (Smith et al. 2015).

Bio-energy The energy contained in waste biomass has received increased attention. Considering the growing energy demand, 1.2 billion people (17% of the global population) without electricity and 2.7 billion people (38% of the global population) still relying on unsustainably harvested wood for cooking (OECD/IEA 2015), biowaste-derived energy products are of high interest (Lohri et al. 2016). In addition, the increasing global mobility combined with the world's dwindling petroleum reserves raise the interest for technologies to convert (and upgrade) biowaste-derived products into transportation fuels.

3.1 Direct use

The direct use of biowaste is an ancient form of waste treatment/disposal. It is associated with low costs and simplicity. Included in this category of 'direct uses' are direct land application, waste fed directly to animals and direct open combustion. The risks of such practices depend on the composition of the biowaste. Contamination can easily jeopardize human, animal and environmental health. Direct biowaste use on land and for feed is still practiced today, mainly in rural settings. In urban settings, characterized by high population density and increasing waste complexity, this practice is less frequent.

3.1.1 Direct land application

Introduction Direct land application, also called landspreading, refers to the practice of raw waste dispersal onto fields. Literature on land application of waste typically describes the spread of raw agricultural waste (manure and/or crop residue) onto fields. However, literature tagged with this terms may also comprise studies on use of composted material, digestate, faecal sludge or wastewater. In this study the term is used in a strict sense only considering the practice when no actual treatment phase is involved, with the exception of segregation. Direct land application is particularly relevant for crops that require large quantities of organic nutrients (Dulac 2001).

Input material Direct land application should focus only on pure organic waste (Gendebien et al. 2001) as non-biodegradable waste fractions or pollutants would affect soil and crop quality or endanger farmers health. A study conducted for the EU Commission came to the conclusion that more than 90% of the waste spread on European land is agricultural waste, mainly animal manure. The remaining 10% is food waste (Gendebien et al. 2001). When considering urban organic waste, studies have shown the potential benefit of using yard waste (Hegberg et al. 1990) and municipal organic waste (EPA 2004) that can enhance organic matter levels, total nitrogen and available phosphorous in soils.

Conversion process With direct land application, raw organic waste undergoes natural aerobic biodegradation after it is spread onto the field. Degradation mobilizes nutrients and increases organic matter content of soil. However, degradation may also cause a nitrogen competition in soil, when the microbial population outcompetes the crop in the use of nitrogen for their own metabolism, with the result that the crop shows signs of nitrogen deficiency. Smith et al. (2015) estimate that untreated waste application results in a 66% decrease of the nitrogen available for crop growth. On the other hand, raw biowaste consisting of very nutrient rich materials may result in leaching of nutrients into groundwater or surface water or the volatilization as ammonia.

Products and uses The main output of direct land application of waste is a soil amendment with high organic matter content. Organic matter plays a threefold role in soil by (1) biologically acting as nutrient and energy supply for microbes, (2) chemically buffering changes in soil pH capacity, and (3) physically influencing soil structure and associated properties. Direct land application of waste is, in a strict sense, not a treatment process and might negatively impact on plants and soil. As waste is likely to contain a certain level of pathogens or trace elements, these can bio-accumulate in plants and soil (Olowolafe 2008). This may result in health threats from food contamination or pollution of water courses from runoff (Smith et al. 2015). According to Dulac (2001), landspreading of raw organic matter is specifically beneficial for degraded soils in arid areas. But the same studies highlight the risk of lower availability of micro-nutrients necessary for plant growth when applying non-stable organic material (Dulac 2001). Landspreading of raw organic waste must therefore be subject to restrictions and control to avoid environmental and human health risks (EPA 2004; Dulac 2001). One control measure is to ensure sufficient time between application of waste and the subsequent crop planting and harvesting (Dulac 2001).

Critical review of challenges and trends in low- and middle-income settings Landspreading of raw organic waste is still a common practice in rural areas of low-and middle-income countries for improving soil nutrients content. The potential benefits and risks of this practice is closely linked to quality of the waste. Landspreading does not ensure pathogen removal. Thus, spreading of plant disease to plants and farming workforce related health is threatened. If the waste is contaminated with inorganic compounds (e.g. heavy metals), these may accumulate in soils or crops. Research on direct land application of biomass puts a focus on these risk aspects, evaluating the impact of specific organic residues on soil and/or crop characteristics in terms of fertility, structure and trace element content (Hegberg et al. 1990; Olowolafe 2008; Walsh and McDonnell 2012). Organic residue properties are highly variable as are soil and crop response. Therefore, it remains a challenge to assess the impact of landspreading on soil. Gendebien et al. (2001), in the European survey of wastes spread on land, highlighted the need of preventive measures such as chemical and physical analysis of waste and field trials prior to any direct application of raw waste. Alvarenga et al. (2007) claim that eco-toxicity tests combined with chemical analysis allow a good environmental risk assessment of direct land application for evaluating contaminant bioavailability, mobility and toxicity. The time period between landspreading and planting of crop should be sufficiently long to ensure minimal risk for soil and plants. In urban settings with intensive use of agricultural land, this recommendation may, however, be difficult to follow. Overall, to avoid negative side effects, it is recommended to avoid direct land application but rather include a treatment process (e.g. through composting) before spreading the waste onto the field. This ensures a hygienization phase and the conversion of nutrients into a more readily available form for the plants.

3.1.2 Direct animal feed

Introduction A simple way to recover value from biowaste is to feed it to animals. Humans have been feeding biowaste to animals since the beginning of animal domestication. In countries such as South Korea, Taiwan and Japan, 38.4, 22.1 and 11.5% of biowaste respectively, is processed into swine, poultry and fish feeds to partly substitute the conventional feed ingredients (Cheng and Lo 2016).

Input material Quality of the waste is again a key issue and source-separated biowaste from vegetable and fruit markets can be a suitable feed for animals. In general, animal feed should contain an adequate amount of carbohydrates, amino acids, minerals, vitamins, essential nutrients, fibers and fats (Lardinois and van De Klundert 1993) and minimize pollutants which endanger the animal or the meat quality. The largest risk lies in the substances contained in the waste. To mitigate the potential risks or to enhance its nutritive value, biowaste is often treated before being fed to animals. The benefit of waste as feed heavily depends on the animals' digestive systems. Ruminants with complex digestive systems can digest materials containing mainly cellulose (e.g. straw, grass), whereas the digestive system of pigs cannot digest straw or low-quality fodder. Completely rotten items should not be used for animal feed (Lardinois and van De Klundert 1993). When biowaste contains meat or has been in contact with meat, there may be risk of animal infection which then may transmit diseases to humans (e.g. salmonellosis), or to other animals (e.g. swine fever or bovine spongiform encephalopathy, BSE) (Lardinois and van De Klundert 1993). After first reports of BSE cases, very stringent legislation regarding the use of animal byproducts as animal feed (e.g. the feed ban) were implemented (EU 1994; Onodera and Kim 2006). Other compounds of concern are heavy metals (Cheng et al. 2016a, b), polycyclic aromatic hydrocarbons (PAH) (Cheng et al. 2015a) and organochlorine pesticides (Cheng et al. 2014), mainly studied in aquaculture.

Conversion process Direct animal feeding with waste can be applied on a decentralized-household level for self-production of animal protein. It can also be performed in a more centralized way, where the biowaste may undergo processing, such as grinding or drying, and can then be fed pure to animals or in a mixed form with other feedstuffs. Once consumed, the biowaste is metabolized by the animals contributing to their physiological needs, an increase in their body mass, and ultimately, into the targeted value products (e.g. meat, eggs, milk).

Products and uses Animal production yields high value products, such as meat, eggs, milk, leather, etc. The largest risk, as highlighted above, is to ensure good quality of waste used in direct animal feed. Although research has shown that the taste of meat and dairy products is not affected when animals are fed with biowaste (Kwak and Kang 2006; Lardinois and van De Klundert 1993), biowaste containing fish was reported to cause minor taste changes in pork meat (Márquez et al. 2011). In other studies improved meat qualities (Cheng et al. 2015b; Mo et al. 2014) and milk qualities (Angulo et al. 2012) were reported when using biowaste-based diets.

Critical review of challenges and trends in low- and middle-income settings The extent to which biowaste is fed to animals is currently largely unknown. Existing information is limited to Asian industrialized countries, such as Japan, Hong Kong, Taiwan and South Korea (Cheng and Lo 2016). Although not published, one can assume that in rural areas direct animal feeding with agricultural waste is with certainty widely practiced. In the urban context, biowaste from certain sources (e.g. restaurants, markets) are often observed to be collected and paid for by livestock holders.

Direct animal feeding diverts considerable amounts of biowaste from the main waste stream, thereby saving costs and infrastructure to waste managers. In

Nouakchott, Mauritania, 40% (on wet weight basis) of household waste is used as animal feed. This results in an organic fraction of only 5% at the point of collection (Alouéimine et al. 2006). Research to quantify this practice in cities and countries would help to better understand how direct feeding impacts on the solid waste management system, and how such practices might be used elsewhere. As animal protein intake by humans is foreseen to increase especially in transition countries where meat consumption has been growing at 5–6% per year and dairy products at 3.4–3.8% per year (FAO 2003), using waste for direct feed might be an interesting option. The same applies for fish consumption, where the expected expansion in production would be in aquaculture (FAO 2016). Nevertheless, the practice of direct animal feed with biowaste also poses risks as contaminants in waste (microbial pathogens, packaging hardware, mercury, polycyclic aromatic hydrocarbons, organochlorine pesticides) may not only endanger the health of the animals but also of humans by consumption of products derived from these animals (Cheng et al. 2014, 2015b, 2016b). Ensuring good quality waste feedstock is required if direct animal feeding is to be implemented in a centralized manner. Properly designed source separation strategies and supply chains can be a way to ensure such feedstock quality. Most of the literature published on this topic deals with animal health and nutrition issues, fish rearing being the most frequently studied case (Cheng et al. 2015a; Mo et al. 2014, 2015), followed by swine (Esteban et al. 2007; Kwak and Kang 2006), cattle (Angulo et al. 2012; Froetschel et al. 2014) and poultry husbandry (Rizal et al. 2015). Many of the publications conclude that food waste can be satisfactorily recycled by converting it into animal feed. In contrast, further research on indirect impact on human health as consumer is needed.

The so-called food waste hierarchy prioritizes efforts to feed food waste to animals over other technologies such as composting and anaerobic digestion (Papargyropoulou et al. 2014). This approach is of particular interest for low- and middle-income settings, where other biowaste treatment options have failed in the past or are still inexistent.

3.1.3 Direct combustion

Introduction Direct combustion, also known as open burning, refers to a wide range of uncontrolled waste combustion practices including burning of waste in backyards or dump sites. The associated benefits are a reduction of waste volume and the hygienization of the waste. On the downside, however, uncontrolled open burning without use of an adequate stack, duct or chimney may directly emit harmful combustion products into the local environment (Estrellan and Iino 2010). This waste management technique is unfortunately one of the primary practices applied in low- and middle-income settings worldwide as it requires very little technical knowledge and minimal costs, and is the easiest way to get rid of litter which was not collected (Smith et al. 2015; UNEP 2007). Open burning is practiced by municipal employees and landfill workers to diminish the waste volume at dump sites, by informal recycling sectors to recover valuable products (e.g. scrap metals), and by individuals who lack waste collection services and want to reduce their waste amounts or require a cheap heating and/or cooking fuel. Despite its extensive use worldwide, open burning is considered an illegal practice in most countries and has been declared an "environmentally unacceptable process" by the Stockholm Convention due to the generation of harmful pollutant products from incomplete combustion (UNEP 2007). For this reason, this review only describes this practice briefly and emphasized the challenges of open burning.

Critical review of challenges and trends in low- and middle-income settings Open burning is not considered an acceptable solid waste management although it is still widely practiced in urban low- and middle-income settings. It poses a substantial threat to human and environmental health from emissions of mixed waste burning and/or incomplete combustion. Open burning has the main objective of waste reduction and does not recover energy nor nutrients.

Analysis of the research conducted over the last 10 years on open burning reveals that the main focus has been on assessing the emissions and the related environmental and health impacts (Babel and Vilaysouk 2016; Nagpure et al. 2015; Prasad Raju and Partheeban 2014; Zhang et al. 2011). Although most of the research so far has focused on emission of nitrogen oxides and complex organic compounds, in the last decade there has been increased interest in the emission and impacts of short-lived climate pollutants (SLCPs). Black carbon receives considerable attention as a SLCP (Stohl et al. 2015) and it is reported that the impact of black carbon from burning waste is still not well documented Bond et al. (2013). The task of assessing the impacts on public health and the environment at local, regional and national scales is a challenging endeavor as open burning relates to a dispersed non-point emissions. Research on open burning impacts helps provide evidence to policy-makers to enforce strict regulations and control mechanisms (Forbid et al. 2011; Park et al. 2013). Thus, there is a need for further research aiming at (1) improved quantifying the amplitude of this practice at a local, regional and national scale, and (2) for enhanced emission assessment and controlling and evaluating the impact of these emissions on health and climate change.

3.2 Biological treatment

Biological treatment processes are understood as the controlled conversion of waste by living organisms. Biotechnological and biochemical conversion processes also fall under this category. Biochemical processes are substantially slower than a thermochemical conversion but require significantly less external energy input (Basu 2013). As all living organisms require water for survival, biological treatment always takes place in a moist environment. Biochemical conversion processes are thus mainly applied to wastes with high moisture levels. The black soldier fly treatment method was selected as an example for waste conversion by insect larvae for protein production, since other insects (e.g. house flies, blow flies) are mainly applied for manure or slaughterhouse waste management.

3.2.1 Composting

Introduction Composting involves the controlled aerobic decomposition of organic matter that results in a relatively stable organic end product called humus. Composting is unquestionably an ancient practice, documented from Greeks, Romans and also early civilizations in South America, China, Japan or India (Hershey 1992). Early scientific publications about composting as a management option in agriculture date back to publications of Sir Howard around 1933. Based in India, Sir Howard was inspired by the use of composting in Chinese agriculture (Diaz and de Bertoldi 2007), so he developed and documented the principles of modern composting which he called the Indore Process (Howard 1935).

Input material Many different types of organic solid wastes are suitable for composting as long as key parameters are fulfilled (see Table 1 for process parameter requirements). Suitable substrates include yard waste (branches, leaves, grass), food waste, agricultural waste, manure, and even septage and human feces (Epstein 1997). Mixed municipal waste may also be composted, however, this is not recommended as the resulting compost quality will be poor (Haug 1993). Depending on the moisture content of the feedstock used in composting and the climate, the addition of water may be necessary at the beginning or during the process to ensure sufficient moisture for microbial activity (Cooperband 2002; Polprasert 2007).

Conversion process Composting of organic matter is driven by a diverse population of microorganisms and invertebrates, where population dynamics vary greatly both temporally and spatially (Insam and de Bertoldi 2007). Microorganisms break down organic matter and produce carbon dioxide, water and heat. Controlling the process implies that the predominant parameters such as organic material composition (carbon–nitrogen ratio), particle size, free air space, aeration, temperature, moisture, or pH are managed, steered and adjusted to achieve fast degradation and good compost quality. When conditions are not optimal, the process may be slowed or may not happen at all. Under optimal composting conditions, the degradation by composting proceeds through three phases: (1) the mesophilic phase, which lasts for a couple of days; (2) the thermophilic, which can last from a few weeks to several months, and finally, (3) a cooling and maturation phase which can last several months (Epstein 1997). During the thermophilic phase the temperature can rise up to 55–70 °C due to the metabolism of the microorganisms, which contributes to hygienization of the material. The end of the composting process is reached when the inner temperature of the pile is similar to ambient temperature and the oxygen concentration in the air cavities within the pile remains >10–15% for several days (Cooperband 2002).

