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Emerging trends in appropriate kiln designs for small-scale biochar production in low to middle income countries

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ABSTRACT

This paper reviews information about the design and performance of existing biochar production kilns to identify areas for further research and development. The kiln designs are categorized into flame curtain kilns, drum kilns, pyrolytic top-lit-updraft cookstoves, retort kilns, masonry kilns and others. Depending on the design, reviewed kilns can attain yield efficiency of 10–46 % and produce biochar containing 26–87 % fixed carbon with a calorific value of 14–40 MJ kg^{-1}. Comparison of available kiln designs is challenging as some of the data required are either unavailable or derived from experiments that use a single feedstock. However, a qualitative schematic comparison indicates that drum retort kilns are best suited for most applications in low-income settings. These designs would likely be improved to approach the theoretical maximum efficiency whilst improving the quality of biochar and reducing emission levels, by combining appropriate design features from other kilns.

1. Introduction

Efficient use of carbon and nutrients contained within agricultural and forest residues is important for achieving a circular economy. Residues can be used to improve soils after decomposition, either by incorporating them directly in situ or by incorporating them after composting or anaerobic digestion (Venkatesh et al., 2015). Alternatively, agricultural residues can be fed to livestock as they have a high fibre content that enhances digestion while also providing nutrition (Obi et al., 2016a). However, for some residues, such as rice husks and straw, the rate of decomposition and digestibility are low because the material possesses a high silicon content and a high carbon to nitrogen ratio (Herrera et al., 2022; Iqbal et al., 2020). Therefore, such residues are often burned or combusted in inefficient cookstoves as an energy source instead of being used for soil amelioration or livestock feed; this results in high nutrient loss, and high particulate matter, ammonium (NH_3) and carbon monoxide (CO) emissions (Herrera et al., 2022; Iqbal et al., 2020). According to Guoliang et al. (2008) and Iqbal et al. (2020), burning wheat straw, rice straw, corn stover and cotton stalks in open environments releases 4 to 9 g kg^{-1} of particulate matter with a diameter <2.5 μm ($PM_{2.5}$) and 57 to 105 g kg^{-1} of CO that causes environmental pollution. Higher exposure to $PM_{2.5}$ can result in respiratory complications and death; for example, between 2003 and 2019, over 44,000 people died annually in India because of $PM_{2.5}$ exposure (Lan et al., 2022). Burning crop residues on-farms exacerbates anthropogenic greenhouse gas emissions: between 2000 and 2017, on-farm biomass burning contributed 1.9×10^7 t to global anthropogenic methane emissions, which represented 5 % of the total from all sources (Patel and Panwar, 2023; Saunois et al., 2020). Burning organic residues on-farm also carries the risk of uncontrolled fires and destruction of property, while burning residues at sites close to the agriculture-forest margins may cause forest fires. In North American forested ecosystems, Campbell et al. (2018) estimated that 10 % of wildfires occur because of burning of forest residues in open environments, but when agricultural and forest residues are left to decompose in piles under very dry conditions, they can self-ignite and become an additional fire-risk (UNEP, 2019).

An effective, innovative, sustainable and simple way of adding value to surplus biomass residues that are currently not used is to produce biochar (Abukari et al., 2021; Nematian et al., 2021). Biochar is defined by the International Biochar Initiative (2013) as a solid material obtained from thermochemical conversion of biomass in oxygen-limited conditions (pyrolysis). Depending on the heating rate and residence time, the mechanisms of biomass pyrolysis can be categorized as slow, fast and flash (Hu and Gholizadeh, 2019). Slow pyrolysis uses low heating rate of less than 10 °C s^{-1} over many hours or days, fast pyrolysis has a heating rate of 10–200 °C s^{-1} for 0.5–10 s, while the heating rate in

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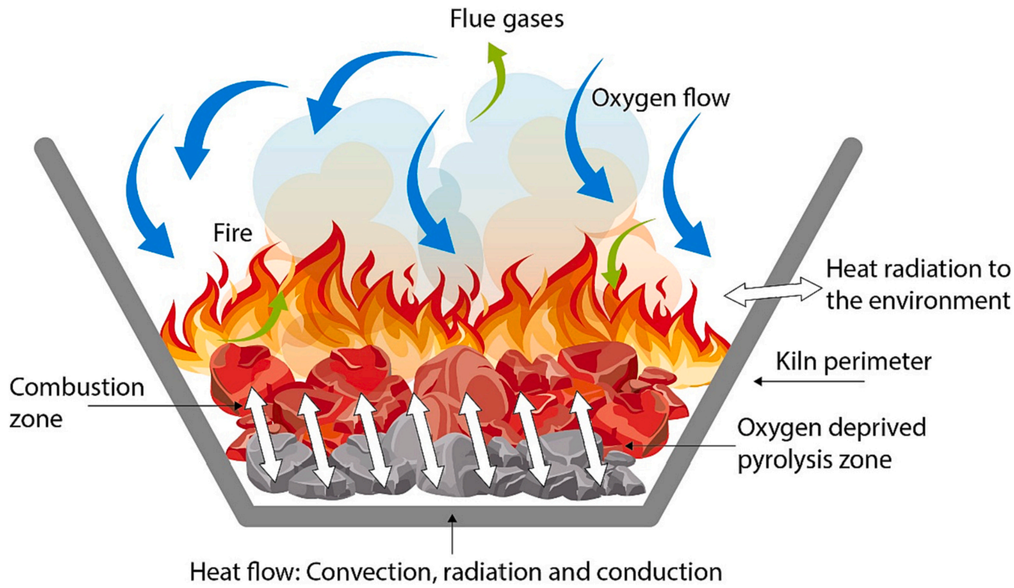

