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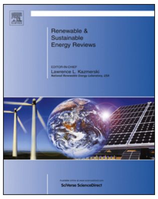

Char fuel production in developing countries – A review of urban biowaste carbonization

Christian Riuji Lohri [a,*], Hassan Mtoro Rajabu [b], Daniel J. Sweeney [c], Christian Zurbrügg [a]

[a] *Eawag: Swiss Federal Institute of Aquatic Science and Technology, Department of Sanitation, Water and Solid Waste for Development (Sandec), 8600 Dübendorf, Switzerland*
[b] *University of Dar es Salaam, College of Engineering and Technology, Department of Mechanical and Industrial Engineering, P.O. Box 35131, Dar es Salaam, Tanzania*
[c] *Massachusetts Institute of Technology, D-Lab, 77 Massachusetts Avenue, Cambridge, MA 02139, USA*

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ABSTRACT

Urban households in low- and middle-income countries (LAMICs) face the challenge of finding affordable, reliable and sustainable cooking fuel supplies. Most city residents use wood-based charcoal derived from mostly informal supply chains, which are linked to unsustainable forest logging, low efficiency production methods and long transportation routes, all factors that contribute to environmental degradation. At the same time, the provision of adequate and equitable solid waste management (SWM) services remains a major urban challenge, with municipal solid waste mainly consisting of organics. Sales of briquettes made from carbonized biowaste can potentially foster waste collection and enhance cost-recovery of SWM systems, while contributing to a sustainable energy supply.

This article provides essential information for understanding the potential for and limitations of char production from urban solid biowaste to tackle both SWM and cooking fuel challenges simultaneously. It reviews the current state of charcoal consumption, provides an overview of the SWM situation and explores the potential of converting biowaste streams into char in LAMICs. Existing carbonization technologies are presented and their advantages and disadvantages examined by means of a weighted assessment matrix (Pugh method) using technical, financial and environmental/health criteria.

For financially viable carbonization the feedstock should be continuously available at no cost and have physical and chemical properties suitable for pyrolysis: dry, unmixed and homogeneous. Thus, separated waste obtained near the source of generation is important. The existing bulk of mixed, wet household and market wastes, however, require carbonization technologies that are associated with high capital investment. Overall, it has been shown that low-tech retorts have the highest suitability for biowaste carbonization in LAMICs. Further research is required to improve energy efficiency, reduce air pollution, guarantee safe operation and assess financial viability. Beyond the technical aspects, policy measures to support sustainable char production from biowaste are necessary to nurture government support.

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[*] Corresponding author.
E-mail address: christian.lohri@eawag.ch (C.R. Lohri).

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1. Introduction

Many low- and middle-income countries (LAMICs) are facing a severe energy crisis with limited access to affordable and reliable energy services [1]. Global concern and mobilization is particularly growing around the issue of households in developing countries [2], where approximately 90% of the energy is consumed for cooking [3]. There are currently 2.7 billion people, around 40% of the global population, who rely primarily on biomass for cooking and more than 95% of these people live either in Sub-Saharan Africa (SSA) or Asia [1]. Despite major efforts to promote sustainable cooking fuels during the past decade, charcoal still remains the primary source of cooking energy for the majority of urban citizens in LAMICs, and the predominately informal charcoal supply chains are associated with unsustainable forest mining, low efficiency production methods, and long transportation routes [4–6]. At the same time, the provision of adequate and equitable solid waste management (SWM) services is a challenge in most LAMICs, where solid waste is characterized by a high fraction of organic matter (=biowaste), and low collection rates and inadequate disposal methods are widespread (e.g. [7–11]). The effects of both of these urban challenges pose considerable risks to the environment and to human health (for charcoal: [12–14]; for SWM: [15,16,7,11]).

The thermochemical method of carbonization is a low-temperature slow pyrolysis process where biomass is heated in the absence of oxygen (or partially combusted in the presence of a limited oxygen supply). The resulting biowaste-derived char can be further processed to fuel briquettes, a product of economic value with stable market and advantageous distribution properties. This biowaste-to-fuel production can partially address the challenges of solid waste management as it can stimulate the collection rate of biowaste in cities of LAMICs and diminish the amount destined for disposal in dumpsites. This would lead to a reduction of emissions linked to the uncontrolled decomposition of inappropriately disposed waste and transportation requirements, as well as the partial substitution of an unsustainably produced cooking fuel (wood-derived charcoal) without requiring significant changes in current cooking appliances and behaviour.

Research on biochar related to its soil and crop yield improvement and carbon capture potential has received increased attention in recent years [17–35]. This review, however, solely focuses on biowaste as a substrate for the production of char and its application as an energy carrier. Studies on pyrolysis of the mixed fraction of municipal solid waste (MSW) requiring more technically sophisticated systems can be found elsewhere (e.g. [36]), as can information about the post-treatment steps required for the briquetting phase (e.g. [37–42]).

The aim of this article is to provide essential information for understanding the potential for and limitations of char production from urban solid biowaste to tackle both MSW and household cooking fuel challenges. It begins by reviewing scientific literature and reports to obtain an overview of the current situation regarding charcoal consumption in LAMICs and the underlying theoretical background dealing with the hindrances to switching to more sustainable fuel sources. The literature review further provides an overview of the MSW challenges in LAMICs and then presents the theoretical background of carbonization. As literature on wood carbonization is abundant compared to that dealing with municipal biowaste and the fundamental conversion processes are similar, this section draws heavily from studies on wood pyrolysis. Existing char production systems are presented and their advantages and disadvantages examined by means of a quantitative weighted assessment matrix (Pugh chart), a technique used to rank the multi-dimensional options of a technology type [43] using technical, financial and environmental criteria. The last section summarizes the feasibility assessment of slow pyrolysis treatment for biowaste in LAMICs by presenting challenges, opportunities and areas for further research.

2. Charcoal consumption context

2.1. Current situation

Charcoal is the residue of solid non-agglomerating organic matter, of plant or animal origin, that results from decomposition by heat in the absence of air at a temperature above 300 °C [44]. It is the primary cooking fuel for millions of households in urban and peri-urban Sub-Saharan Africa [45]. In 2011, global charcoal production amounted to 50 Mton/year, of which 29 Mton/year was produced in Africa [46]. Brazil is by far the largest char producer in the world, producing 9.9 Mton/year. Other important char producing countries and their production rates in Mton/year are Thailand (3.9), Ethiopia (3.2), Tanzania (2.5), India (1.7) and the Democratic Republic of Congo (1.7) [47].

The growing demand for charcoal has generally been driven by population growth and urbanization, i.e., switching from firewood to charcoal is a common practice when people move from rural to urban areas in LAMICs because, unlike firewood, charcoal is relatively clean (smokeless) and requires a relatively small storage space (it has high energy density). Hence, it is a preferred, affordable fuel for use in congested urban settlements. With the expected further increase of urbanization, charcoal will be the major primary source of energy for most urban dwellers for at least another generation [48,49,14]. Hosier et al. [50] estimated that every 1% increase in urbanization leads to a 14% increase in charcoal consumption in Tanzania. The World Bank [51] reported that in Dar es Salaam, Tanzania, the proportion of households using charcoal climbed from 47% in 2001 to 71% in 2007. Felix and Gheewala [52] show that while charcoal is consumed by 94% of urban households either alone or mixed with other fuels, it is used as first choice cooking fuel by about 78% of households in Dar es Salaam city. Yet, data reliability is generally low, as 90% of the charcoal transported into Dar es Salaam City went unreported in official records [53]. In addition, the charcoal sector rarely generates data that captures production and consumption volumes; this is largely due to the clandestine nature of production, poor regulation, and informality of the sector [54].

Several advantages make charcoal and char-products attractive for cooking compared to uncarbonized biomass: its calorific value is roughly double that of uncarbonized material, i.e., higher heating value per unit mass is approximately 30 MJ/kg of completely carbonized charcoal with about 5% moisture content as compared to approximately 15 MJ/kg of firewood with roughly 15% moisture content [55,52]. Furthermore, charcoal is available throughout the year, is relatively lightweight, clean and safe (burns with less smoke compared to firewood). It can be stored easily and for long periods of time because it is not damaged by rain or moisture. In addition, charcoal is economical, with low input, production and consumer costs, can be purchased on the local market in small quantities and burned in inexpensive stoves. It can be used for preparing meals at small- (e.g., household) and large-scale (e.g., institutional) and suits a variety of cooking habits (e.g., high-temperature deep frying, moderate-temperature boiling, etc.). Finally, charcoal is cheaper than kerosene, LPG, and electricity in most cities in developing countries [56–61,12,14].