Composting of organic solid waste can be conducted at different scales and with different use of technology and mechanization. Small-scale home

Table 1 Differences between the composting and vermicomposting process (adapted from Ali et al. 2015; Lim et al. 2016)

Parameters	Composting	Vermicomposting
Type of process	Three stages	One (mesophilic) stage (10–35 °C)
	(1) Mesophilic stage	
	(2) Thermophilic phase (up to 70 °C)	
	(3) Cooling and maturation phase (>15 °C)	
Organic waste characteristics	Sorted organic waste, combination of waste with similar decomposition rate	No hard, oily, salty, acidic and alkaline compounds
Organisms involved in biodegradation	Microorganisms and macroinvertebrates	Earthworms and microorganisms
Stocking density	–	27–35 worms/kg feed
Feed rate	–	1.25 kg feed/kg worm and day
Initial C/N ratio	20–50	25–30
pH	5.5–7.5	5–8
Moisture content	Coarse organic waste: 70–75%	70–90%
	Fine organic waste: 55–65%	
Product characteristics	Texture is coarser and may contain heavy metals	Texture is finer and heavy metals accumulate in earthworm bodies

composting is most frequently conducted in bins or open heaps relying on a passive aeration process. Medium- and large-scale composting facilities more frequently rely on mechanization with regular turning or active aeration and the use of open windrows, bins or in-vessel composting reactors (Couth and Trois 2012).

Products and uses The main output product from composting is compost, a stable dark-brown, soil-like material with a crumbly texture, dark color and earthy smell. Besides compost, other output products emitted during the composting process are leachate, water vapor and carbon dioxide (Polprasert 2007).

Under ideal operating conditions compost can be produced within 3 months (Rothenberger et al. 2006). The quality of the input material and the key biological and physical operating parameters have a major influence on the quality of the final compost (Rothenberger et al. 2006). Impurities in the composted waste can be removed by sieving. Sieving can also serve to produce a range of products suitable to various end uses (soil conditioning, mulching). Compost contains important plant nutrients such as nitrogen, potassium, and phosphorus, though usually not as much as animal manure or chemical fertilizers (Polprasert 2007). It also contains a range of beneficial minerals and is rich in humus and micro-organisms beneficial to plant growth (Brinton and Evans 2001). Compost can be used to amend soils but research also reports the use for landfill cover, land remediation or land restoration schemes. For example, application of composts at acidic heavy metal contaminated sites has ameliorated soil pollution with minimal risk (Farrell and Jones 2009).

Critical review of challenges and trends in low- and middle-income settings In urban waste management, composting can be considered a well-established, mature and proven treatment technology. Composting is well known by waste managers in high- as well as middle- and low-income settings as a simple and robust technology. Nevertheless, urban waste composting is not so widespread as one would expect. If implemented in a municipal system, such initiatives seldom endure over time (Zurbrügg et al. 2004). Reasons may comprise a lack of segregated "pure" organic waste, in other words a low quality feedstock which then yields poor quality compost. Also inadequate attention to, or knowledge of, the biological process requirements may result in a nuisance potential, such as odors and vermin. This can lead to poor acceptance by the resident population or lack of acceptance by the potential compost users. Furthermore, poor supporting policies and governmental measures as well as limited marketing experiences often hinder the economics of composting (Zurbrügg et al. 2012). Without an obvious revenue stream and with the increased cost of operating and maintaining the facility there is little incentive, especially in financial resource scarce settings, to keep such a facility running. Given the simplicity and robustness to process a wide range of biowaste types, the global degradation of soils and the global trend towards nutrient recycling and ensuring food security, it seems imperative that composting be given more attention in waste management. Pure waste streams through segregated collection, a prerequisite for high quality compost, need higher priority by waste managers and marketing efforts need support by policies to favor and incentive the use of compost and strengthen its competitiveness with regard to other organic solid amendments and fertilizers.

When analyzing the research conducted on composting and compost over the past few years, one can distinguish three main directions of research. The first focus, mainly related to low- and middle-income settings, pertains to case study descriptions of specific locations implementing composting schemes as waste management strategies (Zurbrügg et al. 2012). This typically includes application of life cycle analysis methods as well as economic assessments (Karagiannidis et al. 2010; Lim et al. 2016; Pandyaswargo and Premakumara 2014; Sánchez et al. 2015) and the analysis of climate change mitigation measures (Dedinec et al. 2015). Besides the typical case study descriptions, such research is usually not only about composting, but rather tackles the comparison and selection of waste management options, of which composting is one (Van Fan et al. 2016). A second line of research is on the use and benefits of compost, be this in terms of compost quality related to the feedstock (Mahmud et al. 2015; Pérez et al. 2016) and the respective benefits and impact on agricultural crops (Santos et al. 2016; Scotti et al. 2016), or the function of compost as substance for the remediation of contaminated soils (Taiwo et al. 2016). A third line in composting research is the quite regular and frequent research on the complex microbial processes, bacterial and fungal communities and their dynamics during the composting process (Kinet et al. 2015; Xi et al. 2015). The application of such rather basic and lab-based research for waste management could be seen in finding ways to reduce the duration of the composting process or improve compost quality. In waste management practice there is some debate on the value of adding a mixture of enhanced microorganisms to the composting processing to reduce odor emission, speed up the process and improve the output quality. This practice is promoted strongly by the vendors of these mixtures but their claims are not substantiated by independent research studies. Finally, in light of the recent trend towards energy generation from waste a novel line of research involves experiments with paddy plant microbial fuel cells in soil mixed with compost. Cells with compost showed higher values of voltage and power density with time indicating the influence of compost on bio-electricity generation (Moqsud et al. 2015).

3.2.2 Vermicomposting

Introduction Vermicomposting is defined as an aerobic process of organic waste degradation and stabilization by interaction of microorganisms and earthworms under controlled conditions. Microbial communities help degrade organic matter and a high density of earthworms then feed on the waste and generate earthworm castings, also called vermicompost. Such vermicompost has shown to have higher levels of nutrients than compost (Ndegwa et al. 2000). The role of the earthworm in degradation of organic matter in soil was already described by Darwin (Darwin 1881), but regular publication of research papers on the use of vermicomposting as a waste treatment options started only early 1980 (Aalok et al. 2008).

Input material Earthworms are able to process household waste, organic municipal waste, sewage sludge and organic waste residues from different (paper, wood and food) industries (Edwards 1998; Garg et al. 2006). There are some food wastes that earthworms do not tolerate such as dairy products, meat and fish waste, grease and oils, salty and vinegary foods. Smaller feedstock particles will increase surface area of the material and hence increase the speed of degradation and vermicomposting.

Conversion process Vermicomposting depends on the interaction between microorganisms and earthworms. Microorganisms in the waste prepare the waste for the earthworms through a first step of aerobic degradation, i.e. vermicomposting is thus preceded by a pre-composting phase. This facilitates the feeding of the worms on the substrate. Furthermore, microorganisms are also contained in the gut and intestine of the worms. Here they decompose the organic material into finer particles and also provide the earthworm with nourishment. The earthworms in turn feed on the waste and also promote microbial activity by producing microbial active fecal material that is beneficial for quicker organic waste degradation and improves the nutritional quality of the vermicompost product (Singh et al. 2011). Attention needs to be paid to provide the feed in shallow layers into bins or beds. The amounts should be based on the feeding rate of the worms. Otherwise, the microorganisms degrading the feed could increase the temperature in the waste layer or anaerobic conditions could occur; both situations are most unfavorable for the worms.

Appropriate earthworm species for vermicomposting are those that have high adaptability to different waste types and conditions, rapid feeding and digestion, and fast growth and reproductive rate. Epigeic earthworms live right underneath the soil surface (they avoid direct sunlight), are litter feeders and are most suited for vermicomposting operations. Among these, *Eisenia fetida* is the most frequently used species besides *Lumbricus rubellus*, *Eisenia andrei*, *Perionyx excavatus* and *Eudrilus eugeniae* which is popular in tropical and subtropical countries (Kumar 2005). According to Reinecke et al. (1992) the complete life cycle of *E. fetida* encompasses around 70 days. Maturation is attained after ca. 50 days, start of cocoon production after 55 days (i.e. 4–5 days after mating), and incubation period is about 23 days. In average, there are three hatchlings per cocoon. It is important to leave the cocoons in the waste material to ensure continuation of the life cycle. Table 1 shows the optimal ranges of parameters for best worm growth and reproduction, combined with the characteristics and requirements of conventional composting. In contrast to composting, vermicomposting is not an exothermic process, which means that it does not lead to a temperature rise in the vermicompost. Most earthworm species require moderate/mesophilic temperatures in the range of 10–35 °C (Sim and Wu 2010). In this range the worms feel most comfortable and feed most rapidly. Important factors influencing the vermicomposting process are: stocking density, temperature, feeding rate, moisture, C/N ratio and pH.

For optimal engineered vermicomposting many different systems have been developed. They all have in common that waste is fed in shallow layers into bins or beds with a shaded environment (Board 2004). Regarding stocking density, higher density slows the reproductive urge, as competition for food and space increases. A lower population density will enhance growth as enough food is available for each worm, however, it will delay reproduction as the worms do not find each other to reproduce. Moisture content in the waste bins of below 60% delay the sexual development, thus negatively influences the reproduction rate of the worms while high moisture content (above 90%) will hinder breathing of the worms.

Products and uses As feed passes through the earthworm gut the waste material is mineralized and plant nutrients are made available. The grinding effect of the gut leads to the formation of a granules, a typical feature of vermicompost. Nitrogen content of vermicompost is typically 1–2% higher than that of compost and the nutrients are reported to be more easily available to the plants (Adhikary 2012). Furthermore, enzymes and microorganisms from the gut show very beneficial properties for soil and plants, also suppressing diseases. Leachate from the worm bins can also be used as a liquid fertilizer, which is typically used in small-scale systems. Another product from vermicomposting are the earthworms themselves which are rich in protein (65%) with all essential amino acids and they can be used for animal feed (Lalander et al. 2015). They are considered a good pro-biotic feed or used as additives for fish or poultry feed (Adhikary 2012). Pulverized and ingested earthworms have also been studied with regard to their medicinal properties and were found to be effective in treating thrombotic diseases (Christy et al. 2015) and beneficial on the wound healing process (Goodarzi et al. 2016).

Critical review of challenges and trends in low- and middle-income settings Vermicomposting has gained strong interest since the early 1990s and has meanwhile established itself as a recognized organic waste treatment option especially for low- and middle-income settings (Gupta and Garg 2011; Singh et al. 2011). The growing interest derives from the potential of adding more value to waste then only compost. Vermicomposting systems are considered less energy consuming, more cost effective and economically feasible when compared to conventional treatment technologies. Nevertheless, vermicomposting is not a widespread approach used in urban waste management in low- and middle-income settings. Many of the implemented facilities report vermicomposting but when examined in more detail actually revert to the process of composting with worms present in the late maturation stage (which does not qualify as vermicomposting). One expected barrier to vermicomposting might be seen in the requirement of much space. However, this can be easily overcome by stacking the feeding boxes in a vertical axis. Another barrier is the required stage of pretreatment by composting before feeding to the worms. If a composting pile is already required, then often the second step of vermicomposting is considered more effort than benefit. This links again to the barriers already stated with composting: a lack of segregated "pure" organic waste, in other words a low quality feedstock, inadequate attention to, or knowledge of, the biological process requirements, poor supporting policies and governmental measures and finally limited marketing experiences. All this hinder the economic feasibility of vermicomposting. The revenue stream of vermicompost is not attractive enough to sustain operation. In those cases where the worms are marketed there is an increased chance of success. It is often more effective to feed the worms other feedstock than waste. Compared to composting, vermicomposting needs more skills and understanding of the worm lifecycle and the optimal processing conditions. Nevertheless, if a pure segregated biowaste stream can be ensured, the relative simplicity and the prospect of obtaining a nutrient product as well as a protein product should theoretically favor this technology when compared to composting. False expectations of waste managers regarding potential revenues and their limited marketing efforts hinder successful implementation of vermicomposting in urban waste management. Lack of favoring policies constitute additional barriers.

With regard to innovations required from science, a wide variety of research has been published on the factors influencing the vermicomposting rate, worm growth and reproduction rate (Reinecke and Viljoen 1990). Recent research has further studied the potential of using vermicomposting for different waste types, such as food industry waste (Garg et al. 2012), and also for treatment of industrial and polluted waste. Vermicomposting has shown to reduce toxic metal content and break down of chemicals to non-toxic forms (Jain et al. 2004). Used in sludge management, Shahmansouri et al. (2005) show that heavy metals in organic matter are taken up by the skin and intestine of earthworms during ingestion resulting in lower concentrations in the sludge. There is, however, very limited research on aspects of feasibility and sustainability of vermicomposting for urban waste management, especially highlighting possible measures to promote and foster this technology.

3.2.3 Black soldier fly treatment

Introduction Black soldier fly (BSF) treatment is an emerging technology in organic waste treatment. It involves the transformation of biowastes into insect protein and insect oil. Originally native to the Americas, transport of goods has contributed to a broad distribution of the black soldier fly, *Hermetia illucens* L. (Diptera: Stratiomyidae). Today, it can be found in the tropics and sub-tropics all over the world (Rozkosny 1982). Its appetite for decaying organic matter has been discovered already in the early twentieth century by Dunn (1916) who describes masses of BSF larvae found feeding on a dead body. Another publication documented BSF larvae breeding in outhouses in Louisiana (Bradley 1930). Around mid-twentieth century, Furman et al. (1959) scientifically tested if the presence of BSF larvae can suppress the breeding of the house fly, *Musca domestica*, in poultry farms. This statement could not only be confirmed but the authors also discovered a massive reduction of the manure where BSF larvae were present in large numbers. This seminal paper stands at the beginning of a line of scientific studies on the controlled rearing and feeding of BSF for waste treatment.

Input material Suitable waste sources for larvacomposting are manifold and there is no general rule for the suitability of a waste source for BSF treatment. For waste management BSF larvae can be fed with food and market waste (Diener et al. 2011; Leong et al. 2015; Nguyen et al. 2015; Parra Paz et al. 2015), animal manure (Li et al. 2011b; Myers et al. 2008; Sheppard et al. 1994; Yu et al. 2011), human excreta (Banks et al. 2014; Lalander et al. 2013) and fish waste (St-Hilaire et al. 2007). The importance of a certain moisture level in the feedstock was demonstrated by Furman et al. (1959) where moistening chicken manure resulted in significant higher waste reduction. Although BSF larvae can survive in liquid environments, large number of larvae seem to develop only under moist or semi-solid conditions (Newton et al. 1995). Highly cellulosic waste such as wood and dry leaves are not suitable for larva-composting and might at most be added as a structure forming agent. In an industrial BSF treatment facility, incoming waste has to be shredded to reduce particle size and the water content must have a value between 65 and 80%. This requires either a dewatering of wet materials such as fruit/vegetable waste or faecal sludge, or adding water to dry waste sources such as chicken manure. Ideally, wet and dry materials are mixed and combined to generate a suitable larva feed.

Conversion process The growth rate of BSF larvae, and therefore also the waste reduction and bioconversion rate, depends on several factors such as temperature and moisture content of the feedstock. Temperatures between 25 and 32 °C are most suitable for all of the BSF live stages (Tomberlin et al. 2009; Tomberlin and Sheppard 2002). The BSF develops through 6 larval instars with the last larval stage (15–20 mm), the so-called pre-pupa, crawling out of the moist feed source in search for a dry pupation site. Under controlled conditions (Gainesville house fly diet, 28 °C, 75% RH) the total development from egg to adult lasts 20–35 days (Zhou et al. 2013). The larvae can reduce the feedstock weight by 50–80% and convert up to 20% (on a total solids basis) into larval biomass within ~14 days (Diener et al. 2011; Lalander et al. 2014; Zhou et al. 2013). Space requirement for BSF treatment depends on operational parameters such as larval density and feeding rate. Defining these parameters requires deciding on a trade-off between high waste reduction (high larvae density and low feeding rate) and high biomass production (low larvae density and high feeding rate) (Parra Paz et al. 2015). Reported feeding rates range from 1.9 kg/m^2 and day (Diener et al. 2009) to 9.8 kg/m^2 and day (Parra Paz et al. 2015).