Fig. 1. Schematic diagram illustrating the working principle of flame curtain kilns.

flash pyrolysis is over 1000 °C s^{-1} over a period of less than 0.5 s (Fahmy et al., 2020; Hu and Gholizadeh, 2019; Rahimi et al., 2022). Biochar from biomass materials is mainly produced through slow pyrolysis at a process temperature range of 300–500 °C, and the process entails evaporation of free moisture in the feedstock at 100 °C (373 K), rapid depolymerization and volatilization of feedstock at temperature range of 200–450 °C, and sustained period of lignin degradation that starts with breakage of weaker bonds at low temperatures proceeding to stronger bonds across full temperature range of 250–500 °C (Hu and Gholizadeh, 2019; Luo et al., 2022; Pecha et al., 2019). The product is stable and can be used in fuel briquetting, for soil amelioration to enhance soil fertility and sequester carbon, in the pharmaceutical industry and in water treatment as an adsorbent to remove pollutants and heavy metals (Hansson et al., 2021; Konneh et al., 2021; Yu et al., 2022). Biochar production could also provide income and employment opportunities that could help to alleviate poverty in rural areas (Yaashikaa et al., 2020).

Over the past 2000 years, biochar production technologies have undergone development from simple ignition and burying of smouldering biomass to advanced kilns that optimise conditions for production of biochar (Kamarudin et al., 2022). These developments have led to highly automated modern commercial biochar production kilns, such as the fluidised bed kiln, the Henz retort kiln, the auger (screw) kiln, the entrained flow kiln and the tubular kiln (Campuzano et al., 2019; Luo et al., 2022; Rahmat and Rasid, 2016). These modern designs allow feedstock flexibility, uniform temperature distribution within the kiln and tighter control of pyrolysis conditions such as the temperature range, operating pressure, residence time and heating rate to enhance the efficiency of production, reduce emissions during pyrolysis and increase the quality of biochar (Luo et al., 2022; Yaashikaa et al., 2020). Although automated modern kilns that produce certifiable biochar using highly controlled processes with low noxious emissions are available on the market, the investment cost and subsequent maintenance costs are high (Cornelissen et al., 2016). For example, the purchase cost of an automated modern twin screw auger retort kiln that produces over 10 m^3 of biochar in 1–2 days at over 40 % efficiency based on the dry weight of feedstock is US$ 100,000 (Nematian et al., 2021; Vis, 2013). Apart from being complex to operate, these automated kilns also require electricity to power a motor that drives the screws to move the feedstock to the pyrolysis chamber (Campuzano et al., 2019; Luo et al., 2022). This means that their adoption in low to middle income countries, especially in rural areas, has remained largely impractical as they are unaffordable and require a skilled operator and grid connection (Ehrensperger et al., 2017). Therefore, the challenge for pyrolysis research in low to middle income countries has been to develop kilns that are not powered by electricity, can be used on-farm and can also attain a theoretical biochar yield efficiency of 50–80 % on a dry weight basis whilst maintaining low emissions and without compromising the quality of biochar or inflating the cost of the kiln (Bridgwater and Peacocke, 2000; Jayakumar et al., 2023). This will help in production of certifiable biochar among smallholder famers for carbon certification (Cornelissen et al., 2023). Therefore, this review promotes biochar production in low to middle income countries by providing an overview of emerging trends in small-scale biochar production and kiln development in such countries, highlighting areas that require further research and development to reduce emissions, and improve efficiency and biochar quality.

2. Categorization of biochar production kilns

Biochar production kilns used in low to middle income countries can be categorized as either flame curtain kilns, drum kilns, pyrolytic top-lit-updraft (TLUD) cookstoves, retort kilns, brick /masonry kilns or others.