Improving the sustainability of charcoal is considered the most effective and immediate implementable measure for enhancing the sustainability of household cooking fuel in developing countries and should be a key priority [62–67,56,59]. Possibilities to increase charcoal sustainability exist throughout its supply chain from production to use. This starts with community-based forest management in which sustainable harvesting can be guaranteed, to the use of alternative substrates, improved methods for charcoal production and, sustainable charcoal use in improved stoves [56].

This article focuses on alternatives to unsustainably produced wood-derived charcoal and, more specifically, the use of organic waste for carbonization.

2.2. *Household fuel switching*

It had long been assumed that consumers shift to more efficient, more convenient and cleaner energy systems as their incomes rise [68–70]. A common model to describe household fuel choices in developing countries is the "energy ladder" concept, which ascribes differences in energy-use patterns between households to variations in economic status [71–73]. The energy ladder theory postulates a linear movement with three distinct phases. As household incomes increase and individuals and countries economically develop, people's energy preferences will move up on the energy ladder. Thus, families that gain socio-economic status abandon technologies that are inefficient, more costly and polluting, and move from universal reliance on "inferior" biomass fuels (e.g., dung and fire wood) through charcoal – the "transition fuel" in the second phase – to modern cleaner alternatives including LPG and electricity in the third phase [71,74–76,69,49]. However, the energy ladder theory is generally considered too simplistic and a growing body of empirical studies on household energy use show that the energy transition does not occur as a series of simple, discrete steps; instead, multiple fuel use is more common [72,76–88,68,49,67]. This concept of complementing traditional with modern energy sources rather than replacing them, is known as "energy stacking" [68,89,90]. Apparently, putting too much faith in the "energy ladder" or "energy transition" theory has undermined realistic, proactive policy-making related to charcoal. Recent evidence shows that for Africa, several obstacles cause the energy transition to proceed at a slower pace than anticipated given persistent high levels of poverty (affordability), accessibility problems to the main alternatives (LPG, kerosene and electricity), and cultural factors (e.g., cooking behaviours and tradition). Findings, therefore, point to an incomplete transition and continued dependence on charcoal and char-products within a fuel mix in the foreseeable future [71,68,83,91,85,67].

Current policies that prioritize fuel switching are considered to be unrealistic and incomplete, and fail to recognize the realities of actual energy costs, future consumption trends, and the significant potential offered by biomass energy in SSA. However, in response to energy crises, some SSA countries have been re-evaluating their energy policy to develop biomass energy strategies (BEST) [6]. These strategies are meant to: (i) ensure a sustainable supply of biomass energy, (ii) increase efficient and effective use of biomass energy, and (iii) promote access to appropriate, alternative sources of energy. Briquetting in general, and charcoal briquettes in particular, could contribute to attaining all of these objectives within the framework of more realistic, pragmatic and biomass-oriented energy policies [40].

2.3. *Environmental consequences*

The impact of charcoal on ecosystems occurs at every stage in the production–consumption chain [13]. The consequences include adverse effects on the environment, on biodiversity, local and global climates, agricultural productivity and watershed management [58,92]. There is particular concern about the sustainability of charcoal production because, despite charcoal stoves being more efficient than firewood stoves, 4–6 kg of fuelwood is required to produce 1 kg of charcoal [81,64,67,93]. Yet, in contrast to common belief, charcoal extraction as such is not the main driving force of deforestation (e.g., [94,71,95,65]). Deforestation is fuelled by a number of drivers, such as land clearing for agriculture, mining, infrastructure and urban expansion; timber extraction; and livestock grazing. However, the importance of each of these factors is highly disputed [96].

During the 1970s and early 1980s, the harvesting of biomass for fuel was mistakenly portrayed as the leading driver of global deforestation under the "woodfuel gap" theory [97]. Although the expected fuelwood gap was not observed [98–101,49], the fuelwood crisis narrative is still widely established in international organizations, governments and NGOs, despite the lack of empirical evidence [49,102,86,67]. Nowadays, there is a broad consensus among scientists that the clearing of land for arable and pastoral agriculture is the main cause of deforestation rather than the use of wood for energy [2]. Still, it must be recognized that local fuelwood scarcities occur, as has been reported, for instance, in some regions in India, Tanzania and in Southern Africa [103–108,63,64].

Most scientists agree that the increase in charcoal production and demand have caused significant changes in forest ecosystems, and that the associated environmental degradation and soil erosion have led to lower agricultural productivity around numerous rapidly expanding African cities [109–115,104,63,49,64]. Thus, although it is now accepted that biomass harvesting for fuel is only a minor contributor to deforestation [116], charcoal extraction can

Table 1
Current waste generation by income class and projections for 2025 (adapted from Hoornweg and Bhada-Tata [9]).

	Current available data			Projections for 2025			
	Total urban population (millions)	**Urban waste generation**		**Projected population**		**Projected urban waste**	
		Per capita (kg/cap/day)	**Total (tons/day)**	**Total population (millions)**	**Urban population (millions)**	**Per capita (kg/cap/day)**	**Total (tons/day)**
Low income	343	0.60	204.802	1.637	676	0.86	584.272
Middle income	1.865	0.90	1.677.907	4.898	2.699	1.37	3.705.843
High income	774	2.13	1.649.547	1.112	912	2.1	1.879.590
Total	*2.982*	*1.19*	*3.532.256*	*7.647*	*4.287*	*1.4*	*6.069.705*

be a first step towards forest degradation, particularly when it is followed by intensive grazing [50] and conversion of forests into agricultural fields [65], or if charcoal extraction is too frequent [5]. Additionally, land use and land use changes comprise the second largest contribution to global greenhouse gas emissions after fossil fuel use [117].

3. Municipal solid waste management context

3.1. Current situation

The municipal SWM system comprises generation, storage, collection, transfer and transport, processing and disposal of solid wastes from residential, commercial and institutional sources. Proper municipal SWM aims at protecting human health, preventing environmental degradation and recovering valuable resources, and is seen as one of the key challenges of the 21st century [118–121,7,9]. The provision of equitable and reliable municipal SWM remains particularly difficult in LAMICs [8,122,123] Reasons for the exacerbated SWM problems in LAMICs include rapid urbanization, demographic changes, the unregulated growth of settlements and topographically challenging situations on one hand, and a lack of effective organizational structures, financial resources, viable business models, endorsement by governments, compliance to and enforcement of legislation on the other hand [11]. Deficient municipal SWM negatively affects human health (e.g., waste-borne diseases, such as cholera), local and global environmental conditions (e.g., criteria air pollutants, greenhouse gas emissions, and water pollution), as well as social and economic development [15,16,124,125].

Waste generation increases with increasing population, economic development, income levels, urbanization, as well as changes in lifestyle preferences and consumption [126]. The correlation between gross national income and generated municipal solid waste has been shown in many studies (e.g. [127,128,7,10]). According to Hoornweg and Bhada-Tata [9], urban residents produce about twice as much waste as their rural counterparts. Table 1 shows the current and projected municipal solid waste generation in LAMICs and high-income countries. LAMICs in total generate about half as much municipal solid waste compared to high-income countries. Furthermore global municipal solid waste generation is expected to double by 2025, mostly due to the increase in the world's population.

3.2. Waste composition and collection

Waste composition is influenced by diverse factors, such as the level of economic development, cultural norms, geographic location, energy sources, and climate [9]. Thus, waste quantities not only differ significantly between developing and high-income countries, but there are also substantial differences in waste composition [130]. A common characteristic of MSW in LAMICs is their high biowaste content, which often constitutes more than 50% of the total waste generated and can be as high as 85% [131,15,128,132,10,9] (Table 2). Biowaste is mainly comprised of kitchen waste (e.g., food scraps and peeling residues), market and yard waste, wood residues and food processing residues (e.g., shells and husks).

The chemical composition of municipal solid waste and certain organic components potentially suitable for pyrolysis is presented in Table 3.

MSW collection is an important aspect in the maintaining of public health in cities. The amount of MSW collected varies widely by region and even differs widely within cities. The average waste collection rates are directly related to income levels and collection rates in low-income countries are approximately 41% [9] or 45–70% [123]. Uncollected waste leads to health and environmental risks, such as the clogging of drains, which can cause flooding and the formation of cesspools. Furthermore, heaps of indiscriminately dumped waste attract insects, rodents, domestic animals and other disease vectors and lead to leachate that contaminates surface and groundwater supplies. The uncontrolled decomposition of organic wastes also emits unpleasant odours and generates methane, a major greenhouse gas that contributes to global warming.