Different treatment unit designs have been proposed (Diener et al. 2011; Newton et al. 2005). Larger treatment facilities with a waste managerial focus require a productive nursery which produces sufficient young larvae to stock the treatment units and a regular waste flow to achieve economic feasibility. As an emerging technology with high potential for economic success, designs and operating procedures of existing large treatment facilities, however, are not shared. On the other hand, small-scale backyard applications can be well designed systems, but they rely on colonization by the natural fly population (Čičková et al. 2015) and are thus not suitable for a controlled waste management operation.

Products and uses The main products resulting from the BSF technology are the larvae and the residue. Protein content and amino-acid profile of the defatted insect meal is similar to fishmeal and may thus replace fishmeal in animal feed. The grown larvae are suited as a (partial) replacement of fish meal in animal feed and experiments have shown good results when fed to fish, chicken or pigs (Makkar et al. 2014; Stamer 2015). Other possible products to be explored are the production of biodiesel from larvae or the use of the chitin and the oil (Li et al. 2011a). The residue, on the other hand, still contains valuable nutrients and might be used as a soil amendment. However, due to the short processing time, the residue needs to undergo a maturation phase in order to prevent oxygen depletion in the soil which inhibits seed germination or suppresses root and plant growth (Brinton and Evans 2001).

When waste-derived products are recycled into the food chain, identification and management of risks related to pathogens and toxic substances (e.g. heavy metals, pesticides or pharmaceuticals) are critical. Although BSF activity accelerates the reduction of *Salmonella* spp., further processing of both the residue and the larvae is required as other pathogens such as *Enterococcus* spp., bacteriophages and helminth eggs are not reduced (Lalander et al. 2013). Furthermore, heavy metals present in the feedstock may accumulate in larvae and prepupae requiring precautionary measures, ideally by avoiding the use of contaminated organic waste as feedstock (Diener et al. 2015). Interestingly, BSF treatment accelerates degradation of pharmaceuticals and pesticides. A study by Lalander et al. (2016) found a shorter half-life in the residue of all five substances investigated and could not detect any bioaccumulation in the larvae.

Critical review of challenges and trends in low- and middle-income settings The conversion of biowaste into insect protein is a proven process. Published research so far mostly focused on the biological mechanisms such as waste conversion ratio, mating behaviour or survival rates of different life stages, typically studied at lab- or bench-scale. However, the success of the BSF-treatment approach stands or falls with scaling to an industrial setting. Living animals behave differently when managed in big masses, and scaling-up also requires integration of other skills and disciplines, such as logistics of raw material and products, automation, climate control, product refining, hygiene control, market development or legal issues. As currently most R&D activities are private sector driven and take place behind closed doors, it is rather difficult to identify the current state-of-technology development.

Overall, a high potential is attributed to the BSF treatment technology for low- and middle-income settings. This is partly due to the climatic conditions in most of these regions which are suitable for application of the BSF-technology. Establishing a BSF colony in a rough-and-ready manner requires limited skills and efforts. Unfortunately, the importance of a controlled, efficient rearing regime to produce a defined number of young larvae is often underestimated. Yet the production of sufficient young larvae is considered key to the BSF-technology and needs to be synchronized with a reliable waste supply, both in quality and quantity. The emphasized focus on the fly colony rearing is particularly important when operating a waste management business. In comparison to ensuring a productive fly colony, the treatment step itself (i.e. larvae feed on organic waste for a defined amount of time and are then harvested) is rather simple. Therefore, a two-tier model that includes the segregation of these two steps seems promising and may facilitate the uptake of the BSF waste treatment technology. Such a model could consist of a centralized BSF facility, specialized in rearing stocking larvae and refining the harvested products. This facility serves several decentralized, robust biowaste treatment units. In other words, small entrepreneurs or waste generators obtain young larvae from a centralized BSF facility and convert their organic waste into insect protein. The fattened larvae are then either directly sold to chicken and fish farmers or vended back to the centralized BSF facility for post-processing. The separation and centralization of the most delicate and sophisticated task within the BSF-conversion chain, the production of small larvae, can alleviate the growth of a loose network of organic waste processors applying the BSF technology, thus reducing transport costs and emissions of the waste treatment.

Current legal barriers hinder the development of BSF-technology for waste treatment in several countries. The EU regulatory framework has restrictions when it comes to (1) feeding waste to insects and (2) feeding insects to farmed animals. With respect to feeding waste to insects, Annex III of Regulation (EC) No 767/2009 prohibits the use of faeces and separated digestive tract content for insect production. Similarly, regulation (EC) No 1069/2009 considers insects as ‘farmed animals’ and thus does not allow manure, catering waste or former foodstuff that may contain meat and fish as feed. With regard to feeding insects to farmed animals, the so-called processed animal protein (PAP) is allowed for feeding aquaculture species but not in pig and poultry farming. The European Commission is aware of the need for action and changes are on the way. Before taking decision, however, regulatory bodies ask for data on topics such as biosafety, the fate of hazardous contaminants (e.g. heavy metals, hormones, micro-pollutants) or allergens (EFSA Scientific Committee 2015). Universities and research programs are about to fill the knowledge gap to help accelerate the modification of the regulatory framework. Certain research groups are close to disclosing results on the interactions of larvae with bacterial symbionts and its effect on life history traits, bioconversion ratio and waste reduction (e.g. Lee et al. 2014; Zheng et al. 2013). Besides the classic research questions on the fly’s biology and the use of the larvae as animal feed (e.g. Diener et al. 2015; Lalander et al. 2013, 2014, 2016), a closer collaboration between private companies and academia should be pursued as this is considered beneficial for a breakthrough of the BSF treatment technology.

3.2.4 Anaerobic digestion

Introduction Anaerobic digestion (AD), also referred to as biomethanization or biomethanation, is a robust, well-established engineered process to biochemically decompose both liquid and solid organic matter by various bacterial activities in an oxygen-free environment. The AD process occurs naturally in many anoxic environments, such as watercourses, soils, animal intestines, and landfills (Vögeli et al. 2014). The utilization of AD of biowaste originates thousands of years back when biogas was used in Assyrian bath houses for heating water (Suryawanshi et al. 2010). Historically, AD has mainly been associated with the treatment of sewage sludge from aerobic wastewater treatment and animal manure (Esposito et al. 2012). Over the years, the main fields of AD application shifted from municipal sewage sludge to liquid (mainly industrial) wastewater, then to the municipal organic fraction of solid waste and agricultural residues (Jimenez et al. 2015). While the first industrial scale digesters date back to the first half of the twentieth century, interest in AD of solid biowaste has rapidly increased since the energy crises of the 1970s (Cecchi and Cavinato 2015).

Input material A wide range of different biomasses can be used as substrates for biogas production. AD feedstock includes sewage sludge, animal manure, food industry waste (incl. slaughterhouse waste), energy crops and harvesting residues (incl. algae), and the organic fraction of municipal solid waste (Romero-Güiza et al. 2016). As AD typically occurs in an aqueous environment, feedstock with high moisture contents (even containing more than 60% water) can be processed without pre-treatment (Appels et al. 2011). Generally, strong lignified organic substances (e.g. wood) are not suitable for AD as such substances cannot be degraded by anaerobic microorganisms (Mata-Alvarez 2003). However, research on pre-treatment of lignocellulosic waste before AD is ongoing (Sawatdeenarunat et al. 2015). Extensive studies on AD feedstock include the use of food waste (Zhang et al. 2014), and fruit and vegetable waste (Bouallagui et al. 2005; Gunaseelan 2004). Co-digestion is increasingly being applied for simultaneous treatment of several solid and liquid organic wastes as a homogeneous mixture results in increasing process stability and performance (Esposito et al. 2012).

Conversion process The anaerobic biodegradation of complex organic matter to CH_4 and CO_2 consists of a series of microbial processes: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Fundamentals and kinetics of the AD process can be found in Mata-Alvarez (2003). Much is known about the basic metabolism in different types of AD processes, but knowledge on the microbes responsible for these processes is yet limited. A few percent of bacteria and archaea involved in AD have so far been isolated, but little is still known about the dynamics and interactions between these microorganisms (Weiland 2010). The key operational parameters of AD (e.g. temperature, pH, moisture, substrate, C/N ratio, loading rate, retention time, inoculation, stirring) and their influence on process stability and biogas yield and quality are described in Khalid et al. (2011) and Jain et al. (2015). One challenge in the conversion process of AD is to avoid acidification and inhibition of the methanogenic bacteria. Large amounts and high fraction of easy biodegradable organic matter in the feedstock for instance can result in a decreasing pH in the reactor and a larger production of volatile fatty acids, which stresses and inhibits the activity of methanogenic bacteria (Bouallagui et al. 2009). Typically this effect can be avoided by anaerobic co-digestion, which implies the addition of a buffering co-substrate (Mata-Alvarez et al. 2014). More on AD process inhibition due to ammonia, sulfide, light metal ions, heavy metals and other compounds is discussed in Chen et al. (2008), Zhao et al. (2010) and Yenigün and Demirel (2013). A review on the issue of instrumentation and process control can be found in Jimenez et al. (2015), on mathematical models for both simulation and control purposes in Lauwers et al. (2013), and on recent advances in the utilization of inorganic and biological additives to improve digester performance in Romero-Güiza et al. (2016).

The AD processes can be classified according to the reactor temperature (mesophilic, thermophilic), solids content (low- and high-solids concentration), feeding mode (batch, continuous fed), or the number of process steps (single- and multi-stage) (Hartmann and Ahring 2006; Kothari et al. 2014; Mao et al. 2015; Vögeli et al. 2014). Solid-state AD, or dry digestion [TS >15% (Ge et al. 2014)], has lately been in the center of research focus. The benefits of dry over wet AD include smaller reactor capacity requirements, lower energy inputs needed for heating and stirring, more effective performance at higher organic loading rates and higher volumetric biogas productivity, greater tolerance of feedstock impurities such as glass, plastics and grit and producing a compost-like digestate that is easier to handle than the effluent of wet AD (Brown and Li 2013; Brown et al. 2012; Kothari et al. 2014; Li et al. 2011c; Yang et al. 2015a). An overview of the different digester types is presented in Vandevivere et al. (2003) and Rajendran et al. (2012). The main types of AD systems in low- and middle-income settings are fixed-dome digester, floating-dome digester and tubular digester (Vögeli et al. 2014).

Products and uses The main products of AD are biogas and digestate. The biogas is formed through the conversion of the organic carbon of the feedstock into its most reduced form (methane, CH_4) and its most oxidized state (carbon dioxide, CO_2). Apart from CH_4 (55–60%) and CO_2 (35–40%), biogas also contains several other gaseous "impurities" such as hydrogen sulphide, nitrogen, oxygen and hydrogen (Cecchi et al. 2003). Methane is the biogas component mainly responsible for its typical lower heating value (LHV) of 21–24 MJ/m^3 or around 6 kWh/m^3 biogas (Bond and Templeton 2011). Biogas with a CH_4 content higher than 45% is flammable (Deublein and Steinhasuer 2009). Biogas yield of the individual substrates varies considerably, dependent on the feedstock origin, organic matter content and substrate composition. Fats provide the highest biogas yield, but require a long retention time due to their poor availability for the microorganisms. Carbohydrates and proteins show much faster conversion rates but lower gas yields (Weiland 2010). The average methane yield of solid organic waste is between 0.36 and 0.53 m^3/kg VS (Bouallagui et al. 2005; Khalid et al. 2011). The biochemical methane potential (BMP) of 54 fruits and vegetable wastes samples was determined by Gunaseelan (2004) and range from 0.18 to 0.732 L/g VS for fruit waste, and 0.19–0.4 L/g VS for vegetable waste.

Direct burning of biogas in stoves is the easiest way of taking advantage of biogas energy. Alternatively, biogas can be used in lamps or converted to electricity in gas generators. If biogas is valorized energetically in a combined heat and power installation for the simultaneous generation of heat and electricity, an electrical efficiency of 33% and a thermal efficiency of 45% can be achieved (Appels et al. 2011). Refining the biogas from an AD system is recommended when used in a gas-driven engine to produce electricity, and it is absolutely necessary for more novel applications like vehicle fuel and fuel cells. If properly upgraded, which includes dewatering, desulphurization, and removal of CO_2, the biogas can also be introduced in the natural gas grid (Appels et al. 2011). The main bottleneck of biogas utilization is that it cannot be stored over long periods at reasonable costs (Mata-Alvarez 2003). The critical temperature of CH_4 is around −82.5 °C, i.e. even with a very high pressure it is not possible to liquefy methane at higher temperature. If the final methanogenic steps of the AD process are fully inhibited, the resulting products of the process are volatile fatty acids (and carbon dioxide and hydrogen). As the organic acid stream can be concentrated or (bio-) converted to high-value end products, this research has lately received significant attention (Kleerebezem et al. 2015).

The produced slurry (digestate) is rich in nitrogen and, depending on the nature of the feedstock, and adequate crop-specific dilution, can be utilized in agriculture as a nutrient fertilizer and/or organic amendment (Groot and Bogdanski 2013; Möller and Müller 2012). The AD process is only partly able to inactivate weed seeds, bacteria (e.g. *Salmonella*, *Escherichia coli*, *Listeria*), viruses, fungi, and parasites, which is of great importance if the digestate is to be used as fertilizer. The decay rate of pathogens is dependent on temperature, treatment time, pH, and volatile fatty acids concentration, with temperature being the most important factor concerning pathogens reduction during AD. The best hygienization effect is obtained at thermophilic temperatures above 50 °C and long retention times, or with post-treatment of digestate, e.g. aerobic composting (Weiland 2010).

Critical review of challenges and trends in low- and middle-income settings The AD theory and technology is considered mature and well developed (Mao et al. 2015). Current global AD research comprises the identification of microbial community dynamics, extension of existing AD models by inclusion of microbial community data, further development and optimization of pre-treatment methods to enhance the anaerobic degradability, and upgrading and purification of the obtained biogas incl. its transformation into more value-added components (Appels et al. 2011; Krishania et al. 2013). The overall benefits of anaerobic digestion are manifold and fit well into the broader sustainability debate as it transforms waste into a renewable energy carrier, while at the same time also conserving plant nutrients. To unlock the full potential of AD products and by-products, the scientific, regulatory and socioeconomic barriers need to be tackled, which requires good interactions between scientists, regulators and end users (Riding et al. 2015).

In low- and middle-income settings, specifically with tropical climates, mesophilic anaerobic digestion has a high potential for biowaste treatment (Suryawanshi et al. 2010). While agricultural AD systems using manure as feedstock are widely implemented, urban

AD systems with biowaste as feedstock still exist only in limited numbers (Vögeli et al. 2014). It is well acknowledged that many AD projects in low- and middle-income settings face severe operational problems or have failed (Bond and Templeton 2011). Inappropriate technology selection, poor design and construction of digesters, inadequate operation, lack of ownership, responsibility and maintenance by operators, lack of project monitoring and follow-up by the promoters, lack of markets for biogas and digestate, and weak business models are some of the failure reasons (Bond and Templeton 2011; Parawira 2009). Thus prior to construction proper feasibility assessments are needed including the selection of AD systems that are technically, financially and environmentally appropriate for the local context (Lohri et al. 2013; Nzila et al. 2012). Once operation has started, special emphasis should be placed on operational support networks to ensure maintenance and repair of existing facilities (Bond and Templeton 2011). Promising research efforts have also gone into the development of an medium-size plug-flow digester appropriate for low- and middle income countries (Edelmann and Engeli 2015).

One of the bottlenecks of AD and respective gas use is the low energy density of biogas. This requires either continuous gas use at the site of production or transformation into a more easily transportable fuel. A line of research tackles the issues of upgrading, compression and bottling of biogas. The Indian Institute of Technology has successfully developed an automated biogas upgrading and bottling system to obtain biomethane of high purity (90–92% CH_4) with minimal gas losses. While the biogas purification is achieved by water scrubbing at ambient temperature (25 °C) using automated controls, the purified biogas is bottled by means of a high pressure compressor at 200 bar and filled in biogas operated car and three-wheeler using CNG (compressed natural gas) dispensing systems (Vijay et al. 2015). A different concept involves the autogenerative high pressure digestion (AHPD), where methanogenic biomass builds up pressure inside the reactor. Since CO_2 has a higher solubility than CH_4, it will at higher pressures proportionally more be dissolved in the liquid phase. AHPD biogas is thus characterized by a high CH_4 content, reaching equilibrium values between 90 and 95% at a pressure of 3–90 bar (Lindeboom et al. 2012).