2.1. Flame curtain kilns

Flame curtain kilns carbonize biomass residues in an open fire, which is placed either on the earth surface, in a pit or in an open trough (Jayakumar et al., 2023; Schmidt and Taylor, 2014). The kiln is lit from the top to generate enough heat to make the upper layer of fuel emit combustible gases which form the flame curtain (Schmidt and Taylor, 2014). Beneath the flame curtain, the fuel itself does not combust, but instead carbonizes because the flame gases consume all available oxygen, creating a pyrolysis zone where the flame protects the fuel from combustion (Cornelissen et al., 2016; Schmidt and Taylor, 2014). The fuel will continue carbonizing at the bottom part of the kiln as heat from combusting gases and pyrolysis at the top is transferred to the bottom, mainly through heat conduction as convectional and radiative heat transfer are minimal in the oxygen deprived environment (Fig. 1) (Cornelissen et al., 2016). Heat conduction occurs as hot materials near the combustion zone transfer heat to the cold materials that are beneath them through molecular contact (Levenspiel, 2014). Because they are open, most of the radiated and convected heat escapes to the environment, leading to minimal useful heat to assist pyrolysis. However, the strengths of flame curtain kilns are that they are simple, inexpensive and

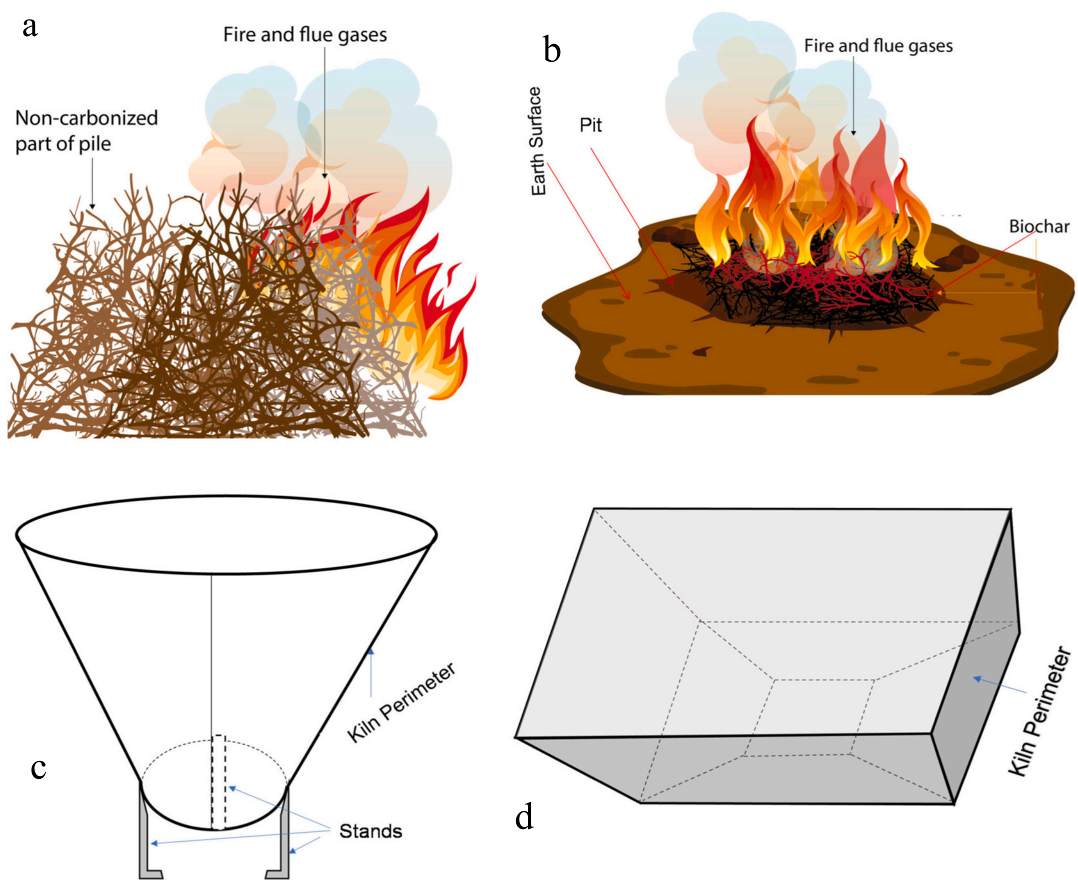

Fig. 2. Samples of flame curtain kilns: (a) open pile burn, (b) open pit kiln, (c) kon-tiki cone kiln and (d) Oregon kiln (Figures c and d modified from Baltar, 2018).

easily constructed by households or a small group of people who lack access to advanced pyrolysis kilns (Cornelissen et al., 2023; Schmidt and Taylor, 2014).