3.3. Recycling, resource and energy recovery

All activities in the waste management system aimed at extracting and recovering resources and value from waste (e.g., materials or energy) can be categorized as recycling and recovery activities [11]. The key advantages derived from these activities are reduced quantities of disposed waste and the return of materials to the economy [9]. High recycling (valorization) rates generally require the processing of both dry recyclable and organic materials [10].

The informal sector, which includes all livelihood opportunities not recognized as normal income sources and for which taxes are not paid, plays a significant role in solid waste recycling activities in LAMICs [133,118]. In low-income countries, waste recycling is most often practiced by the informal sector at the curb side, neighbourhood collection points and disposal sites (often referred to as “waste picking”). Recycling rates are high, depending on the market demand for the materials. This dependency also leads to large price fluctuations. In middle-income countries, the informal sector is still predominant, but is often organized into cooperatives and recycling groups. Recycling rates are still relatively high and the recycling markets are somewhat more regulated; nevertheless, material prices fluctuate considerably [9].

Collaboration between municipalities and the informal recycling sectors offers a major opportunity for win–win solutions as it can result in enhanced recycling rates, the betterment of people's livelihoods, mitigation of the negative health and environmental impacts from current informal recycling, and the reduction of municipal waste management costs [134,135].

Treatment and valorization of the organic waste fraction (biowaste) for char production could be one of the most promising options to stimulate waste collection. High market demand can be

Table 2
Waste composition by income level (adapted from Hoornweg and Bhada-Tata [9]).

Income level	Organic (%)	Paper (%)	Plastic (%)	Glass (%)	Metal (%)	Other (%)
Low income	64	5	8	3	3	17
Middle income	56	12	11	4	3	14
High income	28	31	11	7	6	17

Table 3
Chemical composition of municipal solid waste and specific organic fractions [129].

	Proximate analysis				Ultimate analysis				
	Moisture wt% (ar)	**Ash** wt% (dry)	**Volatiles** wt% (daf)	**Fixed carbon** wt% (daf)	**Carbon** wt% (daf)	**Hydrogen** wt% (daf)	**Nitrogen** wt% (daf)	**Sulphur** wt% (daf)	**Oxygen** wt% (daf)
Municipal solid waste	22.3	25.9	87.2	12.8	49.0	5.5	1.5	0.6	30.6
Organic domestic waste	63.1	37.0	83.1	16.9	53.0	6.5	2.4	1.4	40.2
Bagasse	17.5	7.2	83.6	16.4	49.2	6.0	0.6	0.1	44.4
Coconut husk and shell	8.1	1.1	77.3	22.7	51.9	6.0	0.2	0.2	42.3
Cardboard	5.4	9.7	90.6	9.4	45.6	5.7	0.2	0.3	48.3
Saw dust	4.8	1.3	83.4	16.6	49.5	6.2	0.1	0.0	44.1

ar: as received, weight percentage from the material in its original form (including ash and moisture).
dry: weight percentage from the dry material (including ash).
daf: dry and ash free, weight percentage from the dry and ash free material.

Table 4
Pyrolysis process types and their typical operational parameters and product yields (adapted from [148–151]).

Pyrolysis process	Particle size (mm)	Solid residence time (s)	Temperature (°C)	Heating rate (K/s)	Vapour residence time (min)	Product yield[a] (mass%)		
						Solid	**Liquid**	**Gas**
Slow	5–50	minute to hours	400–660	0.1–1	5–30	35	30	35
Fast	<1	0.5–10	About 500	200–1000	<2	12	75	13
Flash	<0.2	<0.5	>800	>1000	<1	10	5	85

[a] Mass ratio of product formed to initial feedstock based on dry weight.

produced from the products derived from biowaste and can, thereby, drive SWM towards enhanced financial sustainability [136]. Biowaste recycling technologies can be classified according to the generated products, such as those with fertilizer and soil amending properties (e.g., compost through controlled aerobic decomposition [137,138]), protein-rich chicken- or fish-food (bioconversion through black soldier flies [139–141]) or energy carrying properties (e.g., biogas through anaerobic digestion [142–144]). A variety of processes exist for biowaste-to-energy conversion. Conversion of biomass into valuable liquids, gases and solids can be accomplished via biochemical (e.g., anaerobic digestion, enzymatic hydrolysis) and thermochemical (e.g. pyrolysis, torrefaction, gasification, and combustion) methods. The choice of conversion methods depend on the characteristics of the biomass feedstock (e.g., type, physiochemical properties and quantity), the desired form of the energy carrier, end use requirements, health and environmental standards, economic conditions and project-specific factors [145].

4. Carbonization technology

4.1. Pyrolysis types, process and operational parameters

Carbonization is defined as the process by which high carbon content solid residues are formed from organic material usually by pyrolysis in an inert atmosphere [146]. During this thermal decomposition process, moisture and volatiles are driven off, leaving a solid residue (char), liquids (condensable vapours) and permanent gases. Slow pyrolysis is a preferred process for carbonization since it maximizes char yield and is characterized by slow heating rates (typically 5–80 °C/min), long solid and gas residence times, and relatively low temperatures (typically 300–600 °C) in the absence of oxygen [147]. Table 4 provides an overview of the different pyrolysis types, based on reaction conditions and product yields.

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 large quantities of intermediate products that are produced, and the variation in composition of biomass feedstock [152,153]. Conversion characteristics can be grouped into thermochemical (e.g., ash and volatile yields, reactivity of volatile products), intra-particle rate (e.g., particle thermal properties, moisture content, size, kinetics and energetics of chemical processes) and extra-particle rate (vapour-particle heat transfer, residence time and mass transfer conditions are dependent on the type of conversion unit) [154]. Pyrolysis of biomass is generally modelled on the basis of apparent kinetics accounting for the primary decomposition reactions, as well as the secondary reactions [155,152]. Primary char is formed directly from the solid-phase biomass carbon atoms. Secondary char is formed from volatiles that redeposit within the structures of the initial primary char [156].

Many researchers have studied the influence of pyrolysis operating conditions on product yields and it is generally accepted that the process parameters which most influence the product distribution are pyrolysis temperature, heating rate, residence time and reactor pressure [157–163,152,150]. 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 [164,165]. Several authors have analysed the product composition resulting from the pyrolysis of cellulose [166–168], hemicelluloses [167,169,170] and lignin [171,172]. These constituents differ markedly in their thermal stability with lignin being the most stable. Shafizadeh [173] has shown that hemicellulose decomposes at 225–325 °C, cellulose at 325–375 °C, and that lignin decomposes gradually over the temperature range of 250–500 °C.

From a practical standpoint, the pyrolysis conditions which favour high char yields are [58,174,156,149]:

- High lignin and nitrogen content in the biomass.
- Low moisture content.
- Pyrolysis temperatures less than 400 °C, but lower temperature also leads to lower fixed carbon content.
- Elevated process pressure (1 MPa) because a higher concentration of pyrolysis vapour increases the rate of secondary reactions.
- Long vapour residence time because extended vapour–solid contact promotes secondary char formation.
- Low heating rate due to slow formation (and escape) of organic vapours from feedstock particles.
- Large biomass particle size to reduce heat and mass transfer rate within feedstock particles.
- Efficient heat transfer to feedstock to minimize biomass burn off.

4.2. *Heating methods*

Different heating methods exist to initiate pyrolysis and maintain sufficiently high temperatures during carbonization. These methods vary as to whether oxygen is present (oxic pyrolysis) or oxygen is absent (anoxic pyrolysis). The energy required to drive the process can be supplied either: (i) directly from heat produced from exothermic reactions, (ii) directly from combustion of pyrolysis fuel gases derived from by-products and/or feedstock, (iii) indirectly from flue gases through a heat transfer surface, or (iv) indirectly from heat carriers other than flue gases (e.g., sand, metal spheres, etc.) [149]. The first three heating methods are considered relevant for low-tech, small-to medium-scale production of char [156,47].

4.2.1. *Oxic pyrolysis by partial combustion (autothermal systems)*

During oxic pyrolysis, a portion of the feedstock in the reactor is combusted with controlled addition of air to produce hot gases which provide heat to convert the remaining biomass (Fig. 1). By combusting a portion of the biomass, the yield of char is reduced. Therefore, it is best to operate these systems in areas where raw materials are inexpensive. To preserve the produced charcoal, air must be limited, which results in the formation of products of incomplete combustion (PIC), including methane and other species with high global warming potential. Many of these PICs condense and form particulate as soon as they are released in the atmosphere, creating visible and respirable smoke. Nevertheless, this is the method by which most fuel charcoal is made in developing countries. Without proper control and expertise in the art, these rudimentary methods can be very inefficient, with yields as low as 5%. Oxic pyrolysis methods include controlled open fires, traditional earth mound kilns and masonry or metal kilns, and there is often poor control of the reactor's internal temperature with regard to spatial uniformity and duration of treatment. These systems typically have low capital costs partly because no heat transfer surfaces are needed and condensable products are usually not recovered.