3.2.5 Fermentation

Introduction Fermentation is the key process step in the production of bio-ethanol (ethyl alcohol, CH_3-CH_2OH or EtOH), the leading biofuel on the global market (Mussatto et al. 2010). Bio-ethanol/gasoline blends are promoted as an environmental-friendly, clean-burning fuel that reduces vehicle exhaust emissions (Balat and Balat 2009). Currently, about 820 million cars and light trucks are running with bio-ethanol (Sarris and Papanikolaou 2016). Bio-ethanol can be produced from several sugar-, starch-, and lignocellulose-based biomass sources by means of different conversion technologies. Currently, it is predominately produced from corn-derived (starch-based) feedstocks and from sugarcane-derived (saccharose-based) feedstocks. The USA (corn) and Brazil (sugarcane) are the two major ethanol producing countries, contributing 56.7 and 26.7% of the world production (Gupta and Verma 2015). However, bio-ethanol production from such edible (1st generation) feedstock has raised substantial concerns in regard to competition to food and feed. Non-edible lignocellulosic (2nd generation) feedstock derived from several waste streams is suggested as a sustainable alternative substrate (Vohra et al. 2014).

The first prototypes of internal combustion engines built in the nineteenth century were able to use ethanol as fuel (Mussatto et al. 2010). Henry Ford, whose first cars were capable of running exclusively on ethanol, even termed ethanol the "fuel of the future" (Vohra et al. 2014). As the production of ethanol became more expensive than petroleum-based fuel, its potential was largely ignored until the oil crisis of the 1970s (Balat and Balat 2009). Extensive research and novel commercial approaches for bio-ethanol production from low-grade lignocellulosic biomass have started only a few decades ago (Hahn-Hägerdal et al. 2006). Major attention is currently given to the development of efficient processes to use agricultural crop residues, hardwood, softwood, cellulose wastes, herbaceous biomass, and municipal solid waste (Zinoviev et al. 2010).

Input material Carbohydrate sources for bio-ethanol production can be divided into three major groups: (1) simple sugars (sucrose-containing) feedstocks: e.g. sugarcane, sugar beet, sweet sorghum, molasses and fruits, (2) starchy materials: grains, e.g. corn, wheat, barley, rice; root crops, e.g. potato, cassava, and (3) lignocellulosic biomass: e.g. woody materials, straw, agricultural waste and crop residues (Balat and Balat 2009; Mussatto et al. 2010). The first two groups are classified as 1st generation, edible feedstock, whereas the third group (lignocellulose) is described as 2nd generation, non-edible feedstock. Currently, about 40% of the global bio-ethanol production derive from sugar crops and nearly 60% for starch crops (Vohra et al. 2014). For lignocellulosic feedstock, the involved technologies are more complex and the costs of bio-ethanol production higher compared to sugar-cane, beet or corn feedstock. However, most ligno-cellulosic materials are by-products of agricultural activities and industrial residues, thus they are seen as main feedstock for ethanol production in the near future (Mussatto et al. 2010). Due to the complex nature of the lignocellulosic feedstock, numerous pre-treatment strategies have been developed to increase cellulose digestibility, such as physical treatment, chemical treatment (alkaline or acid), biological treatment, physicochemical treatment and thermo-chemical treatment (Alvira et al. 2010). Enzymatic hydrolysis is the most common pre-treatment method in ethanol production from food waste (Pham et al. 2015). Recently, even source-separated urban solid biowaste including kitchen waste, food waste, garden waste and fruit waste are being considered as suitable substrates for ethanol production (Gupta and Verma 2015; Liguori et al. 2013).

Conversion process Bio-ethanol production is usually performed in three steps, with an additional pretreatment step if lignocellulosic feedstock is used: (o) pre-treatment (delignification) to render cellulose and hemicellulose more accessible to the subsequent steps, (1) acid or enzymatic hydrolysis (saccharification) to break down polysaccharides to simple sugars, (2) fermentation of the sugars (hexoses and pentoses) to ethanol using microorganisms, mainly yeast, (3) separation and concentration of ethanol produced by distillation–rectification–dehydration (Vohra et al. 2014). The conversion can be performed as a batch process, fed-batch or continuous process, however, the fed-batch process is most widely used (Fodor and Klemeš 2012). The anaerobic fermentation reaction occurs at temperatures of 25–30 °C and lasts between 6 and 72 h depending on the composition of the hydrolysate, cell density, physiological activity and yeast species. The broth typically contains 8–14% ethanol on a volume basis. Above this concentration, inhibition of yeast activity may occur. The distillation step yields an azeotrope made up of 95.5% alcohol and 4.5% water, which is then dehydrated to obtain an 'anhydrous' ethanol containing up to 99.6% alcohol and 0.4% water (Vohra et al. 2014). The thermochemical/gasification and fermentation process is another relatively new technological conversion route (Balat and Balat 2009).

Products and uses The hypothetical ethanol yields from sugar and starch are superior compared to the yield from lignocelluloses agro-residues (Gupta and Verma 2015). An average energy content of 8.3–11.6 MJ/kg TS is estimated for ethanol produced from food waste based on 26.9 MJ/kg energy content of ethanol (Pham et al. 2015). In average one liter of ethanol contains 66% of the energy provided by one liter of petrol (Nigam and Singh 2011). Bio-ethanol can be used in blends from 5% (E5) to 100% (E100) with gasoline. The most popular blends are E85 (85% bioethanol, 15% gasoline), E20 (20% bioethanol, 80% gasoline) and E10 (10% bioethanol, 90% gasoline; also called gasohol in the US). The fuel mixtures up to E10 can be used in the internal combustion engines of modern automobiles and light-duty vehicles without modifications on the engine or fuel system. As the ethanol percentage in the blend increases some modifications are necessary, e.g. in the fuel injection system and in the evaporation system (Sarris and Papanikolaou 2016). Ethanol, which has a higher octane level and lower sulphur content compared to gasoline, improves the fuel combustion and thus the vehicle's performance, and shows reduced emissions of carbon monoxide, unburned hydrocarbons and sulphur oxide, a carcinogen and major component of acid rain (Nigam and Singh 2011). Ethanol can also be used in the transesterification process of vegetable oils for biodiesel production (Sarris and Papanikolaou 2016). By-products of the bioethanol production are thin stillage (the centrifuged, liquid, non-volatile components of the fermentation slurry) and condensed distillers solubles (thin stillage after evaporation). The latter can be dried to produce dried distillers grains with solubles, which can either be sold as animal feed or used for the production of lactic acid (Moon et al. 2014).

Critical review of challenges and trends in low- and middle-income settings While technologies to produce ethanol from sugar or starch are well established, technologies using 2nd generation biowastes are still under development all over the world (Mussatto et al. 2010). In India, for instance, many research groups have set up pilot plants to study the production of ethanol, but mature technologies for lignocellulosic bioethanol production are still lacking and processing costs are high (Sukumaran et al. 2010). Cost minimization of ethanol production is the prime objective of most research programs in general (Kumar et al. 2009b). Yet reaching financial feasibility with the current political and institutional set-up is particularly difficult in low- and middle-income countries. Supportive policy measures could help to enhance the competitiveness of bioethanol production.

Current biowaste fermentation research with regard to low- and middle-income settings primarily centers around assessment studies on the suitability of various waste types and bio-ethanol potentials of different countries, e.g. Pakistan: (Bhutto et al. 2015), Colombia: (Quintero et al. 2013), India: (Sukumaran et al. 2010), China: (Fang et al. 2010). In the African context, existing bioethanol plants are mostly concentrated in the Southern tip of the continent such as South Africa, Malawi, Swaziland, Mauritius, and Zimbabwe. Other commercial ethanol producing countries are Ethiopia and Kenya (Amigun et al. 2008). According to Sukumaran et al. (2010) one of the major difficulties faced by bio-ethanol technology developers as well as future entrepreneurs is the choice of feedstock. India, for instance, generates a huge amount of diverse agro- and forest wastes, but due to problems in collection and logistics only crop residues are considered a feasible feedstock. Yet also the availability of these crop residues is limited for bioethanol production as a major fraction is needed as feed and fuel in rural areas (Sukumaran et al. 2010).

On the way to cost-effective and competitive bioethanol production from lignocellulosic feedstock several challenges remain, such as developing more efficient pre-treatment technologies and integrating the optimal components into ethanol production systems (Chen and Fu 2016; Liguori et al. 2013). These challenges can be attributed to four aspects, which are (1) feedstock: obstacles are cost, supply and handling, (2) conversion technology: hindrances are biomass processing, proper and cost effective pre-treatment technology, (3) hydrolysis process: challenge is to achieve an efficient process for depolymerization of cellulose and hemicellulose to produce fermentable monomers with high concentration, and (4) fermentation configuration: challenges involved are xylose and glucose co-fermentation, and the use of recombinant microbial strains (Mussatto et al. 2010; Sarkar et al. 2012). Analyzed from an African perspective, Bensah et al. (2015) suggest that for commercial production of cellulosic ethanol research and development should highlight favorable pre-treatment methods such as extrusion, steaming/boiling, and chemical methods employing lime, KOH and crude glycerol (from biodiesel production), as well as the development of crude enzyme complexes from local materials. With the rationale of achieving significant reduction of the operating process costs an important innovation recently developed in biotechnological processes refers to the accomplishment of the bioprocess under completely non-aseptic conditions (Sarris and Papanikolaou 2016).

3.3 Physico-chemical treatment

Physico-chemical treatment summarizes conversion processes that are induced by chemical reactions or apply physical, mechanical force. The chemical process of transesterification for biodiesel production, and the physical densification process for the production of pellets and briquettes are included here. Transesterification for biodiesel production is only covered briefly in this review, given the liquid nature of the feedstock and thus limited applicability for urban solid wastes. Densification is applied to raw biowaste, as pre-treatment step for biomass pellet/briquette use in pyrolysis, gasification and combustion systems, and also in the post-processing step for char, the product of slow pyrolysis. The resulting char-briquettes are suitable for use as cooking fuel (Kaliyan and Morey 2010).

3.3.1 Transesterification

Introduction To obtain biodiesel, vegetable oils or animal fats are subjected to a chemical reaction termed transesterification, also called alcoholysis (Knothe et al. 2010). It entails a catalyzed reaction of oil or fat in the presence of alcohol to form fatty acid methyl esters (biodiesel) and glycerol (Bhuiya et al. 2016a, b).

The purpose of the transesterification process is to lower the viscosity of the oil or fat to enhance its suitability for diesel engines.

Input material In terms of urban biowaste, waste cooking oil, animal fats from slaughter houses, and grease from grease traps, typically collected in the septic tanks of restaurants, are potential feedstocks for biodiesel production (Canakci 2007; Park et al. 2010; Wang et al. 2008).

Conversion process To produce biodiesel, moisture-free vegetable oil is first pre-heated, then mixed with alcohol and a catalyst in a closed reactor to start transesterification. After a few hours under mechanical stirring, the mixture is allowed to settle at room temperature. The settled glycerol is then separated from the top crude biodiesel layer. Discussion on the variables affecting the transesterification, reaction kinetics and mechanisms and issues on analytical monitoring of the reaction can be found in Meher et al. (2006) and Verma and Sharma (2016). While smaller biodiesel production plants often use batch reactors, most larger plants (>4 million liters/year) use continuous flow processes involving continuous stirred-tank reactors or plug flow reactors (Gerpen 2005).

Products and uses Biodiesel is a yellowish liquid with an energy density of 38–45 MJ/kg (HHV), which is approximately 90% of that of petroleum-based diesel (Guo et al. 2015). It can be used in neat form or mixed with petroleum-based diesel. Glycerol, the by-product of transesterification has become an issue for biodiesel plants (Almeida et al. 2012; Leoneti et al. 2012). Several methods for valorizing glycerol have been studied, e.g. using it as feed ingredient for animal (Yang et al. 2012), converting it microbially to valuable chemicals using various bacteria, yeast, fungi, and microalgae (Li et al. 2013), using it as substrate or co-substrate in anaerobic digestion (Hutňan et al. 2013; Larsen et al. 2013), for ethanol production (Liu et al. 2012), or microbial fuel cells to generate electricity (Reiche and Kirkwood 2012).

Critical review of challenges and trends in low- and middle-income settings The scaling-up of biodiesel production from lab to industrial level remains difficult, mainly due to heat and mass transfer inefficiencies with current catalysts and operational set-ups (Baskar and Aiswarya 2016). Up-scaling also includes a shift from batch operations to continuous operated systems, entailing the major obstacle of requiring higher initial investment (Amigun et al. 2008). Biodiesel is currently more expensive to produce than petroleum-based diesel, which is one of the primary reasons preventing its more widespread use (Yaakob et al. 2013). Available literature shows that the costs of vegetable oils as feedstock of biodiesel represents 70–95% of the total production cost (Bhuiya et al. 2016a). Waste cooking oil is considered a more promising feedstock as it is 2–3 times cheaper than virgin vegetable oils in most countries (Bhuiya et al. 2016a). However, waste cooking oil also has some drawbacks, such as the high free fatty acid and high water content. To remove these impurities, drying and chemical pre-treatment is required, which considerably increases the biodiesel production cost (Yaakob et al. 2013).

In the low- and middle-income context, a major impediment to large-scale biodiesel production is feedstock availability. In Bali, for instance, a climate change mitigation project has been implemented which involves the conversion of used cooking oil into biodiesel to substitute fossil fuels. The main challenge was to obtain the amount of oil required to operate the transesterification process on a cost effective basis (Reckerzügl 2013). Recycled oil is the feedstock used for most biodiesel plants operating in Southern Africa, however, the existing market for waste oil and grease for use in soap and lubricant manufacturing makes the inconsistent cost and availability of this feedstock untenable for large-scale biodiesel production (Babajide et al. 2015). Due to this, most research on biodiesel implementation in low- and middle-income regions has focused primarily on the cultivation of feedstock oil crops. However, this stands in competition with land use for food crops cultivation and is therefore a questionable approach.

3.3.2 Densification

Introduction Densification involves the compaction of biomass by applying mechanical force or sometimes binding agents to create inter-particle cohesion, resulting in homogenous briquettes or pellets with consistent shapes and sizes, and bulk densities ranging from 450 to 700 kg/m^3 (Kaliyan and Morey 2010; Karkania et al. 2012). Densification helps overcome the challenges of dealing with lignocellulosic biomass residues, which are characterized by low bulk density, low heating value per unit volume, high dust level, and a wide range of physical shapes. Increasing bulk density facilitates easier handling, reduces storage and transportation costs, and the improved consistent physical properties improve fuel quality and make the densified biomass suitable for many residential and industrial applications (Tumuluru et al. 2011).

Densification typically follows the century-old mature technology of coal briquetting (Demirbas and Sahin-Demirbas 2004). In India, the briquetting industry started in the early 1980s with the introduction of low density and high density technologies. While the former technology requires pyrolysis of the biomass followed by briquetting using a binder, high density briquetting technology compacts the biomass and holds the structure together without a binder. Europe and the US have pursued and perfected the reciprocating ram and piston press to achieve this, while Japan has independently invented and developed the screw press technology in 1945 (Grover and Mishra 1996).

Input material Biowaste used for densification can be divided in two types of lignocellulosic residues: crop wastes and agro-industrial residues. Crop wastes include the residues which remain in the field after harvesting, for instance, paddy straw, bean straw, soya straw, maize straw and wheat straw. Agro-industrial residues on the other hand are generated during the processing of crops or logwood, and include rice husk, coffee husk and soybean husk, bagasse, sawdust and other wood processing products (Felfli et al. 2011). Other lignocellulosic wastes (e.g. groundnut shells, mustard stalks, cotton stalks, coconut fibers, palm fruit fibers) have also been researched as suitable feedstocks, as well as urban solid biowastes such as leaves, grass, tree trimmings and waste paper (Carone et al. 2011; Demirbas and Sahin-Demirbas 2004; Manickam et al. 2006; Yank et al. 2016). For waste to be densified, moisture content should be as low as possible, generally in the range of 10–15% (Chen et al. 2009; Felfli et al. 2011). Pre-treatment steps can include grinding, drying/pre-heating, torrefaction, and slow or wet pyrolysis (Liu et al. 2014; Tumuluru et al. 2011).

Conversion process A typical biomass densification process comprises drying, grinding, pelletizing or briquetting, cooling, screening, bagging, storage and delivery (Karkania et al. 2012). Common biomass densification systems have been adapted from other processing industries like feed, food, and pharmaceuticals (Tumuluru et al. 2011). Conventional processes for biomass densification can be classified into three types according to their working principle: extrusion, pelletizing, and roll briquetting. In an extruder, the raw material is conveyed and compressed by a screw or a piston through a die to form small cylindrical shapes (Li and Liu 2000). A pelletizer (or pellet mill) consists of a perforated hard steel die with one or two rollers with cylindrical shaped press channels. By rotating the die and/or rollers, the feedstock is forced through the channels to form densified pellets. Heat is generated from the high friction between the biomass and the press channel walls (Stelte et al. 2011b). In a briquetting roller press, the feedstock falls in between two rollers rotating in opposite direction and is compacted into pillow-shaped briquettes (Li and Liu 2000). Briquetting machines can handle larger-sized particles and higher moisture contents without the addition of binders compared to pelletizers (Tumuluru et al. 2011). Most producers preheat the biomass to form stable and dense pellets or briquettes. This also significantly increases the throughput of the pelletizing machine and reduces the energy requirement per kg of the biomass pellets formed (Li and Liu 2000). The density and mechanical strength of the resulting biomass is affected by many factors including the type of densification equipment, the applied compression force and temperature, the particle size, moisture content and chemical composition of biomass feedstock, and the use and type of binding materials (Manickam et al. 2006; Rhén et al. 2005; Stelte et al. 2011a). Lignin in biomass can serve as a natural binder when the pelletizing temperature is higher than the lignin's phase transition temperature (140 °C). Protein content also plays a major role as a binding agent between different particles during compaction (Chen et al. 2009; Liu et al. 2014). Stelte et al. (2011b) and Kaliyan and Morey (2010) have studied the binding mechanisms in briquettes and pellets. Studies have reported briquette production at modest pressures of 5–7 MPa (Chin and Siddiqui 2000; Yank et al. 2016), and pellet production using medium pressure of 46–114 MPa (Rhén et al. 2005), and high pressure of 170–180 MPa (Carone et al. 2011). In addition to these mechanized densification technologies for higher capacity operations, several low-tech, non-automated small-scale briquetting technologies, such as hand presses or molds, exist (Ferguson 2012; GVEP 2010; Njenga et al. 2009).

Products and uses A pellet has uniform product characteristics in terms of size (length: <35 mm, diameter: <10 mm), shape (cylindrical), and unit densities (1000–1400 kg/m^3). Briquettes have other properties, larger sizes (typically 40 × 40-mm cylinders) or a particular size range (length: 75–300 mm, diameter: 50–90 mm), and unit densities in the range of 800–1000 kg/m^3 (Nunes et al. 2014; Stelte et al. 2011a; Tumuluru et al. 2011). Physical quality attributes describing densified biomass include moisture content, unit and bulk density, durability index, percent fines, and heating value. The standards for densified biomass application as a solid fuel in the USA are given by the Pellet Fuels Institute and in Europe by the European Committee for Standardization (Karkania et al. 2012; Tumuluru et al. 2011).

Briquettes and pellets can theoretically both be used for domestic heating, cooking and as industrial fuel, thereby replacing wood-based fuels and fossil fuels. Roy and Corscadden (2012) investigated the potential of burning hay and switch grass briquettes in domestic stoves and compared their performance and emissions to commercially available wood briquettes. The average HHV of grassy briquettes (17.0 MJ/kg) and overall combustion efficiency (74.6%) were found to be comparable to that of woody briquettes (HHV: 17.9 MJ/kg; combustion efficiency: 74.2%). Grassy briquettes showed lower CO emissions, higher NO_x emissions and similar SO_2 and particular matter emissions in comparison to woody briquettes. Overall, Roy and Corscadden (2012) concluded that hay and grass briquettes can successfully be used in domestic wood stoves with similar or better performance and emissions compared to a range of biomass briquettes available in the market.

Critical review of challenges and trends in low- and middle-income settings Densification of biomass has been in practice for a long time and is considered a robust and mature technology. However, some research gaps still need to be addressed to fully understand the interaction of feedstock, process variables, and pre-treatment methods on the quality of the densified biomass (Tumuluru et al. 2011). Densification is particularly suitable for lignocellulosic biowaste, thus often practiced in the rural, agricultural context, where it stands in competition with the use for animal fodder and soil amendment. For mixed biomass pellets, the availability of a sales market, and not of the biomass resource, is considered to be the most critical factor (Karkania et al. 2012). Overall, current research mainly focuses on feedstock suitability and end-use of the densified products. For efficient and safe combustion of pellets without harmful emissions, households need to use appropriate equipment and ensure adequate operation. Considerable efforts have gone into promotion of improved cooking stoves (UNF 2016) to enhance indoor air quality (Bruce et al. 2015; WHO 2014). On household level, top-lit updraft (TLUD) semi-gasifier stoves, which can be fed with densified biomass, are a promising alternative to traditional stoves (Roth 2014). They are increasingly being researched as they have shown to be the lowest-emitting type of solid biomass cookstoves (Jetter et al. 2012; Tryner et al. 2014). These efforts might further increase the potential of the urban biowaste densification technology. On industrial level, combustion of pellets and briquettes are also feasible, however, legal and institutional frameworks and standards are required to guarantee efficient and safe combustion.

One of the advantages of the densification technology is its flexibility to be operated at a wide range of scales, from manual, low-cost production up to sophisticated, high-throughput systems. Although locally produced briquettes are an attractive energy carrier for individual consumers in different parts of the world, especially in low- and middle-income settings (Stolarski et al. 2013), briquetting technology has yet to get a strong foothold in these countries because of the technical constraints involved and the lack of knowledge to adapt the technology to suit local conditions (Alade and Betiku 2014). In China, for instance, the main drawback of the biomass densification (screw-, piston- and roller-press) technologies is the high energy consumption along with severe wear and short working life of the main components. This increases the biomass fuel cost and contributes to the difficulty in increasing the popularity of the densification technology (Cui et al. 2014). However, research and development of biomass briquetting technology was one of the key projects within China's Eleventh Five-Year Plan (2006–2010). The objectives of this project were (1) to investigate the effect of preprocessing on densified biomass properties, (2) to explore the binding mechanism of biomass densification, (3) to develop briquetting technology which can process a wide range of biomass material, (4) to develop briquetting device with high productivity and low energy consumption, (5) to establish demonstration projects of densified biofuel (3000 tons/year) using agro-forest residues as raw materials (Chen et al. 2009). The biomass briquetting industries and their perspectives are also being studied in other countries such as Nigeria (Alade and Betiku 2014), Kenya (GVEP 2010), Uganda (Ferguson 2012; Okello et al. 2013) and Brazil (Felfli et al. 2011), indicating a growing interest in this technology and the corresponding sector.

3.4 Thermochemical treatment

Thermochemical conversion processes apply heat to induce chemical reactions as a means of extracting and creating energy carriers as products. These processes include combustion, pyrolysis, liquefaction and gasification. Each of these differs in terms of temperature, heating rate, and the oxygen level present during the process. Direct combustion of raw waste is not covered here as it has been described in Sect. 3.1.3 as part of the biowaste treatment category 'Direct use'. The energy stored in biomass can be directly released as heat via combustion, or can be transformed into solid (e.g. charcoal), liquid (e.g. bio-oils), or gaseous (e.g. syngas) fuels via pyrolysis, liquefaction, or gasification with various utilization purposes (Zhang et al. 2010b). Thermochemical conversion processes proceed faster than biochemical processes, but require substantial energy input.

3.4.1 Pyrolysis

Introduction Pyrolysis entails the decomposition of biomass by heat in the absence of oxygen ($\lambda = 0$), resulting in the production of solid, liquid and gaseous products. In principle, there are two main types of dry pyrolysis techniques, named according to their heating rate: slow pyrolysis, where the main output is a solid product called char, and fast pyrolysis with bio-oil as the main product. Other sub-types of pyrolysis also exist such as intermediate, flash, ultra and vacuum pyrolysis, which differ in their residence time, heating rate, temperature and major products produced (Mohan et al. 2006; Vamvuka 2011). Slow pyrolysis involves heating biomass for hours to days and has traditionally been used in earth pit/mound kilns for the conversion of wood into charcoal. Fast pyrolysis is characterized by high heating rates and rapid condensation of the vapors in a continuous flow system with the main goal to produce bio-oil (Tripathi et al. 2016) (see Table 2). Torrefaction is a mild form (lower temperature) of pyrolysis (Ciolkosz and Wallace 2011; Eseyin et al. 2015; van der Stelt et al. 2011). Studies on pyrolysis for treating a mixed fraction of municipal solid waste requires a technically more sophisticated system which are discussed in Chen et al. (2015). A growing body of literature is available covering wet pyrolysis (or hydrothermal carbonization, HTC) where the main products is char (Funke and Ziegler 2010; Kambo and Dutta 2015; Libra et al. 2011).

The pyrolysis technology dates back thousands of years when it was used for charcoal production (Jahirul et al. 2012). In the 'Bronze Age' 5000 years ago, humans started using charcoal in metallurgy to obtain the temperatures necessary to smelt ores for copper and iron (Guo et al. 2015). Pyrolysis has also been used to produce tar for sealing boats and for embalming purposes in ancient Egypt (Jahirul et al. 2012). The modern petrochemical industry owes a great deal to the invention of the fast pyrolysis process for kerosene production in the mid-1840s (Basu 2013). Today, charcoal is still one of the primary cooking

Table 2 Typical feedstock requirements, operating conditions and product yields (dry basis) of slow and fast pyrolysis (adapted from Duku et al. 2011; Tripathi et al. 2016; Vamvuka 2011)

	Feedstock	Operating conditions			Product yield (wood pyrolysis)		
	Particle size	Residence time	Heating rate	Temp. (°C)	Solid (%)	Liquid	Gas (%)
Slow pyrolysis	Medium (cm to logs)	Minutes to days	Low (0.1–1 K/s)	300–500	35	30% bio-oil (70% water)	35
Fast pyrolysis	Small (<1 mm)	Seconds	High (10–200 K/s)	400–650	12	75% bio-oil (25% water)	13

fuels in many low- and middle-income settings, with 80–90% of urban households in sub-Saharan Africa depending on it (Lohri et al. 2016). Apart from cooking, charcoal is used for heating, air and water purification, in industrial processes requiring heat, and as soil amendment (Guo et al. 2015). Pyrolysis with a focus on high oil yield is a relatively new 're-discovery' since it was recognized in the 1980s that fast pyrolysis is a good alternative to the expensive hydrocracking technology (Vamvuka 2011). Over the last two decades, fundamental research has been conducted on fast pyrolysis using carbonaceous feedstock and the use of its liquid product as fuels and chemicals (Mohan et al. 2006).

Input material Common feedstock characteristic requirements for both slow and fast pyrolysis processes are: dry, unmixed, homogeneous, uncontaminated substrate, preferably with high carbon and low ash content, available at no or low costs. Other feedstock that might not meet these requirements can also be pyrolyzed if a pre-treatment step is added. For instance drying of feedstock to a moisture content of 10–15% is usually required unless the substrate is a naturally dry material such as straw (Bridgwater 1999; Isahak et al. 2012). High moisture contents result in large amounts of energy losses as every kilogram of water in biomass requires 2.26 MJ for vaporization (Basu 2010). In addition, the biomass feedstock frequently requires some form of pre-treatment to evenly destruct the lignocellulosic structure and enhance pyrolysis efficiency (Kan et al. 2016). The feedstock particle size has a major influence on the heating rate and yields (Isahak et al. 2012). In theory, virtually any form of biomass can be considered for pyrolysis. In the urban solid waste context, lignocellulosic waste from carpentries and saw mills, park and garden waste (trimmings/pruning), paper and cardboard waste are suitable for pyrolysis. Wood remains the substance most extensively studied given its uniformity that allows comparability among tests. For fast pyrolysis, nearly 100 types of biomass have been tested, ranging from agricultural wastes to energy crops, forestry wastes and other solid wastes, including sewage sludge and leather wastes (Mohan et al. 2006; Yaman 2004). To select suitable waste types as feedstock for slow pyrolysis, simple assessment tools have been developed with criteria such as feedstock, market, technology selection and production cost selection (Biomass Technology Group 2013), or availability/accessibility criteria and physico-chemical properties (Lohri et al. 2016).

Conversion process The exact decomposition mechanism and reaction scheme for the conversion of most biomass types into gaseous, liquid, and solid fractions are not fully understood due to the complexity of the process, the many intermediate products that are produced, and the variation in composition of biomass feedstock (Babu 2008; Burhenne et al. 2013). A large number of reactions take place in parallel and series, including dehydration, depolymerization, isomerization, aromatization, decarboxylation, and charring (Kan et al. 2016). From a thermal standpoint, the pyrolysis process can be divided into four stages, which partly overlap (Basu 2013).

1. Drying (ca. 100 °C): The biomass is heated at low temperature and releases moisture and loosely bound water through evaporation.
2. Initial stage (ca. 100–300 °C): Exothermic dehydration of the biomass takes place during the torrefaction stage with the release of water and low-molecular-weight gases like CO and CO_2.
3. Intermediate stage (>200 °C): Primary pyrolysis takes place in the temperature range of 200–600 °C. Most of the vapor or precursor to bio-oil is produced at this stage. Large molecules of biomass particles decompose into (primary) char, condensable gases (vapors and precursors of the liquid yield), and non-condensable gases.
4. Final stage (ca. 300–900 °C): The final stage of pyrolysis above 300 °C involves secondary cracking of volatiles into char and non-condensable gases. If they reside in the biomass long enough, relatively large-molecular-weight condensable gases can crack, yielding additional (secondary) char and gases. Fast pyrolysis involves the quick removal and rapid quenching of the condensable gases at the end of the process to terminate the secondary conversion process and results in higher bio-oil yield.

The typical operating conditions of slow and fast pyrolysis were shown in Table 2. Many researchers have studied the influence of operating conditions on product yields and it is generally accepted that the process parameters which most influence product distribution are temperature, heating rate, residence time and reactor pressure. Particle size, shape and physical properties (ash content, density, moisture content, etc.), and the chemical composition of the biomass, which is constituted by three main polymers (i.e. cellulose, hemicelluloses and lignin), also play an important role (Lohri et al. 2016). Discussion of the pyrolysis conversion steps of the aforementioned polymers can be found in Collard and Blin (2014), information about tar reduction in Han and Kim (2008). For slow pyrolysis, the effect of process parameters on production of char are discussed in Tripathi et al. (2016), the effect of processing parameters during fast pyrolysis on liquid oil yield in Akhtar and Amin (2012), whereas discussion of the kinetics of pyrolysis is found in Babu (2008), and of reactor types in Meyer et al. (2011), Isahak et al. (2012) and Jahirul et al. (2012).

Products and uses The relative amounts of the main products of pyrolysis, char (the black, solid residue), bio-oil (the brown vapor condensate), and syngas (the non-condensable vapor), depend on several factors including the heating rate, peak temperature and residence time (Basu 2013; Guo et al. 2015) as shown in Table 2.