4.2.2. *Anoxic pyrolysis by indirect heating*

For indirect heating, the reactor is arranged as a retort, a reactor vessel that is heated externally and arranged to capture gaseous and vapour products, and into which no air can go in (Fig. 1). The biomass feedstock is placed in the retort and an external source provides the heat necessary for pyrolysis through the vessel walls. Initial heating dries the feedstock after which the continued heat addition results in the temperature reaching the point where pyrolysis starts. Pyrolysis gases are emitted and are routed to a combustion zone outside the retort vessel, where they can be combusted completely, and the heat generated is used to maintain pyrolysis in the retort. In an efficient system, only a portion of the heat produced from combustion is needed to drive the pyrolysis, leaving excess heat to dry feedstock, initiate pyrolysis in subsequent reactors or is harnessed for other purposes (e.g., heating water). This method is suitable for the recovery of volatile matter and produces relatively high yields of char and by-products (Toole et al., 1961; [47]). Additionally, indirectly heated pyrolysis with a retort offers improved process control and reduced harmful emissions compared to most oxic pyrolysis methods. Since all heat required for pyrolysis is transferred through the reactor walls and heat transfer inside the biomass bed is relatively slow, large reactors cannot depend solely on indirect heating, but need to be supplemented with internal heat transfer surfaces or direct heating.

4.2.3. *Carbonization by contact with hot gases (direct heating with inert gases)*

As the size of the retort increases, retort designs suffer from increasing problems, which include poor heat transfer and, thus, slow carbonization. Both raw biomass and charcoal are good thermal insulators; therefore it can often take hours or days for the externally applied heat to fully carbonize the biomass feedstock. This problem can be addressed by introducing hot combustion gases, which are almost oxygen-free, into the retort. The hot gases make direct contact with the bed of feedstock and significantly increase the rate of heat transfer to the material. Once pyrolysis of the feedstock is occurring, the pyrolysis gases are combusted and recirculated into the retort vessel (Fig. 1). One challenge when recirculating the combustion gases into the retort is the dilution of pyrolysis gases with non-combustible CO_2 and H_2O combustion products. The amount of combustion gases which are fed back through the reactor must be controlled and limited to maintain reactor product gas flammability [156]. Since some fuel is needed to initiate combustion, wood of inferior quality, leaves or other low-value residues can be combusted to initially provide heat. During carbonization with recirculated combustion gases, char and by-product yields are typically high, and due to the relatively high complexity and equipment requirements, these systems are suitable for use at medium- to large-scale [47].

4.3. *Slow pyrolysis products*

The product distribution between the three phases (solid, liquid, gas) is influenced by process conditions, i.e., the heat transfer rate to unreacted feedstock particles, the maximum reactor temperature and the feedstock particle residence time [176]. A fraction of all three product types (solids, condensable and non-condensable gases) are present, even in slow pyrolysis.

4.3.1. *Solids*

The slow pyrolysis process is tailored to maximize the yield of the solid product. Char intended for domestic cooking typically contains 20–30% (by mass) volatile matter, with as much as 40% being marginally acceptable [147]. Charcoal containing high volatile content is easier to ignite, but may emit more visible smoke, while low volatile charcoal is more difficult to light and burns with low emissions of visible smoke. A good-quality commercial charcoal can have a net volatile matter content (moisture free) of about 30% [177]. The ash content of a good-quality charcoal is between 0.5% and 5%, resulting in a range of calorific values between 28 and 33 MJ/kg [99]. The ash content of the feedstock varies widely and influences the yield of

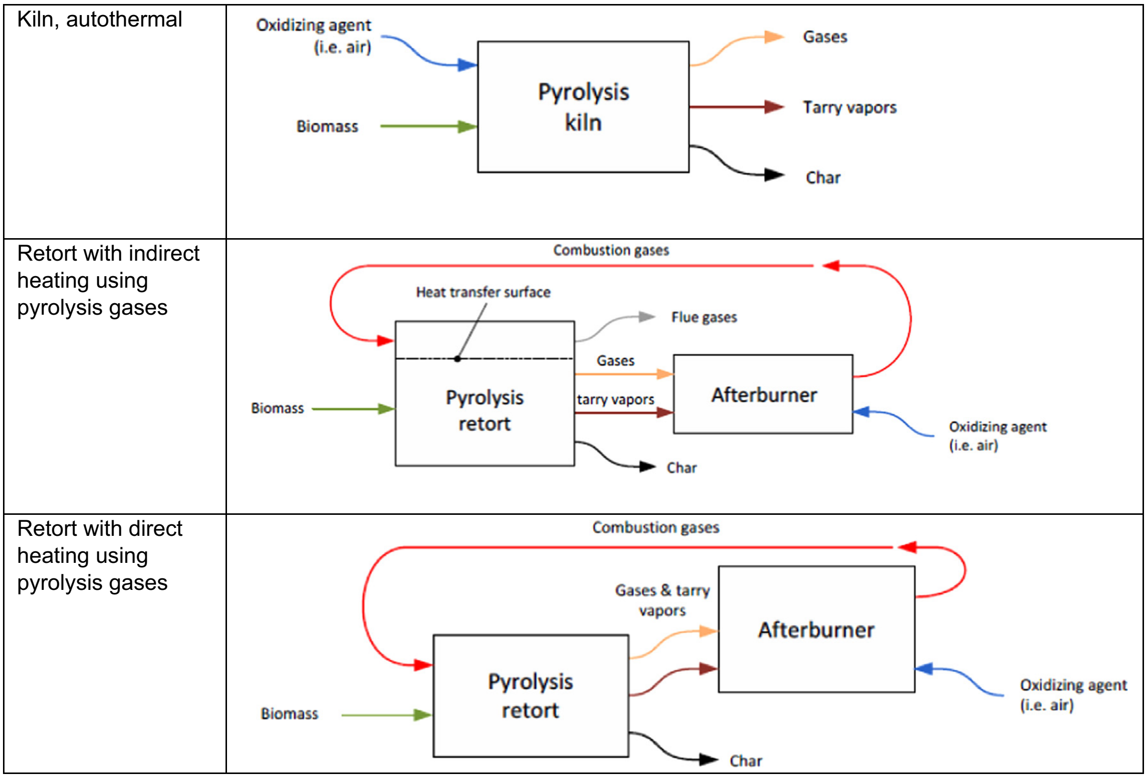

Fig. 1. Reactor and material flow arrangements in carbonization [175].

char [178,179]. Generally, woody feedstock produces char which contains low proportions of ash ($<1\%$ by mass), whereas biomass with high mineral content such as grass, grain husks and straw residues produce char with high ash contents [178]. These feedstock may contain ash content up to 24%, or even 41% by mass, such as rice husk and rice hulls, respectively [149].

Aside from feedstock type and moisture content, the physical and chemical composition of the char product is also dependent on the heating method and heat treatment temperature (HTT) during the conversion process (see Section 4.2). Lehmann and Joseph provide a thorough review of the effects of conversion process conditions, particularly treatment temperature, on biochar properties [26]. Char properties, such as elemental composition and microstructure, are more important for the production of activated carbon and less so for fuel applications.

The elemental composition of char can be represented by the ratios of oxygen-to-carbon (O/C) and hydrogen-to-carbon (H/C), which are indicators of maturation and aromaticity. Both ratios decrease with increasing pyrolysis temperatures, heating time and presence of reagent oxygen. Reported H/C and O/C values are typically ≤ 1 and ≤ 0.6, respectively [180,181]. Pyrolysis in oxic conditions generally produces char with lower O/C and H/C ratios due to partial oxidation of volatile matter.

The density and porosity of char has been shown to be highly dependent on heating conditions. The internal surface area of char increases by increasing the heat treatment temperature (HTT) up to the point of deformation. Laboratory tests of wood and crop residue pyrolysis show that at HTT 500–750 °C, the internal surface area is $>300\ m^2/g$, an order of magnitude greater than pyrolysis below 500 °C [182,183]. As pores are formed in char, the bulk density of the char particles decreases. However, the molecular packing and alignment of carbon atoms increases with pyrolysis reaction severity resulting in an increased particle density.