Char Char has received increasing attention due to its suitability for several applications (Nanda et al. 2016; Qian et al. 2015; Xie et al. 2015), which include the use as a solid fuel (Lohri et al. 2016), soil amendment (bio-char) (Ennis et al. 2012; Lehmann et al. 2011; Tang et al. 2013; Xu et al. 2012), or precursor for making catalysts and contaminant adsorbents (Inyang and Dickenson 2015; Manyà 2012; Mohan et al. 2014; Tan et al. 2015). As discussed above, the feedstock type and pyrolysis operating conditions influences the physical, chemical, and mechanical properties of chars which in turn have an effect on the potential to utilize char for the various applications (Kan et al. 2016; Qian et al. 2015). Waste-derived char needs further processing (densification) into charcoal-briquettes and can then be used for household cooking as alternative to wood-based charcoal (Mwampamba et al. 2013). Higher heating value of char is reported to be between 20 and 36 MJ/kg (Kan et al. 2016; Lohri et al. 2015; Vamvuka 2011). Char can contain 15–45% (by mass) of volatile matter, which facilitates the ignition of the char, but at the same time emits more visible smoke. In comparison a good-quality commercial charcoal can have a net volatile matter content (moisture free) of about 30% (Lohri et al. 2016; Vamvuka 2011).

Bio-oil The liquid pyrolysis product is known as bio-oil, pyrolysis oil, bio-crude oil, wood oil, wood distillates, pyroligneous acid, liquid wood and liquid smoke (Mohan et al. 2006). It is typically of dark red-brown to almost black color, has a distinctive acid, smoky smell, and can irritate the eyes (Venderbosch and Prins 2010). Bio-oils are a complex mixture of water and organic chemicals with more than 300 identified compounds. Due to the high moisture content and acid content, crude pyrolysis bio-oil is instable, corrosive, viscous, low in energy density, and difficult to ignite (Guo et al. 2015). Because of the presence of large amounts of oxygenated components, the oil has a polar nature and does not mix readily with hydrocarbons. The high water content, typically 15–35 wt% which cannot be removed by conventional methods like distillation, is a serious drawback in terms of the heating values: the higher heating value (HHV) is between 15 and 20 MJ/kg (Basu 2013; Kan et al. 2016; Venderbosch and Prins 2010). Bio-oils have been extensively tested as combustion fuels for electricity and heat production in boilers, furnaces, and combustors, diesel engines, and gas turbines, or they alternatively can be upgraded to produce bulk chemicals (Isahak et al. 2012; Kan et al. 2016). Due to the undesired properties (Xiu and Shahbazi 2012), it is essential to chemically upgrade bio-oil, i.e. reduce volatility, increase thermal stability, reduce viscosity through oxygen removal and molecular weight reduction to make it useful as transportation fuel (Jacobson et al. 2013). Reduction and control of the oxygen functionalities should be the ultimate goal instead of the reduction in oxygen content itself (Venderbosch and Prins 2010). Upgrading of bio-oil has extensively been researched (Gollakota et al. 2016; Jacobson et al. 2013; Xiu and Shahbazi 2012; Zhang et al. 2013; Zhang et al. 2007). More challenges related to bio-oil are discussed in Bridgwater (2013).

Gas The pyrolysis gas contains carbon dioxide, carbon monoxide, methane, hydrogen, ethane, ethylene, minor amounts of higher gaseous organics and water vapor (Vamvuka 2011). The typical LHVs of the pyrolytic gases range between 10 and 20 MJ/Nm^3 (Basu 2013; Kan et al. 2016). The pyrolysis gas has multiple potential applications, such as direct use for production of heat or electricity, either directly or co-fired with coal, production of individual gas components, including CH_4, H_2 or other volatiles, or in production of liquid bio-fuels through synthesis. In some applications, the hot pyrolytic gas can be used to preheat the inert sweeping gas or can be returned to the pyrolysis reactor as a carrier gas (Kan et al. 2016).

Critical review of challenges and trends in low- and middle-income settings Due to the lower process complexity (hence lower investment costs) and the high demand for cooking fuel such as charcoal and char-briquettes, slow pyrolysis and the production of char has received more attention in the low- and middle-income settings context compared to fast pyrolysis. Low-tech slow pyrolysis systems were mainly designed for carbonization of wood logs, thus need to be adapted for biowaste as alternative feedstock. It is further recommended to measure and critically evaluate the emissions, which are released during the carbonization process, including critical pollutants and products of incomplete combustion (PICs) such as carbon monoxide (CO), polycyclic aromatic hydrocarbons (PAHs) and particulate matter (Lohri et al. 2015). Apart from these environmental and public health risks, further challenges include socio-economic barriers, negative perceptions and attitudes towards (bio)char, and a lack of finance, empirical data and supportive policy framework. These constraints have been reported in the context of Ghana (Duku et al. 2011), sub-Saharan Africa (Gwenzi et al. 2015) and in general (Manyà 2012). Similarly, Murugan and Gu (2015) highlight the R&D pyrolysis activities in India over the last three decades and conclude that enhancing the quality of pyrolysis products for better marketability, use and safety, and minimizing process energy input and losses are the points that require major further attention on the path towards commercialization. An efficient, environmental friendly and thus much-noticed low-cost kiln-retort system (called Adam-retort) was developed for carbonization of biomass waste (Adam 2009). It has been further optimized and implemented in various low- and middle income countries (Adam 2013; Adam 2014). However, it is generally acknowledged that continuous feeding in contrast to batch operation is not only recommended for facilitation of emission treatment, but also for enhanced energy efficiency (Lohri et al. 2016). A promising continuous operating semi-automated biomass pyrolysis system has been developed by the Center of Appropriate Technology and Social Ecology (CATSE) of Ökozentrum Langenbruck and is also being constructed and tested in Vietnam. This system, initially designed for wet coffee pulp, but also successfully tested using other feedstocks with water content of up to 55%, can treat approximately 50 kg/h biowaste. The system is characterized by a high energy efficiency, partly due to a lambda sensor controlled FLOX® burner, and very low emissions (Schmid et al. 2015).

In terms of fast pyrolysis, several fundamental research challenges still need to be overcome to facilitate commercialization (Bridgwater 2013; Jahirul et al. 2012; Mettler et al. 2012; Venderbosch and Prins 2010). These challenges, which partly also apply for slow pyrolysis, comprise (1) improving the operational reliability of demonstration scale pyrolysis reactors and processes, (2) achieving feedstock flexibility (accepting all kinds of biomass residues, instead of only wood), (3) increasing the heat transfer to the pyrolysis reactor and transfer from the char combustor, and (4) improving the process heat integration and its control. R&D should be directed to improving the quality (and stability) of the resulting oil depending on the end-application envisaged. The poor quality and undesirable properties of bio-oil imply the need of high cost upgrading efforts and hinder the use of bio-oil as a substitute for petroleum-based fuel (Jacobson et al. 2013). Thus novel integrated refinery processes are required to systematically upgrade bio-oils into transportation fuels that have desirable qualities, while producing other value-added co-products to make the process economically feasible (Xiu and Shahbazi 2012).

3.4.2 Liquefaction

Introduction Hydrothermal liquefaction (HTL), also known as direct liquefaction, implies processing of biomass in a hot, highly pressurized water environment for sufficient time to break down the solid biopolymeric structure into mainly liquid components called bio-oil or bio-crude (Elliott 2011; Elliott et al. 2015; Peterson et al. 2008). Water is an important reactant and catalyst, and thus wet biomass can be directly converted without an energy consuming drying step (Arturi et al. 2016; Toor et al. 2011; Xue et al. 2016). The thermochemical processes of HTL and fast pyrolysis are sometimes confused with each other as both can convert feedstock organic compounds into liquid products. Demirbaş (2000) and Doassans-Carrère et al. (2014) compare these two technologies in terms of operating conditions, products yields and characteristics.

Direct biomass liquefaction applied to coal has been an active research topic since the first Arab oil embargo in the 1970s (Elliott 2011). Low oil prices influences the research characterized by rather short-term projects, a lack of cooperation and exchange of knowledge, and problems finding capital for commercial size plants (Toor et al. 2011).

Input material The nature of the process allows processing of feedstock with high moisture content. Thus any wet biomass, including complex mixtures of lignocellulose, protein and fats, can be converted into bio-oil through HTL (Arturi et al. 2016). Therefore, many types of urban biowaste such as kitchen, market and garden wastes are theoretically suitable for HTL. Publications report liquefaction of wood, forest and agricultural residues, urban biowastes, sewage sludge, manure, and algae (Ramirez et al. 2015). Lignocellulosic and algal biomass are the most commonly used feedstock types, with cellulose exhibiting higher bio-oil conversion than lignin (Xue et al. 2016). HTL of 18 types of Indonesian agricultural and forest residues was reported in Minowa et al. (1998), producing bio-oil with a heating value comparable to high rank coal and revealing a positive energy balance.

Conversion process Hydrothermal liquefaction is a conversion process occurring in a liquid phase at temperatures of 280–370 °C and pressures between 7 and 30 MPa (Peterson et al. 2008). The high temperature is needed to initiate pyrolytic mechanisms in the bio-polymers, and the pressure has to be high enough to maintain a liquid water processing phase (Elliott 2011). HTL exploits the properties of superheated fluids to reduce mass transfer resistances, whereas the high pressure enables higher penetration of the solvent into the biomass structure to facilitate fragmentation of biomass molecules (Ramirez et al. 2015). Biomass is broken down into fragments of light molecules and these unstable and active light fragments are subsequently re-polymerized into heavier oily compounds. Hydrogen and organic solvents are often added into the reaction system (Demirbaş 2000) to prevent undesired side reactions of intermediate products and heavy solid char formation during re-polymerization. A significant amount of research and development on catalytic methods for HTL has been undertaken (Elliott et al. 2015). Catalysts (e.g. alkaline hydroxides and carbonates) lower the amount of solid residue and improve the yield of bio-oils (Srirangan et al. 2012). Akhtar and Amin (2011) and Xue et al. (2016) discuss the influence of operating parameters such as biomass type, biomass/H_2O ratio, particle size, reaction temperature, heating rate, solvent density, pressure, residence time, catalysts and reducing gas/hydrogen donors on bio-oil yield and quality.

Products and uses HTL products are typically a two-phase mixture of bio-oil (bio-crude) and process water with suspended char particles, and small amounts of synthesis gas (Arturi et al. 2016). Almost all of these gaseous-, aqueous-, and solid-phase by-products can be utilized in the field of advanced carbon materials, chemicals, or as fuel for the transportation industry (Xue et al. 2016). HTL bio-oil is semi-liquid, dark-colored and has a smoke-like smell (Ramirez et al. 2015). To lower the bio-oil's viscosity, organic solvents (e.g. propanol, butanol, acetone, methyl ethyl ketone and ethyl acetate) need to be added to the reaction system. All these solvents, except ethyl acetate, may be produced from wood during liquefaction, suggesting that the solvent can be recovered for reuse (Demirbaş 2000). In addition to carbon, hydrogen and oxygen content, the HTL-generated bio-oil contains both nitrogen and sulfur, depending on the composition of the biomass substrate. The energy density in the bio-oil ranges between 30 and 37 MJ/kg and can be directly used as a heavy fuel oil (Toor et al. 2011). Bio-oil, however, still contains 10–20% of oxygen (Peterson et al. 2008), making it more polar than crude oil. This causes a number of disadvantages, such as a relatively high water content, corrosive properties, and thermal instability etc. The oil product can be upgraded through catalytic hydro-processing, primarily to remove oxygen (Elliott 2011; Toor et al. 2011) but this will increase production costs. A review of the available upgrading technologies and how they can be used to convert HTL bio-crude into a transportation fuel that meets current fuel property standards can be found in Ramirez et al. (2015).

Critical review of challenges and trends in low- and middle-income settings Technological advances in hydrothermal liquefaction of biomass are still in their infancy (Srirangan et al. 2012). The low level of technology maturity is underlined by the fact that HTL has only been demonstrated at lab- or bench-scale for short time periods (Lee et al. 2016; Toor et al. 2011). Numerous research gaps still exist in terms of the technology development, the influence of the input material, and the upgrading of the bio-oil. Several authors present a number of critical issues hindering commercialization (e.g. reactor corrosion, precipitation of inorganic salts, coking and deactivation of heterogeneous catalysts), which all need to be resolved before hydrothermal technologies can be piloted and ultimately scaled up (Peterson et al. 2008; Tran 2016). Challenges regarding feedstock and upgrading of bio-oil include questions about decomposition of lignin in the HTL process, as well as the challenge of high oxygen and nitrogen levels in the bio-oil (Xue et al. 2016). Although technologies for the upgrading of the bio-crude exist, applications of these techniques are limited by economic considerations (Lee et al. 2016). Moreover, the overall economic feasibility of HTL is uncertain due to the high cost associated with the complex reactor and feeding system (Srirangan et al. 2012). Different technological approaches are mentioned in literature to solve the remaining challenges, but none of them have proven their technical and financial feasibility on scale (Behrendt et al. 2008; Tran 2016).

One major bottlenecks for commercialization of hydrothermal technologies in general and specifically HTL application in low- and middle-income settings is the high pressure needed for processing. This demands special reactor and separator designs and thus requires substantial capital investments for full-scale plants (Peterson et al. 2008). Such high pressures furthermore present a significant safety issue. From a technical, financial, and safety perspective, HTL is currently considered an unsuitable biowaste treatment technology for low- and middle-income settings.

3.4.3 *Gasification*

Introduction Gasification is a thermal treatment that converts carbonaceous material into a gas (producer gas, synthesis gas or syngas), which can be used as fuel or for the production of value-added chemicals. The main difference between the two closely related thermochemical processes of gasification and combustion is that gasification packs energy into chemical bonds in the gas by adding hydrogen (H_2) and stripping away carbon (C) from the feedstock, whereas combustion oxidizes the H_2 and C of the feedstock into water and carbon dioxide, thus breaking those bonds to release the energy (Basu 2010).

The basic principles of biomass gasification have been known since the late eighteenth century. By 1850 an established industry had emerged using 'heat gasifiers' to make gas mainly from coal and biomass fuels, to supply the town gas lights. By the 1920s, producer gas systems for operating stationary engines as well as trucks, tractors, and automobiles were demonstrated in Europe and elsewhere, but they failed to gain widespread acceptance because of their inconvenience and unreliability (Strassen 1995). Due to an acute shortage in liquid fuels a revival of small-scale gasification was seen during World War II (Kirkels and Verbong 2011). More recently, the disruption of oil supply and high oil prices in the 1970s have played a major role in the renewed interest for biomass gasification. Waste gasification has been applied in Japan since 1997, where the shortage of landfill space and the policy to avoid incineration and dioxin emissions have been the main drivers.

Input material Similar to other thermochemical conversion processes that do not take place in a liquid medium, gasification also requires dry biomass with moisture contents between 10 and 20% as feedstock. Biomass with higher moisture content must be dried before gasification (Ahmad et al. 2016). Other pretreatment steps comprise homogenizing the biomass feedstock in size and composition (Kumar et al. 2009a; Molino et al. 2016). The most prevailing feedstock considered for biomass gasification is wood. But also peat, black liquor (a by-product of the paper industry) and rice husk, particularly in Asia, have been gasified (Kirkels and Verbong 2011). Contrary to biomass gasification that comprises conversion of pure, source separated organic material (e.g. trimmings, pruning, leaves of urban park and garden waste), gasification has also been applied to mixed municipal solid waste (Arena 2012; Couto et al. 2015).

Conversion process The gasification process consists of a complex thermal and chemical process that converts organic matter into a gaseous product under oxygen-deficient conditions and temperatures between 750 and 1000 °C (Fodor and Klemeš 2012). Only limited air, oxygen or steam is supplied to the reaction as an oxidizing agent ($\lambda = 0.2$–0.5). The influence of operating parameters (e.g. residence time, reaction temperature, pressure, type and amount of oxidizing agents and catalysts) on gasification product yield and quality is described in Kumar et al. (2009a), Ruiz et al. (2013) and Ahmad et al. (2016). Broadly speaking, typical biomass gasification involves the following, overlapping stages (Balat 2009; Basu 2010; Puig-Arnavat et al. 2010; Ruiz et al. 2013):

1 *Drying* Occurs at temperatures between 100 and 200 °C and reduces the moisture content to below 5% (endothermic).
2 *Devolatilization* (pyrolysis) Occurs in the temperature range of 150–400 °C. This endothermic stage involves the thermal breakdown of larger hydrocarbon biomass molecules into smaller (condensable and non-condensable) gas molecules and results in the formation of char. One important product of this stage is tar, formed through condensation of vapor produced in the temperature range between 250 and 300 °C.
3 *Oxidation* This is a reaction between solid carbonized biomass and oxygen, generating CO_2 and oxidization of hydrogen present in the biomass to generate water. With this exothermic oxidation of carbon and hydrogen a large amount of heat is released. When oxygen is present in only sub-stoichiometric quantities, partial oxidation of carbon may occur, generating CO.
4 *Reduction* Occurs in a temperature range of 800 and 1000 °C. In the absence (or sub-stoichiometric presence) of oxygen, several endothermic reduction reactions take place in this stage.

The designs of gasification reactors can be classified by the gasification agent, heat source, gasifier pressure, or by reactor design used. Gasification agent can involve air blown into the systems, supply of oxygen, or the supply of steam. Heat source variations are: heat provided by partial combustion of biomass, (autothermal), or heat supplied by an external source via a heat exchanger or an indirect process (allothermal or indirect). Gasifiers can further be operated at atmospheric or under pressure. Finally, different reactor designs can also be distinguished such as fixed-bed, fluidized-bed, entrained-flow, or stage gasification (Puig-Arnavat et al. 2010). Details on technical reactor components are described in Balat (2009).

Products and uses The resulting hot fuel gases (syngas) from gasification contain large amounts of incomplete oxidized products. These have a heating value which can be utilized in a separate process, even at different times or locations (Arena 2012). The syngas mixture consists of carbon monoxide (CO), hydrogen (H_2), methane (CH_4) and carbon dioxide (CO_2) as well as light hydrocarbons, such as ethane and propane, and also heavier hydrocarbons, such as tars. Hydrogen sulphide (H_2S) and hydrogen chloride (HCl), or inert gases, such as nitrogen (N_2), can also be present in the syngas (Molino et al. 2016). Amount of syngas produced from gasification range from 1 to 3 Nm^3/kg on a dry basis, with an average LHV spanning between 4 and 15 MJ/Nm^3. These results are affected by the gasification technology and the operating conditions. Air as gasification medium results in values between 4 and 7 MJ/Nm^3 whereas steam will result in ranges between 10 and 18 MJ/Nm^3 and oxygen between 12 and 28 MJ/Nm^3. (Basu 2010; Molino et al. 2016). Syngas can be used in a conventional burner, connected to a boiler and a steam turbine. In a more efficient energy conversion device, such as gas reciprocating engines or gas turbines, heat or electricity can be generated (Arena 2012; Balat 2009). Syngas is also a key intermediate substance in the chemical industry and used in many highly selective syntheses of chemicals and fuels, such as Fischer–Tropsch liquids, methanol and ammonia or as a source of pure hydrogen and carbon monoxide (Ahmad et al. 2016). Syngas from gasification requires conditioning, which involves cooling and disposal of particulate matter and tar (Abdoulmoumine et al. 2015; Heidenreich and Foscolo 2015).

Critical review of challenges and trends in low- and middle-income settings Biomass gasification is a complex technology which is considered immature, inflexible, less competitive than other technologies, and with a high risk of failure (Ruiz et al. 2013). There is a wide range of gasification designs and technological set-ups, many of which are still in the research stage (Molino et al. 2016). The main overall research challenges comprise finding solutions to deal with heterogeneous feedstocks, developing the knowledge to maximize syngas yield, optimizing gas quality and gas purity, increasing the overall process efficiency, and decreasing system and production costs to improve its economic viability (Heidenreich and Foscolo 2015). The feedstock requirements are similar to other dry thermochemical treatment processes in terms of low moisture and ash content, but gasification requires an even higher degree of homogeneity and particle size reduction. Modeling and simulation of biomass gasification are required to predict the effect of process parameters (Ahmad et al. 2016; Baruah and Baruah 2014). Since the late 1990s a significant amount of research efforts have focused on gas cleaning (Kirkels and Verbong 2011). Considering the fact that only a few pilot or industrial plants for the production of liquid or gaseous biofuels from syngas are functioning at present, Molino et al. (2016) stated that a new approach, capable to valorize all gasification products (chemicals, fuels and heat), is required to enable the diffusion of biomass gasification into the international market.

In the low- and middle-income context, the low technology maturity, high complexity and financial requirements reduce the application potential of biowaste gasification. However, the promise of rural electrification and local development have been driving gasification projects in India and China, where hundreds to thousands small fixed bed gasifier systems have been installed (Kirkels and Verbong 2011). Yet applications remain troublesome, with reported predominant problems of tar generation, operation, maintenance and economic feasibility (Buragohain et al. 2010; Kirkels and Verbong 2011). Micro-gasification for cooking is a relatively new and promising development as it allows biowaste (e.g. in the form of pellets) to be efficiently and safely burned for cooking purposes at household level (Roth 2014).

3.5 Comparative overview of biowaste treatment technologies

Table 3 (treatment technologies with agricultural and animal feed products) and Table 4 (treatment technologies with bio-energy products) provide a comparative overview of the presented biowaste treatment technologies in terms of feedstock suitability, main operational parameters and output products. In the thermochemical treatment category 'controlled combustion', which occurs in a controlled manner (i.e. high temperatures with sufficient oxygen supply to ensure complete combustion of the organic matter), is also listed for the sake of completeness although it can substantially differ from the 'direct combustion' (or open burning) of biowaste as covered in this review.

4 State-of-research overview

4.1 Quantification of scientific articles published on Scopus 2005–2015

A search of articles on treatment technologies for biowaste published from 2005 to 2015 (search level 2) reveals that the highest number of scientific publications relate to the topics of anaerobic digestion, composting and pyrolysis. Least publications were found covering liquefaction, direct combustion and black soldier fly conversion (Fig. 3a).

Filtering these results with regard to low- and middle-income settings (Fig. 3b) reveals that composting and anaerobic digestion are also the technologies on which most articles were published. The categories 'direct use' which comprise land application and animal feed are also well represented in the frequency of publications and show that these topics are relevant for low- and middle-income settings, likely due to the simplicity and low costs involved, and thus stimulate interest of researchers. The same applies for slow pyrolysis, whereas fast pyrolysis as more complex treatment process involves higher costs, and a different set of technical capacities. The highest fraction of technology-specific articles on low- and middle-income settings (search level 3) compared to biowaste treatment articles (search level 2) is found for 'direct combustion' (35%: 39 out of 111) followed by 'direct land application' (16%: 206 out of 1257), indicating their relevance in these settings. The technologies with the lowest absolute number of publications in the economically developing context are fermentation, black soldier fly and liquefaction. The high investment and operating costs of fermentation and liquefaction could be a reason for their limited publication output in low- and middle-income settings. Such innovative approaches are typically conducted in and for high-income settings where more

Table 3 Comparative overview of biowaste treatment processes with agricultural and animal feed products

	Direct use		Biological treatment		
	Direct land application	Direct animal feed	Composting	Vermicomposting	Black soldier fly treatment
Input					
Feedstock	Biowaste	Biowaste	Biowaste (C/N: 20–50; TS: 55–75%)	Biowaste (C/N: 25–30; TS: 70–90%)	Biowaste (TS: 20–35%)
Conversion					
Operating conditions	Not specified	Not specified	Process needs moisture and aeration. Low ambient temperatures (<15 °C) slow the process	Bedding layer, moisture aeration and shading needed. Ambient temperature of 10–35 °C ideal	Ambient temperature of 25–32 °C ideal
Resource requirements (water, energy, space, etc.)	Large land requirement	Energy for shredding feedstock Space for animal keeping (Coffin 2013)	Water needed during process. Avoid water saturation by rainfall. Energy for shredding feedstock, turning and aeration of windrows, and sieving of compost. Space of 200–250 m^2/ton daily input (windrows 2 × 2 m)	Water added in hot arid climates. Energy for shredding feedstock. Space of 800 m^2/ton daily input or 200 m^2 when assuming 4–5 vertical stacks of treatment bins	Water for cleaning. Energy for climate control (if required), shredding feedstock and sieving product. Space of 125–200 m^2/ton daily input. Decreased space requirements when using vertical stacking
Processing time	Not specified	Not specified	>90 days for mature compost	>45–60 days for vermicompost (includes 15 days pre-treatment by composting)	10–20 days, depending on feedstock quality and ambient temperature
Hygienization	No hygienization	No complete inactivation of pathogens. Possible bioaccumulation of heavy metals, PAHs, organochlorine pesticides	Inactivation of pathogens and weed seeds by temperature	No complete inactivation of pathogens and weed seeds	No complete inactivation of pathogens
Emissions	CO_2 and water vapor	Animal dependent (Gerber et al. 2013)	CO_2 and water vapor. Leachate control	CO_2 and water vapor. Leachate control	Characteristic odor
Skill requirement	Only simple labor skills required	Only simple labor skills required	Only simple labor skills required	Only simple labor skills required	Only simple labor skills required for treatment. Fly nursery requires understanding of fly life cycle

Table 3 continued

	Direct use		Biological treatment		
	Direct land application	Direct animal feed	Composting	Vermicomposting	Black soldier fly treatment
Output					
Value products	Soil amendment	Meat, eggs, milk, leather, etc.	Compost: Nitrogen: 1–2%; P: 0.4–4%; K: 0.5–2.5% (depends on feedstock and technology)	Vermicompost (30% of input in wet weight) and worms (3–10% yield of stocking density per week). Nitrogen: 1–2%; P: 0.4–4%; K: 0.5–2.5% (depends on feedstock and technology)	Larvae 35% protein, 30% fat Residue suitable as soil amendment after maturation
Product yield	Not specified	Conversion: 50–60% (poultry), 25–30% (pig), 15% (cow)	50% compost in dry weight or 30% in wet weight	50% compost dry weight or 30% wet weight	15–20% dry weight larvae 15–40% wet weight residue
Comments	Salt, heavy metals, chemical components may affect crop	Non-ruminants cannot digest lignocellulose. Products (meat, fish, dairy) require cold storage	Feedstock quality affects compost quality. Salt and metal content may affect soil and crops	Worms avoid tannins and oily, salty, acidic and alkaline compounds	Larvae cannot digest lignocellulose Local legislation regarding feedstock use and larvae use as animal feed may be a barrier
Prevalence in low- and middle-income settings	Widespread practice	Widespread practice	Widespread. Large scale successful examples in Dhaka, Bangladesh, Bali, Indonesia	Vermicomposting by farmers frequent in India and Cuba. Use by waste managers less frequent but documented from India	Small-medium scale (10–200 kg input/day) in countries like Ghana, Uganda, Indonesia, Vietnam, Colombia, etc. Large-scale application in South Africa and China
Key literature	Gendebien et al. (2001) and Hegberg et al. (1990)	Cheng et al. (2015a) and Esteban et al. (2007)	Lim et al. (2016) and Rothenberger et al. (2006)	Ali et al. (2015) and Wang et al. (2007)	Čičková et al. (2015), Diener et al. (2011) and Surendra et al. (2016)

Table 4 Comparative overview of biowaste treatment processes with bio-energy products

	Biological treatment		Physico-chemical treatment		Thermochemical treatment			
	Anaerobic digestion	Fermentation	Transesterification	Densification	Pyrolysis	Liquefaction	Gasification	Controlled combustion
Input								
Feedstock	Biowaste (C/N: 16–25)	Biowaste	Waste oil, fat, grease	Biowaste (TS: 85–90%)	Biowaste (TS: 85–90%)	Biowaste	Biowaste (TS: 80–90%)	Biowaste (TS >85%)
Conversion								
Operating conditions (Temp., air supply, pressure)	30–40 °C. Anaerobic, atmospheric pressure	25–30 °C. Anaerobic, atmospheric pressure	50–70 °C. Anaerobic, atmospheric pressure	<200 °C, 250 MPa pressure by manual or electrical equipment	Slow heating rate: 300–500 °C Fast heating rate: 400–650 °C, anaerobic (λ = 0), atmospheric pressure	280–370 °C 7–30 MPa	700–900 °C. Partial air or steam supply (λ = 0.2–0.5), atmospheric pressure	800–1000 °C Excess air supply (λ > 1), atmospheric pressure
Resource requirements (water, energy, space, etc.)	Depending on technology and feedstock some water may be required Wet AD: TS <15% Dry AD: TS >15% Land use depends on system type	Water and energy for heating required Alcohol, catalyst (e.g. sodium hydroxide or potassium hydroxide)	Energy for heating and stirring, minimal land requirements	Energy: 37 kWh/t for sawdust. Space needed for biowaste, binding agent storage, and drying of densified product	Energy for heating (partly substituted by pyrolysis gas)	Water required. High energy requirements, catalyst often used	High energy requirements Catalysts used in more sophisticated reactors to improve reaction rates	Limited space requirements
Processing time	30 days	6–72 h	30 min to few hours	Few minutes	Slow: minutes to days Fast: seconds	10–60 min	10–20 s	Minutes to hours (depending on TS)
Hygienization	No complete hygienization	Hygienized by distillation	Hygienized by temperature	Hygienization of pellets/briquettes surface by temperature	Hygienization by temperature	Hygienization by temperature	Hygienization by temperature	Hygienization by temperature
Emissions	Methane leakage may occur. Low amounts of toxic H_2S (if not combusted)	Bioethanol combustion shows lower emissions when compared to petrol combustion	Water pollution potential by caustic chemical runoff	Not specified	CO, CH_4, NO_x, SO_2, PAHs, particulate matter	Not specified	Not specified	CO_2, H_2O Particulate matter and gases with incomplete combustion
Skill requirement	Technical skills for building gas-tight digester. Trained technicians for operation and maintenance	High-skilled labor	Chemical engineering skills for planning/design. Well-trained technicians for daily operation	Manual production with low-skilled labor. Larger scale requires mechanical engineering skills	Fast pyrolysis requires high skilled labor	High-skilled labor	High-skilled labor due to complexity	Depending on scale of operation

Table 4 continued

	Biological treatment		Physico-chemical treatment		Thermochemical treatment			
	Anaerobic digestion	Fermentation	Transesterification	Densification	Pyrolysis	Liquefaction	Gasification	Controlled combustion
Output								
Value products	Biogas (55–60% CH_4, 35–40% CO_2), digestate (nutrient content depends on feedstock and retention time (Makadi et al. 2012))	Bio-ethanol, thin stillage, condensed distillers solubles (as animal feed or forlactic acid production	Biodiesel, glycerol (soap), alcohol, water	Pellets, briquettes	Char, bio-oil, gas	Bio-oil, process water and syngas	Syngas (CO, H_2, CH_4, CO_2), light hydrocarbons and heavier hydrocarbons (tar)	Heat
Energy density (depends on feedstock)	Biogas: 21–24 MJ/Nm^3	Bio-ethanol: 23–27 MJ/kg	Biodiesel: 37 MJ/kg	Pellets: 17–18 MJ/kg (wood/straw based)	Char:18–30 MJ/kg Bio-oil:10-18 MJ/kg Gas: 10–20 MJ/Nm^3	Bio-oil: 30–37 MJ/kg	Syngas: 4–15 MJ/Nm^3	Not specified
Product yields	Rule of thumb: 10 kg biowaste = 1 m^3 biogas (≈22 MJ). Methane yield: 0.36–0.53 m^3 CH_4/kg VS of feedstock. Liquid digestate (input ≈ output)	Average 8.3–11.6 MJ/kg TS (ethanol production from food waste)	Biodiesel 83–100%	100% dry weight, but smaller volume	Slow: 35% solid, 30% liquid, 35% gas. Fast: 12% solid, 75% liquid, 13% gas	Bio-oil: 27–60% weight basis	85% gas, 10% char (solid), 5% liquid (tar), 1–3 Nm^3 syngas/kg waste (dry basis)	Not specified
Comments	Lignified material not suitable. Smaller particle size accelerates process. Biogas requires large storage space if not continuously used on site (e.g. for cooking or generator)	Lignocellulosic wastes require pre-treatment. Enzymatic saccharification blending (5–100%) with gasoline	Drying for lowering water content and lower the free fatty acid (FFA) concentration by chemical pre-treatment	Drying, torrefaction, pyrolysis as possible pre-treatment. Ease of product storage and transportation. Severe wear and tear of equipment	Inorganic content (e.g. ash, sand) in feedstock lowers yield and heating value of products. Stability of bio-oil is an issue	Results in process water with suspended char particles. Bio-oil can contain 10–20% of oxygen (polarity leads to high water content, corrosive properties, and thermal instability). High process pressure is a safety issue	Low inorganic content of feedstock preferred. Safety: produced gas is toxic (CO, H_2S) and flammable. Tar formation problematic	Negative impacts on public and environmental health (climate change) with incomplete combustion
Prevalence in low- and middle-income settings	Fixed-dome systems widespread in China, India, Nepal, Vietnam Tubular digesters in South America. Floating-dome systems in India	Biowaste as feedstock: limited experiences	Experiences with small-scale, batch systems	Widespread experiences (biomass and charcoal briquetted)	Slow: Widespread experiences. Fast: experience limited to lab-scale	Only lab-scale (e.g. Indonesia)	China and India, micro-gasification in TLUD stoves	Open burning widespread, controlled burning less frequent (high investment costs)