4.3.2. Liquids

Bio-oil represents the condensed vapour fraction with a lower heating value of 13–18 MJ/kg wet basis [184]. The major composition of bio-oils produced via pyrolysis are organic acids, esters, alcohols, ketones, phenols, aldehydes, alkenes, furfurals, sugars and some inorganic species [185]. They can be converted into valuable chemicals, fuels, and distillates used in engines and turbines for power generation. Currently, bio-oil production is not economically viable in small-scale pyrolysis units [175]. Bio-oils are complex mixtures of at least 74 different compounds, which are chemically unstable, not distillable and recognized as being toxic and corrosive due to their low pH, 10–15% water content, and high concentration of oxygenated and phenolic compounds, which can cause eye and skin damage and have been demonstrated to be non-carcinogenic and -mutagenic [186,175]. As in all dry pyrolysis processes, condensation of bio-oils and tar on the char product should be avoided to prevent contamination with polycyclic aromatic hydrocarbons (PAHs) [176]. Due to their crude and inconsistent nature, thermal instability, and corrosive properties, liquids obtained through biomass pyrolysis cannot be directly used as transportation fuel [161,187]. Several intensive upgrading steps (such as hydrodeoxygenation, catalytic cracking, emulsification, steam reforming, and chemical extraction) are required to refine bio-oils to usable transportation fuels [188].

4.3.3. Gas

Pyrolysis gases consist of condensable and non-condensable (permanent) fractions. The condensable fraction, described under liquids, contains methanol (CH_3OH), acetic acid (CH_3COOH), water vapour (H_2O), and tars (Brito, 1990 in [189]). The non-condensable gases include CO_2, CO, H_2, CH_4 and other light hydrocarbons, as well as particulate matter and more complex compounds like polycyclic aromatic hydrocarbons (PAH). The exact combination of compounds present in the mixture depends on the original feedstock pyrolysis process conditions. The resulting mixture, usually lower than $1\ Nm^3/kg$ [36], is combustible with a calorific value of

Table 5
Average emissions factors (g emissions/kg dry wood) for a traditional and small-scale charcoal kiln (adapted from Smith et al. [193]).

	CO_2	CO	CH	TNMHC	TSP	PIC	Gases+TSP	N_2O
Drum kiln[a]	434	98.1	16.6	20.9	1.17	136.8	571	7.75e−3
Earth mound kiln	334	65.7	8.09	27.2	0.66	101.6	435	1.44e−3

TNMHC: total non-methane hydrocarbons.
TSP: total suspended particulates.
PIC: products of incomplete combustion.

[a] Constructed using a repurposed 200 L oil drum (e.g. ARTI and D-Lab kilns).

5–15 MJ/kg (Raveendran and Ganesh, 1996 in [189]) or 11–22 MJ/Nm^3. During slow pyrolysis, approximately 70% of the mass and 50% of the energy embodied in the woody feedstock escapes in the form of pyrolysis gases [189].

4.4. Emissions and health aspects

Emissions associated with the char production units and use-phase devices are not adequately understood [190]. Apart from CO_2, water vapour, CH_4 and NO_X, particulate matter, products of incomplete combustion (PIC) such as CO, condensable hydrocarbon vapours, soot and acids (e.g. formic and acetic) are emitted. PAH species, many of which are known to be carcinogenic, are also emitted during char production [38].

Inadequate characterization of production-related emissions is especially troublesome for small systems, for which environmental regulations are less stringent or completely absent, and because the operation is variable from unit to unit and never reaches steady-state [191,190]. Traditional methods are less efficient than modern systems. The emissions from traditional systems can be high as all volatile gases and vapours are vented directly to the atmosphere, resulting in the release of harmful air pollutants which can pose risks to human and environmental health. This has resulted in significant concern regarding the increased adoption of these methods [192]. Average emissions factors for traditional (earth mound) and small-scale (drum) kiln technologies are presented in Table 5 [193]. Of note are the significant emissions of PIC which pose the most significant human health and environmental risks. Other research (Moskowitz, 1978 in [93]) has reported that the total suspended particulates (TSP) from an uncontrolled batch kiln can range from 197 to 598 g/kg charcoal produced, meaning that between 20% and 60% of the biomass entering the kiln leaves as TSP. Controlled, continuous kilns still have TSP emissions, ranging between 9 and 30 g/kg (Moskowitz, 1978 in [93]). Black carbon (BC) is a powerful climate-forcing agent formed through the incomplete combustion of fossil and biomass fuels. The fact that the TSP emitted from char production and use contains BC, which is likely significant, reduces the climate benefits derived from such projects. To mitigate atmospheric emissions of PIC, pyrolysis gases can be connected to a central flue and afterburner, which further oxidizes kiln emissions (Yronwode, 2000 in [191]).

To reduce the negative impact from pollutant emissions, modern slow-pyrolysis technology developers need to design technology that conforms to relevant regulatory and economic requirements. This means that high environmental standards have to be met, and the losses of potentially valuable products to the atmosphere eliminated. Like temperature and pressure, emissions can be more readily controlled in modern pyrolysis and gasification systems using process and control technology [190]. Typical exhaust gas emission control devices include particulate filters, cooling towers, wet scrubbers, etc. [36]. There is extensive literature on the reaction conditions conducive to the formation of PAHs and dioxins (e.g. [194,195]). It should be noted that these are usually in reference to more commonly employed thermal-conversion processes, such as gasification and incineration; however, this knowledge can be adopted for pyrolysis reactor design [196].

Health and environmental risks exist along the entire process chain for solid fuels from carbonized waste. During the collection and transportation steps (waste chain), the risks can include long-term adverse effects on soil nutrient content and pollutant emissions from transportation. Potential risks during the production step include personal injury (e.g., burns, smoke inhalation), concentrated emissions of particulate and PIC, and land scorching. During the application/use step, the risks include emissions from product distribution and human exposure to air pollutants (namely, carbon monoxide and respirable particulate) produced during fuel combustion [190]. However, research investigating use-phase emissions and efficiency show that carbonized fuels exhibit significant advantages over uncarbonized fuels (e.g., firewood, briquettes) [197].

Because pyrolysis systems are designed to only partially combust biomass, emissions that are harmful to the environment, such as methane, carbon monoxide, alkanes, oxygenated compounds, and particulate matter, as well as organic compounds, such as ethane, ethanol and polycyclic organic matter (POM), and pyroacids are produced. Continuous char production technology is more amendable to emissions control than batch production technology because the composition and flow rate of emissions are relatively constant. Afterburners and cyclones are effective means to control the emissions and recover products from continuous multiple hearth kilns at industrial scale. Emissions control in batch-operated kilns is challenging due to the inconsistency in emissions composition and quantity over the course of the conversion process. Some batch kilns employ afterburners to reduce harmful emissions, but most do not [47].

4.5. Overview of existing technologies

Until the beginning of the 20th century, nearly all charcoal was produced using traditional methods, which typically consisted of either an earthen pit that was filled with wood, ignited and covered with earth, also known as an *earth pit kiln*, or a pile of wood that was ignited and covered with earth, also known as an *earth mound kiln*. Carefully placed openings in the earthen mound allowed for the exit of gaseous and aerosol pyrolysis products and the entry of air for combustion and heat generation. These technologies are low-cost, simple to construct, scalable, profitable and can be applied nearly anywhere, accounting for their continued widespread use. Charcoal yields from traditional kilns are variable and mostly dependent on the moisture content of the woody feedstock and the experience of the kiln operator. Yields as low as 10% and as high as 30% have been reported [65]. Inconsistency in the quality of the charcoal produced due to the difficulty in controlling the process, and detriments to the environment, among other effects (e.g., unsustainable forest resource extraction), contribute to challenges and concerns with traditional methods. Overviews of traditional charcoal-making technologies can be found in [177,99], and a review of the technical, economic, and climate-related aspects of biochar production technologies is presented in [198].

In general, slow pyrolysis technologies can be classified in terms of their reactor type, operation type (batch or continuous), scale, construction material, conversion efficiency, emissions and auxiliary requirements. Table 6 provides an overview of existing carbonization technologies, ranging from small scale, low-cost pyrolysers to a few more modern, rather complex and expensive carbonization systems.

In industrialized countries, commercial MSW pyrolysis technologies typically do not run only with primary products (gas, oils and char) as end products. Rather, most are combined with gasification, combustion and smelting; the moderate-calorific-valued fuel gas produced through gasification is predicted to be a competitive choice in the future [224,36]. For most modern combined technologies in which process products are collected or recycled, the large capital cost may be unaffordable in developing countries where improved pyrolysis technology is needed. As these MSW pyrolysis technologies only accept pre-treated MSW instead of raw MSW, feedstock pre-treatment is a necessary step for pyrolysis operations. This generally includes separation of undesirable materials (e.g., metals), size reduction and sometimes drying prior to the feeding the pyrolysis reactor. All commercial pyrolysis processes are equipped with emissions' abatement devices similar to those found in incineration plants, ensuring a clean pyrolysis process [36]. A more comprehensive overview of advanced systems is presented in [47,36].