Table 4 continued

	Biological treatment		Physico-chemical treatment		Thermochemical treatment			
	Anaerobic digestion	Fermentation	Transesterification	Densification	Pyrolysis	Liquefaction	Gasification	Controlled combustion
Key literature	Khalid et al. (2011), Mata-Alvarez (2003) and Vögeli et al. (2014)	Gupta and Verma (2015) and Sarris and Papanikolaou (2016)	Gerpen (2005) and Yaakob et al. (2013)	Demirbas and Sahin-Demirbas (2004), Manickam et al. (2006) and Tumuluru et al. (2011)	Mohan et al. (2006), Tripathi et al. (2016) and Vamvuka (2011)	Elliott (2011), Peterson et al. (2008) and Toor et al. (2011)	Ahmad et al. (2016), Basu (2013) and Kirkels and Verbong (2011)	Werther et al. (2000)

research funds are available. Black soldier fly conversion is also still a rather new biowaste treatment technology, which is likely one of the reasons for the low numbers of publications. However, with 13% BSF conversion ranks 3rd regarding the fraction of publications that covers low- and middle-income settings out of all articles on BSF biowaste treatment.

Examination of the publications on biowaste treatment technologies in low- and middle-income settings over time (in 5-year groups) reveals that densification is the only technology of which substantially more articles were published 2006–2010 (72%) compared to publications in 2011–2015 (28%). In contrast, fermentation, direct combustion, anaerobic digestion and transesterification show an increase of publications from 2006–2010 (33–36%) to 2011–2015 (64–67%). The most striking increase of published articles relates to pyrolysis (22–78%) and BSF (0–100%), although for the latter the small absolute number of articles (3) must be considered.

4.2 Type of research in scientific articles

Of the total 3653 articles on biowaste treatment technologies published between 2005 and 2015 (search level 2) and categorized according to their research type, an average of 53% fall into the category of research on process engineering, while 22% are on technology implementation, and 25% deal with sustainability aspects. Figure 4 shows the distribution of research type for each treatment technology. The highest fraction with a focus on process engineering show in the publications on BSF conversion. Pyrolysis, fermentation, liquefaction and vermicomposting follow with more than 66% of articles of process engineering type, while anaerobic digestion still shows a fraction of 53% of process engineering type. These results can be explained by the technology readiness level, where for an immature technology stage it can be expected that research will largely focus on research results from laboratory/bench scale studies with an increased focus on generating a basic understanding and fundamentals of the process as well as lab-scale studies which target opportunities of optimizing the process steps. With an increasing technology level readiness one would then expect more publications on pilot/demonstration scale or case studies discussing the field application. However, even for technologies that are already mature and in a

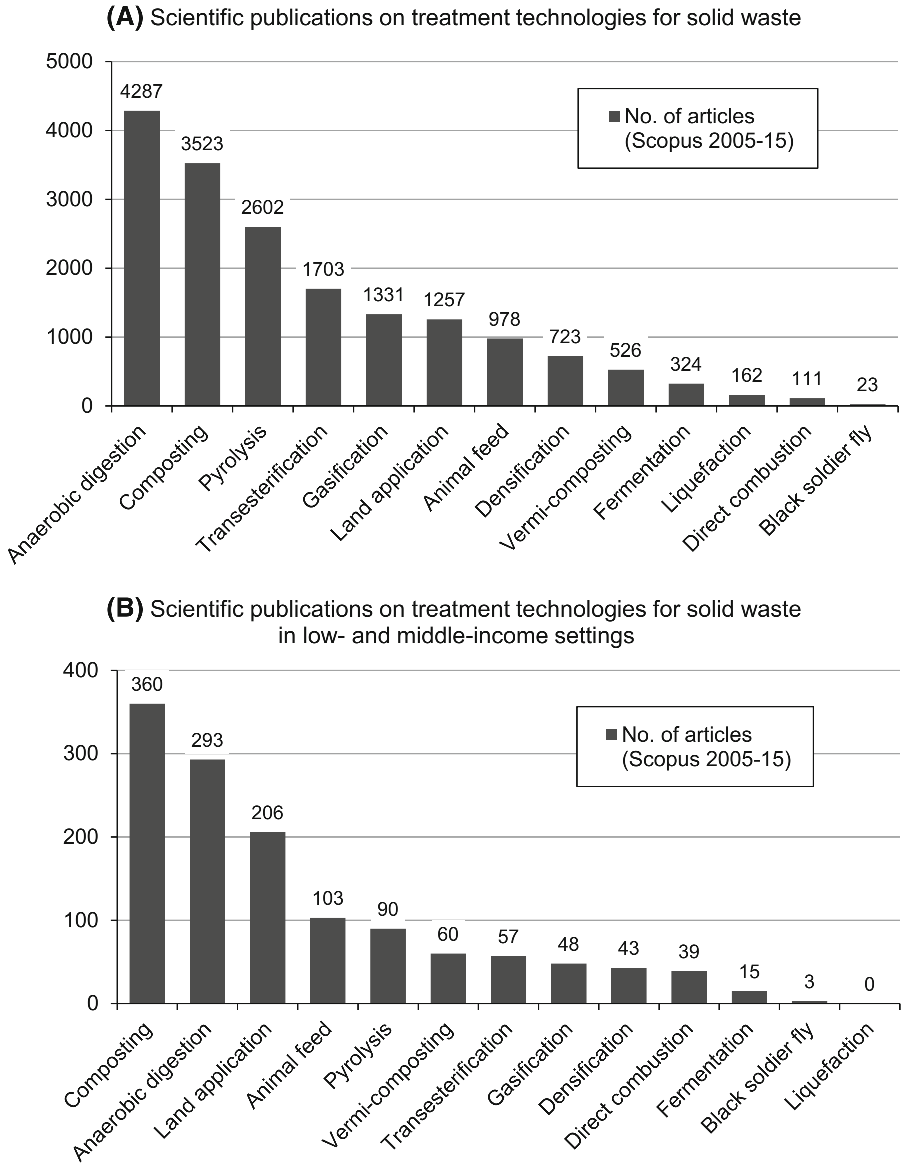

Fig. 3 Total number of articles in Scopus (2005–2015) regarding solid waste treatment technologies (**a**), and when adding terms related to a low-and middle-income setting (**b**)

commercialized phase at larger or even industrial scale, the results show that the main bulk of research publications can still be categorized as process engineering type.

An example of this may be reflected in the results regarding vermicomposting, which although being a relatively old and well-understood process, still shows a strong frequency towards research on better understanding the digestive functions and genetic variations among worms and their performance for waste management. Similarly, also the technology of anaerobic digestion, although widely applied in waste management, shows a high fraction of research on process engineering such as studies on interaction and/or transition of different microbial communities during the process. Such research has probably also gained increased momentum given new detection and methods of analysis. Technologies such as densification and direct combustion, both technologies of low-complexity seems less conducive for process engineering

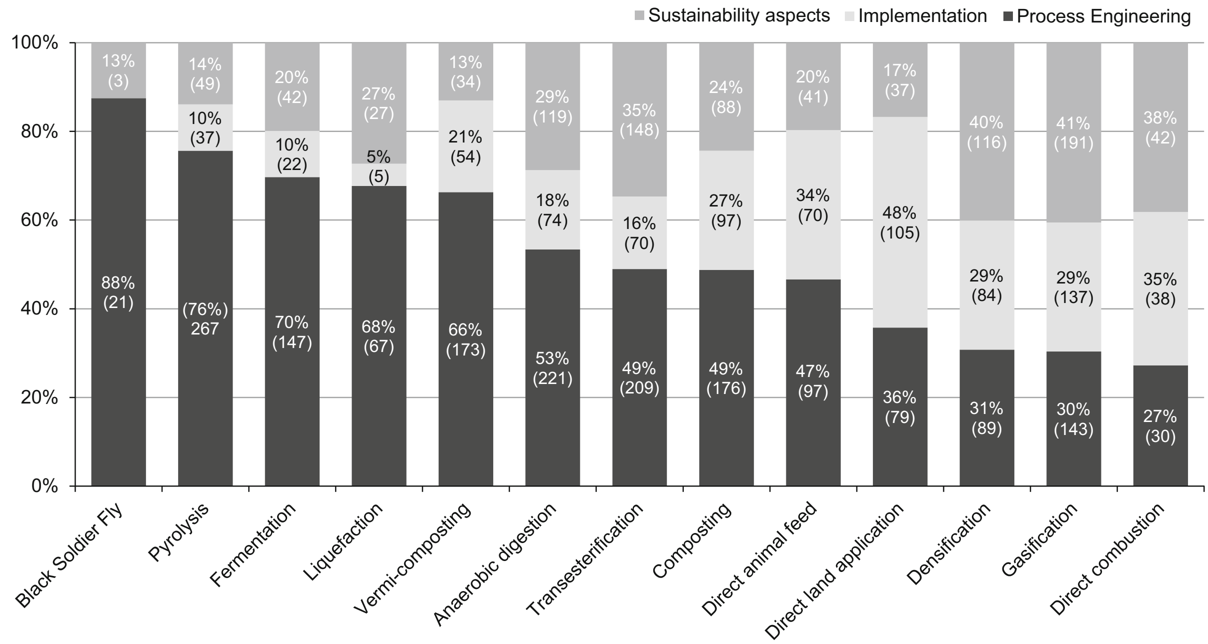

Fig. 4 Type of research of scientific articles on solid waste treatment technologies retrieved from Scopus (2005–2015). The figures in *brackets* indicate the absolute number of articles

research. Here a relatively high fraction (38-40%) of publication covers the aspect of sustainability, which includes assessments and application of methods such as Life Cycle Analysis (LCA), economic analyses and studies regarding the emissions and impacts of the technology with regard to environmental pollution or human health. Publications on gasification, despite being a technology of higher complexity and lower maturity level, also predominantly cover sustainability issues. This can be interpreted as a substantial interest in bringing gasification to scale (e.g. due to the attractiveness of the products), while at the same time acknowledging the need to further assess the impacts (costs and benefits) of this technology. The topic of direct land application shows a high fraction of published articles on implementation issues. This can be explained by the fact that lab or bench scale process engineering research makes limited sense and most experiments and analysis have to be conducted on-field at a specific case study location. One overall argument that explains the comparatively low numbers of articles with type “implementation” is that this remains a blind spot for the research community where significant R&D is rather conducted by the private sector or involved enterprises. This information, given the competitive nature of the business then does not make its way into scientific journals.

5 Conclusions and outlook

A wide range of treatment technologies for solid biowaste already exist and have been extensively researched over the last decades. All these treatment technologies can convert organic waste into a variety of output products with more or less market value and ecological benefits. This review distinguishes four categories of technologies: (1) direct use, (2) biological treatment, (3) physico-chemical treatment, and (4) thermochemical treatment (Fig. 2) and highlights the expected biowaste derived products and their possible end-use. Each technology can handle a specific type of waste feedstock whereby some technologies are more restrictive in their requirements than others. Each technology can be described by relevant process steps and parameters to generate products with different properties.

Regarding feedstock requirements, a waste manager’s perspective might consider those technologies that can treat the widest range of urban biowaste feedstock type and quality (i.e. one technology treats most waste), although investment and operational cost cannot be neglected. Another more entrepreneurial viewpoint, however, would be to focus on the value of products generated without necessarily prioritizing the overall contribution to waste management. A focus on the value and market demand of waste-derived products will tend to select a specific high quality waste feedstock. Accessing such specific waste types of high quality thus directs the attention to specific waste sourcing, in other words, a collaboration with waste generators (segregation at source) and a specific separate collection system. A comprehensive assessment of the available waste streams (quantities, characteristics, purity, etc.) in combination with a good overview of the different biowaste treatment technologies, the products they generate and how these fit into the local market demand, is thus key information for informed decision-making with regard to the most appropriate technology for the local context. The 'waste as a resource' paradigm has increasingly been adopted in the scientific arena, which for instance resulted in the incorporation of market-demand assessments for biowaste-derived end-products. Yet, also considering the by-products and their further use is necessary to foster a bioconversion approach with overall economic benefits. Combining different treatment technologies to an integrated system that makes best use of the products and sub-products is an interesting route to pursue. Yet, it adds complexity to the system understanding and also requires an extended set of interdisciplinary knowledge. This can be shown on the example of BSF waste treatment where waste is converted into protein for fish feed on one hand, biodiesel production from BSF larvae fat as fuel source, anaerobic digestion and production of biogas from the BSF residue, and use of this biogas to pre-treat waste (e.g. shredding) or post-processing of the larvae (e.g. drying and pelletizing larvae meal). Such a more holistic biowaste valorization approach could be exemplary for the shift from linear to circular design thinking with diverse and far-reaching benefits.

Technology readiness for a low- and middle-income setting is another important element. A systematic search on Scopus directed towards research on biowaste technologies that targets low- and middle-income settings shows substantial differences in the amount and type of research published over the last decade. This can be explained with the maturity of the technology and its readiness for implementation in practice. For new, complex or less mature technologies (e.g. BSF, pyrolysis, fermentation, liquefaction) analysis of the research type published, shows more focus on process engineering and lab-scale or bench-scale experiments. On the other hand, research on proven approaches (composting, anaerobic digestion) shows more research at scale, looking at case studies, economics or sustainability. Finally, research on "unscientific practices" (e.g. direct land application, densification, direct combustion) focuses more on the issues of environmental impacts. For all technologies, research from case studies and field research at scale seem disproportionately underrepresented, even when considering mature technologies which are already considered state-of-the-art, and would seem affordable even in low- and middle-income settings. One may argue that this underrepresentation reflects the main tasks of researchers—to conduct fundamental research to enhance basic process understanding whereas less research value is seen in practical implementation challenges. But this may also be the result of the waste sector traditionally being embedded in the discipline of engineering science thus directing research towards process engineering research questions. In view of improving waste management in low- and middle-income settings, more unbiased, well-structured and reproducible evidence from case studies at scale would clearly be desirable to foster sharing and transfer of knowledge to practitioners and also enhance the exchange and communication between academia, policy and practice. Research results on aspects of sustainability (incl. feasibility studies) are also important on the way to technology application and dissemination. As the broader context of technology application also involves consideration of waste sourcing, the value of research on municipal solid waste segregation at source should not be underestimated. It is considered key for effective recycling and to ensure high quality of the end-products (Wilson 2015).What has been stated for the case of China by Zhang et al. (2010a) also applies to other low- and middle-income settings: The solid waste recycling sector not only needs further technology development, but also improved operating standards, product standards, and enhanced market development.

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