5. Discussion and evaluation of suitability

5.1. Assessment criteria

To assess the suitability of different technologies for the carbonization of urban biowaste in LAMICs, three interrelated categories are used, namely technical, financial and environmental criteria.

- Technical aspects

– Suitability for biowaste: Traditional slow pyrolysis technologies were designed to carbonize wood logs. The physical characteristics of biowaste (e.g., wet, non-uniform feedstock with smaller particle size) require different treatment methods, which need to be considered in the system design.

- Feedstock pre-treatment: Some technologies require pre-treatment of feedstock (e.g., drying, particle-size reduction), which increases labour-, time- and energy-intensity.
- Throughput: The throughput of a carbonization system is the amount of waste treated per time unit. This depends on a combination of the reactor volume, mode of operation (batch or continuous) and conversion time. Higher throughput means higher treatment capacity and is, hence, preferable.
- Portability: The ability of a pyrolysis system to be moved from one location to another can be an important criterion in system selection for spatially dispersed and low-density resources. Bringing the system to the point of waste generation reduces collection and transportation costs. A portable system could be hired when a suitable quantity of feedstock has accumulated or if storage capacity is used up at the point of generation/collection. Additionally, concerns over security and theft favour portable technologies that can be stored in a safe location.
- Labour intensity: A technology that requires high labour input is not necessarily a positive or a negative aspect. The system has to be distinguished by the type of labour: manual, low-skilled labour is favourably perceived as it contributes to the generation of local employment. Highly automated processes, however, require knowledge, skills and equipment which might not be available locally, require extensive training or have to be imported and, thus, present a risk to sustained operations. The ability of a process to operate without the need of highly skilled labour is an advantage to its application in LAMICs.
- Controllability: Carbonization technologies which allow for the control of process conditions (e.g., temperature, residence time, energy consumption) generally exhibit higher char yields, quality and a favourable energy balance and are, thus, preferred. The carbonization process in autothermal systems is more difficult to control compared to externally heated systems. A process that is inherently self-correcting or operator controllable is preferred in a LAMIC context.
- Lifespan: The lifespan of a technology in the LAMIC context depends on the construction material, number of parts, maintenance requirement, and susceptibility to failure. High-tech industrial equipment might be well designed, but is not necessarily suitable for potentially harsh conditions and infrequent maintenance, which can be the case in LAMICs. Technologies that are robustly built from readily available materials and parts, with few components that are susceptible to failure, are preferred for LAMICs.
- Conversion efficiency: Char yield is higher in externally heated and pressurized systems compared to autothermal and unpressurized systems. Yield data was collected from literature and the technologies were evaluated on a relative basis.
- Demonstrated use: Technologies that have proven their technical functionality over prolonged periods of time and in various settings are rated higher compared to those still in the research or experimental stage.

- Financial aspects

- Capital cost: High investment costs reduce the accessibility of the technology to potential users in LAMICs interested in establishing local and independent operated carbonization systems. Cost estimates are gathered from literature or estimated based on components, and technologies are rated on a relative basis.
- Operating cost: Operating costs are linked to the staff and energy needed to sustain the process, but also to the pre-treatment requirements of the feedstock and maintenance. Technologies with complex operation and high operating costs might not be affordable or financially sustainable in the long-term.
- Gas recovery: The economic viability of a char production business is greatly improved if the pyrolysis products other than char can also be used for heat or other applications. However, depending on the mode of operation, the composition of gas and vapour products varies throughout the carbonization process, making the recovery of valuable co-products difficult. Continuously operated systems have an advantage compared to batch-fed systems as product recovery is easier. In between batch and continuous operations are semi-batch or quasi-continuous operations, i.e., having multiple retorts/kilns, each one operating at a different stage of the carbonization process (i.e., loading, drying, heating, pyrolysis, cooling and unloading) at a given point in time. By sharing a common afterburner in a semi-batch process, heat utilization can be improved among different retorts/kilns [175].

- Environmental and health aspects

- Pollutant emissions: Emissions of environmentally hazardous compounds with high global warming potential are related to system controllability, by-product recovery and handling, and complete combustion of gaseous products (i.e., using an afterburner). Improved kilns generally lead to lower quantities of emissions compared to traditional kilns [193,201]. In general, continuous systems have lower emissions than batch systems due to steady gas production that can be consistently treated. Additionally, pollutant emissions from significant auxiliary inputs (e.g., electricity generation) are considered, although with lower consideration than direct emissions. Pollutant emissions data was obtained from literature or inferred based on the description of operations. Technologies are evaluated on a relative basis.
- Tar recovery: Tars present environmental and human health hazards and can have alternative uses (e.g., treating lumber, being refined to liquid fuels). The recovery of tars and tar contaminated process water is favourable.

Table 6
Classification and important characteristics of carbonization technologies.

Reactor type	Process type	Capacity	Construction materials	Conversion efficiency (mass%)	Energy source	Residence time	Emissions (g/kg charcoal)	Auxiliary requirements	Portability/permanence	Capital Cost	References
Earthen kilns											
Earth pit, mound	Batch	50–32,000[1] kg, 3–100 m^3, 180–330 m^3[2]	Soil, sod	$<$ 15, 22–35[1], 90 kg char/m^3 wood[2], 20[3], 15–16 (oven dry)[4], 27[5]	Partial oxidation	5[1]–20 days, 20 days/180 m^3[2], 14–24 days[4]	CO_2: 1058–3027 CO: 143–333 CH_4: 32–62 TSP: 13–41[1]	None	Impermanent	$27/ton charcoal[3]	[177] FAO 1983, [199] Stassen 2002, [62] Girard 2002, [200] Noble 2011, [1][201] Pennise et al. 2001, [2][202] USFS 1961, [3][203] Ando et al. 2004, [4][204] Nturanabo et al 2011, [5][205] KEFRI 2006, [6][193] Smith et al. 1999
Casamance, Kasisira, Bus kiln	Batch	50–1000 kg, 60–130 m^3[1]	Soil, sod, sheet metal/drum	15–31[3], 100 kg/m^3 wood[1], 30 (oven dry)[4]	Partial oxidation	5 days[1], 6–8 days[4]	n/a	None	Impermanent	$200	[1][206] Karch et al. 1987, [2][62] Girard 2002, [3][199] Stassen 2002, [4][204] Nturanabo et al. 2011, [205] KEFRI 2006
Brick kilns											
Brazilian Beehive	Batch	20 t wood[1], 8–50 m^3, 180–330 m^3[2]	Brick, mortar	13–35, 29[1], 90 kg char/m^3 wood[2]	Partial oxidation	2[1]–10 days, 20–30 days/270 m^3[2]	CO_2: 1533 CO: 373 CH_4: 57[1]	None	Stationary	$150–1500[3]	[207] Simmons 1963, [177] FAO 1983, [199] Stassen 2002, [200] Noble 2010, [208] Stewart 1984, [1][201] Pennise et al. 2001, [2][202] USFS 1961, [3][209] Kristofferson 1986, [193] Smith et al. 1999
Argentine half orange	Batch	30 t wood	Brick, mortar	27	Partial oxidation	13–14 days	n/a	None	Stationary	n/a	[177] FAO 1983
Metal kilns											
Missouri	Batch	80 t wood[2]; 300 tpy charcoal[3], 350 m^3[4]	Steel, brick/concrete	5–20[1], 36[2], 25–33[4]	Partial oxidation	80 h[2]	CO_2: 543[2]-560[3] CO: 140[3]-162[2] CH_4: 37[2]-54[3] TSP: 160[3]	Tar recovery[2]	Stationary	$15,000[4]	[207] Simmons 1963, [1][210] FAO 2008, [2][201] Pennise et al. 2001, [3][211] EPA 1995, [4][209] Kristofferson 1986
Mark V	Batch	300–400 kg wood[1]	Steel	20–25[1], 30–31[2]	Partial oxidation	23–42 h[2], 38 h[3]	n/a	None	Portable	$2000–5000[1]	[1][209] Kristofferson 1986, [2][208] Stewart 1984, [3][212] Killmann and Fink, 1996
CDhimney kiln	Batch	4–14 m^3	Sheet metal & iron beams	0.3–0.4 m^3 char/m^3 wood	Partial oxidation	52-84 h	n/a	None	Portable	N/A	[213] Olsen and Hicock 1941
Drum reactors											
Vertical (D-Lab, ARTI, Kinyanjui)	Batch	200 L, 12–15 kg wood[4]	Mild steel	3–30, 21[2], 19[3], 23–28[4]	Partial oxidation	0.5–4 h, 1 day[2]	CO_2: 1517 CO: 336 CH_4: 57.7 TSP: 4.2[5]	None	Portable	$13–17[1], $61/ton charcoal[2]	[177] FAO 1983, [1][214] Singh 2010, [215] Rao 1984, [208] Stewart 1984, [2][203] Ando et al. 2004, [3][206] Karch et al. 1987, [4][209] Kristofferson 1986, [5][193] Smith et al. 1999
Horizontal (KEFRI)	Batch	200 L	Mild steel	24[1], 28–30 (bamboo)[2]	Partial oxidation	6–12 h[2]	n/a	None	Portable	$13-17	[1][208] Stewart 1984, [2][205] KEFRI 2006

Large drum, Mark V, TPI, Black Rock Forest, Ring, New Hampshire	Batch	7 m^3, 2–5 m^3 [1], 100–150 tpy	Mild steel	20–30	Partial oxidation	1–4 days	20–45% CO$_2$, 31–34% CO, 12–16% CH$_4$	None	Portable	\$60–1000	[177] FAO 1983, [200] Noble 2011, [208] Stewart 1984, [216] Levy 1995, [1][202] USFS 1961, [205] KEFRI 2006
Low-tech retorts											
Adam (ICPS: Improved charcoal production system)	Batch	3 m3, 750 kg wood (wet)	Brick or earth blocks	30–42 (dry basis)	Partial oxidation & volatile combustion	12 h	n/a	None	Stationary and portable version	€300	[217] Adam 2009
JMU horizontal drum, Meko kiln	Batch[1], Semi-batch[3]	6–7 kg/batch[1], 113 L	Concrete block, fire brick, steel plate, drum & pipe	19–24[1]	Ext. heat & volatile combustion	60 min (hot period)[1], 13 h (wood)[2]	n/a	None	Stationary/ portable	\$800[1],	[1][218] Prins et al. 2011, [2][219] KFS 2013
High-tech retorts											
Carbo Twin Retort	Batch	900 tpy (hardwood), 2 × 5 m^3 [1]	Steel	30–33[2]	Ext. heat & volatile combustion	32–36 h (includes cooling)[1]	complies w/ Dutch emission standards	Oil burner, fork lift, hoist & rail, sand lock, EGR	Stationary	€1 million+[1]	[1][210] FAO 2008, [2][220] Rautiainen et al. 2012
Wagon, Arkansas retort	Batch	6000 tpy (wood)	Steel	n/a	Volatile combustion	25–35 h (includes cooling)	n/a	Rail & car system w/ mech. drive; exhaust gas & heat exchange piping; external comb. chamber	Stationary	High maintenance & operating cost	[210] FAO 2008
Calusco Tunnel Retort	Batch or semi-continuous	6000 tpy	High-temp. steel	n/a	Volatile comb.	25–35 h	n/a	n/a	Stationary	High	[210] FAO 2008
Lambiotte, SIFIC, CISR	Continu-ous	≤ 12,500 tpy (oak wood)[1], 3000–20,000 tpy[3]	Steel	30–35[2,3]	Volatile combustion	n/a	n/a	lock-hopper; closed gas loop piping; condensers & scrubbers (SIFIC), ext. comb. chamber	Stationary	\$0.5–2 million	[1][210] FAO 2008, [2][149] Duku et al. 2011, [3][209] Kristofferson 1986
Rotary, Pro-Natura Pyro 7 rotary/screw	Continuous	n/a		20–30	Ext heat & volatile combustion	n/a	Low	Electricity		High	[210] FAO 2008, [149] Duku et al. 2011, [221] Pro-Natura International 2004
Continuous multiple hearth	Continuous	2.75 tph charcoal[1]	Steel vessel and piping components	25–30[2]	Volatile combustion	n/a	CO$_2$: 492 CO: 160 CH$_4$: 50 TSP: 200[1]	Electricity (fan & motorized drive), gas recirculation piping	Stationary	n/a	[1][211] EPA 1995, [2][149] Duku et al. 2011
Flash carbonization											
HNEI Flash Carbonization	Batch	594 tpy/m^3 [3]	Steel vessel and piping components	30–40[1], 34–50[2,4]	Partial combustion	20 min[1]	n/a	Compressed air source, elec. ignition	Stationary	€180/ton charcoal[3]	[1][222] Antal et al. 2003, [2][210] FAO 2008, [3][41] BTG 2013, [4][149] Duku et al. 2011
Hydrothermal carbonization											
HTC-O by AVA-CO$_2$	Batch	3500 TS tpy, 2664 tpy char produced[2]	Steel vessels and piping components	37–60[1]	Steam[2]	5–10 h[2]	n/a	Mixing tank, high pressure reactors (22–26 bar), buffer tank, solid–liquid separation system, water treatment system	Stationary	€10–12 M[2]	[1][190] Brick et al., 2010; [2][223] Robbiani, 2013

n/a = not available; EGR = exhaust gas recovery; Tph/d/y = tonne per hour/day/year; TSP = total suspended particulates.

Table 7
Technology assessment matrix (drum reactor as baseline technology).

Assessment criteria	*Weight*	Reactor type							
		Earthen pit/ mound	Brick kiln	Metal kiln	Drum reactor (baseline)	Low-tech retort	High-tech retort	Flash carbonizer	HTC reactor
Technical aspects									
Suitability for biowaste	*3*	−1	−1	−1	0	0	0	0	+2
Feedstock pre-treatment	*2*	−1	−1	−1	0	0	−1	−1	+2
Throughput	*2*	−2	−1	−1	0	0	+2	+1	+1
Portability	*2*	−2	−2	−1	0	−1	−2	−1	−1
Labour intensity	*2*	−1	+1	+1	0	0	−1	−1	−1
Controllability	*2*	−2	−1	−1	0	+1	+2	+2	+2
Conversion efficiency	*2*	0	0	0	0	+1	+1	+2	+2
Lifespan	*2*	−2	+2	0	0	0	+2	+2	+1
Demonstrated use	*2*	+1	0	0	0	−1	−1	−2	−2
Financial aspects									
Capital cost	*3*	+1	−1	−1	0	−1	−2	−2	−2
Operating cost	*3*	+1	0	0	0	0	−2	−2	−2
Gas recovery	*2*	0	0	0	0	+1	+1	+1	+1
Environmental and health aspects									
Pollutant emissions	*3*	0	0	0	0	+1	+1	+1	+1
Tar recovery	*1*	−1	0	0	0	+1	+1	+2	+2
Water requirement	*2*	0	0	0	0	0	0	0	−2
Safety	*3*	−1	+1	0	0	+1	+1	−2	−2
Total weighted score		**−19**	**−7**	**−12**	**0**	**+6**	**+1**	**−7**	**−1**
(Overall ranking)		*(7)*	*(5)*	*(8)*	*(3)*	*(1)*	*(2)*	*(5)*	*(4)*

Note: The italic numbers in the 2nd column are weights (and not scores). The italic numbers in brackets in the last row are ranks (and not scores). All other (non-italic) numbers are scores.

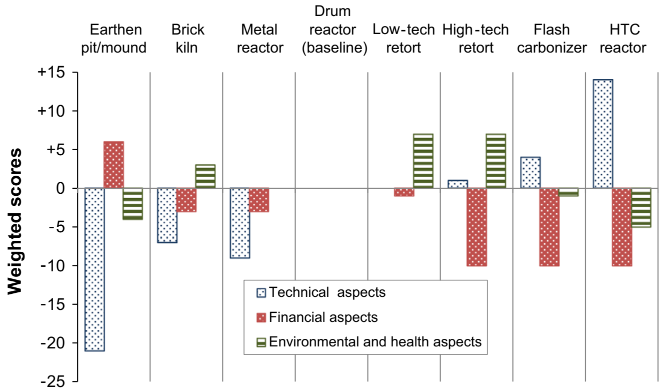

Fig. 2. Assessment results by criteria categories: technology suitability compared to drum reactor.

– Water requirement: Water is a precious resource in many LAMICs; thus, systems that run without water addition are preferred

5.2. *Technology assessment matrix*

The main technology categories were assessed by the authors based on their experience and the literature review provided in this article. A five-point scale (+2: much better than, +1: better than, 0: equal to, −1: worse than, −2: much worse than) was used to compare the different options with the baseline technology. Drum reactors were taken as the baseline technology as this is a widespread carbonization technology in developing countries, and are mostly used for the treatment of agricultural waste. Weights were attributed to indicate the relevance of each criterion for overall technology suitability (3: high importance, 2: medium importance, 1: low importance). Total scores were achieved by multiplying weights and scores, which then allowed for overall ranking. Table 7 presents the overall suitability assessment matrix.

The low-tech retorts such (e.g., Adam retort, Meko kiln) received the highest weighted score and, thus, ranked first in terms of overall suitability for biowaste carbonization in LAMICs, followed by high-tech retorts (e.g., Pro-Natura Pyro 7). Ranking third were drum reactors (e.g., ARTI, D-Lab). Metal kilns and earthen pit/mounds ranked lowest.

A more informative overview is provided in Fig. 2, which illustrates the suitability of the assessed reactor types grouped into the technical, financial, and environmental and health categories. The summed results of each aspect category are expressed as weighted score differences in comparison to the baseline (drum reactor). It reveals that the high-tech systems (retorts, flash carbonizer and HTC) score positively from a technical point of view, but receive considerably negative scores in the financial category. Low technical scores are attributed to earthen pit/mounds, followed by metal reactors. Low-tech and high-tech retorts perform better than the drum reactors in terms of environmental and health aspects.

5.3. *Other relevant aspects*

Not only is the appropriateness of the technology important to consider, but also the specific suitability of waste types for carbonization should be taken into account. To select suitable wastes, simple tools for the assessment of waste carbonization suitability have been developed by BTG [41] and Lohri et al. [225]. The former is named Alternative Charcoal Tool (ACT) and consists of the following four parts: (i) feedstock selection, (ii) market selection, (iii) technology selection, and (iv) production cost selection. The latter distinguishes between: (i) availability/accessibility criteria and (ii) physical-chemical properties.

For source-segregated waste, moisture content is one of the most relevant parameters. Most pyrolysis units work best using a

Table 8
Differences between conventional wood charcoal and charcoal briquettes (adapted from Mwampamba et al. [40]).

	Wood charcoal	Charcoal briquettes
Raw material	Wood	Agricultural & specific urban biowaste, char dust
Location of production	Almost exclusively rural	Peri-urban and urban
Efficiency of production	Traditional earth mounds and pits and metal and brick kilns: 15-–25%	Drum kilns and retorts: 15–20%
Energy value (HHV)	31–33 MJ/kg	22–29 MJ/kg
Ash content	$<5\%$	10–30%
Price	100–300$/t	150–250$/t
Ease of lighting	Easy to light	Harder to light (due to higher ash content)
Length of burn	Fast burning due to high energy and low ash	Slow burning due to higher ash content
Extinguishability	Can be put out for later re-use	Generally crumbles if extinguished, (depending on combustion stage) can be put out with sand for later re-use

feedstock with moisture content in the range of 10–20% [226]. However, as-collected biowaste can have a moisture content up to 70%, it requires a large energy input for the drying process. Although the drying process can reduce the overall efficiency of the process, directing the waste heat from the pyrolysis units to the dryers can mitigate inefficiencies [47].

The energy balance of a carbonization system can be improved by pre-treatment (drying) of feedstock, efficient heat transfer from heat source to substrate and reduced radiation loss from the reactor to the surroundings.

Due to the fragility of wood-based charcoal, handling and transportation results in breakages and in the formation of charcoal fines and dust accumulation in retailing sites, which cannot be sold or used without further processing [41]. According to Owen [227], around 10% of Africa's charcoal is thrown away before it reaches the stove, representing a tremendous waste of precious biomass in an industry already criticized for inefficiency and poor environmental practices. Charcoal dust has the shortest and simplest production chain of all alternative biomass feedstock considered for char carbonization. As a result, this is normally also one of the most cost-effective options to produce alternative charcoal for energy purposes [41]. Yet, it is a matter of debate how far charcoal dust briquettes can be considered sustainable, since they rely on the existence of a charcoal industry that most agree is currently operating unsustainably [39]. A number of commercial operators in Sub-Saharan Africa have recognized their opportunity and produce char briquettes either solely from charcoal dust or add it as a supplement to biowaste-derived char, and mixing together in the briquetting process [41,40].

Although wood-based charcoal and char briquettes have similar combustion characteristics, there are differences which have to be considered when promoting their use as cooking fuel (Table 8).

6. Conclusion

The present production practices of wood-based charcoal and the current management of solid waste in LAMICs are detrimental to environmental and public health. Increasing the value chain of organic waste by sales of recycling products offers a possible solution to these issues and can stimulate waste collection and enhance cost-recovery. Charcoal briquettes made from biowaste have the potential to contribute to a sustainable energy supply in LAMICs, particularly in markets where prices for wood-based charcoal are starting to reflect the real costs.

For economically viable waste-to-char-briquette-production, the high availability and accessibility of suitable feedstock is ideal and product acceptability on the part of the customer is crucial. For low-cost carbonization of organic solid waste, the feedstock should, thus, be continuously available in substantial quantities at no or low cost and its physical–chemical properties have to be suitable for pyrolysis: dry, unmixed, homogeneous, uncontaminated and with low ash content-in other words, separated and obtained near the source of generation. Hence, the majority of the organic fraction of municipal solid waste, such as household and market waste, are, therefore, not feasible for simple, low-cost carbonization as it is too wet and mixed.

A wide range of improved carbonization technologies with various capacities have been developed and deployed in the last decades, aiming at speeding up the process and increasing char yields. Low-tech retorts have been shown to be the promising systems as they combine various advantages of different technologies at reasonable costs. The highest and most consistent product yields can be achieved using (semi-) industrial retorts. However, due to high investment costs, these technologies are often not suitable for use in LAMICs. A technology assessment for biowaste carbonization in LAMICs revealed the technical, financial and environmental advantages and disadvantages of each reactor type. Each technology has distinct benefits and drawbacks and the reactor selection has to take into consideration the specific context and project objectives. For this, the Pugh Matrix is a viable tool which can be adapted accordingly (e.g., modification of weighting factors, baseline technology, scoring range, etc.).

The most widely utilized char production techniques in LAMICs pollute and are energy-inefficient. Further improvements are necessary to make them more efficient and more effort is required to meet the following objectives [191,228–230,151]:

- *Feedstock flexibility*: operational parameter adaptability, allowing broader range of potential feedstock to be processed.
- *Improved char yields and quality*: pyrolysis process control to ensure high, consistent product quality.
- *Energy efficiency*: continuous feed rather than batch processing, exothermic operation without air infiltration, waste heat recovery, and insulated reactors.
- *Reduced pollution*: emission control to minimize smoke, PICs, and criteria pollutants, continuous operation to facilitate emission treatment, recycling of volatile gases, and emission and environmental standards.
- *Operability*: continuous, steady-state operation, resulting in control of product quality, as well as workplace health and safety standards.
- *Scalability:* optimal for scale-up to sufficient size to reach the required economies-of-scale or smaller to not be limited by biomass availability.

Further research is needed to address the challenge of optimizing the carbonization process in order to maximize product quality and quantity, while also paying proper attention to minimizing costs and environmental concerns. It is recommended that the combined pyrolysis/gasification technology, equipped with gas scrubbing devices, should be distributed for MSW treatment in cities that can afford it. Also, in terms of low-cost systems, technology design and operational conditions should prevent the uncontrolled emission of toxic compounds and comply with environmental standards, similar to commonly employed thermal-conversion technologies such as gasifiers and incinerators. However, the favourable attributes of existing technologies that have gained broad adoption should be preserved where appropriate (e.g., ease-of-use, capital costs). Instead of focusing solely on char use as cooking fuel in households, the potential of char for small- and medium-scale industrial applications, where proper process monitoring and emission control can be guaranteed, should be explored. Beyond the technical aspects of char production in LAMICs, strategies for integrating alternative biowaste feedstock into existing supply chains should be explored. Additionally, suitable, context-specific policy recommendations to support the sustainable growth of energy from available biowaste materials should be made to garner government support.

Char production and utilization systems entail three components: (i) feedstock acquisition and preparation, (ii) feedstock conversion, and (iii) char post-processing, handling, transport and use. While this review mainly focused on the second component, the others also need to be included for a holistic overview of the opportunities and limitations of the use of biowaste-derived char as cooking fuel in LAMICs. Presently, there is a lack of technical demonstrations of commercial-scale slow pyrolysis char systems in LAMICs. However, comprehensive systems, including feedstock preparation and handling, pollution control, and product management, are essential for understanding full project dynamics and economics.

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