Biochar kilns working on the flame curtain principle can be grouped into open-pile burn /slash burn (Fig. 2a), top-lit open earth pits (Fig. 2b), kon-tiki cone kilns (Fig. 2c), or Oregon kilns (Fig. 2d). The operation and performance of the different types of flame curtain kilns are summarized in Table 1. A top-lit open pile burn entail piling the material on the ground without any container, lighting it from the top and allowing it to burn downwards (Nobert and Bruton, 2019). Similarly, an open pit can be constructed by digging a rectangular or conical open pit, filling it with the fuel and lighting it from the top (Smebye et al., 2017). The Kon-tiki cone kiln is made by folding a steel sheet into an open-topped conical structure with a wall inclination of 63° (Cornelissen et al., 2023; Schmidt and Taylor, 2014). The open Oregon kiln is made by folding and welding or riveting a 14-gauge (1.9 mm thick) flat sheet of steel to create an inverted, truncated pyramid (Puettmann et al., 2018).

Production of biochar by pile burning or using an open pit has a low efficiency (<15 % based on original mass of organic matter used), produces heterogeneous biochar and emits large amounts of $PM_{2.5}$ (4–18 g kg^{-1} of dry biomass) (Table 1). However, pile burning methods and pit kilns are simpler and cheaper than other methods because they require no investment cost, are easy to construct near the source of the fuel with manual labour provided by family members and can rely on the indigenous knowledge of operators that is passed between generations (Aurell et al., 1994; Iiyama et al., 2014; Smebye et al., 2017). Pit kilns have a slower pyrolysis rate of ((2–4) $\times$ 10^{-2} m^3 of biochar per hour) because the surrounding soil absorbs heat, making it difficult to attain the optimal temperature of pyrolysis of 500 °C (Adam, 2009; Brown, 2009; Korb et al., 2004). Open piles also operate at temperatures below 500 °C with much higher pyrolysis rates of 3 m^3 of biochar per hour (Table 1) (Hubbert et al., 2015). High pyrolysis rates among open piles may be attributed to the ability of the technique to carbonize large volumes of biomass and its openness to high velocity winds that infiltrate the interior, creating high heat fluxes that reduce the residence time (Tao et al., 2020). In one study, increasing wind speed from 0 m s^{-1} to 2.0 m s^{-1} increased heat fluxes by a factor of at least two while shortening the burning duration from 1170 s to 465 s due to intense burning (Bearinger et al., 2021).

Kon-tiki cone and Oregon kilns can reach higher temperatures (>600 °C) compared to open pile and pit kilns (Table 1). This higher temperature is achieved by partial reflection of the pyrolysis and combustion heat back into the kiln from the steel walls (Schmidt and Taylor, 2014). Reaching higher temperatures improves the quality of biochar, lowers $PM_{2.5}$ and methane emissions, and shortens residence times (Table 1). According to Ippolito et al. (2020), higher pyrolysis temperatures reduce $PM_{2.5}$ and methane emissions due to more complete combustion of flue gases while increasing carbon content through reduced volatilization. However, the performance may vary depending on the characteristics of the feedstock. For example, using Kon-tiki kiln, Cornelissen et al. (2023) recorded methane emission of 0–3.6 g kg^{-1} of biochar when dry feedstocks (<15 % moisture) were used compared to >500 g kg^{-1} when using wet feedstock (>40 % moisture). In addition, Kon-tiki and Oregon kilns require an initial investment cost of US$ 60 to 800 in countries such as Nepal as they are fabricated by specialized manufacturers, and their operation requires some simple informal training (Table 1). Informal training of operators on optimal operating conditions is important because Jayakumar et al. (2023) established that apart from pyrolysis temperatures, feedstock layering rates during operation affects the quality of biochar, methane emissions and efficiency in kon-tiki kilns. Note that the high cost recorded for the Oregon kiln design (US$ 800) may be because it was fabricated and sold from

Table 1
Comparison of Flame Curtain Kilns.

		Top-lit open pile burn/slash-and char	Open earth pit kiln (rectangular or cone shaped)	Kon-Tiki Cone kiln	Oregon kiln
Feedstock		Branches and small wood	Solid organic residues, withies, and branches	Solid organic residues, withies, and branches	Solid organic residues, withies, and branches
Construction materials		No material	No material	Mild stainless steel	Mild steel
Portability		Not permanent	Not permanent	Portable	Portable
Source of heat		Partial oxidation	Partial oxidation	Partial oxidation	Partial oxidation
Labour requirements		Little labour required	Digging pits is manual labour intensive	Monitoring little; requires skilled labour	Monitoring requires little labour
Provider		Semi-skilled family and community member	Semi-skilled family and community member	Skilled artisan	Skilled artisan
Simplicity		Needs Indigenous knowledge training	Needs Indigenous knowledge training	Require simple informal training	Require simple informal training
Initial investment cost (US$)		0.0	0.0 (a)	60–150 (g*)	500–800 (p*)
Residence and cooling time (Hours)		<0.5 (i*)	24–48 (r)	2–8 (d)	4–6 (q*)
Pyrolysis rate (m^3 hr^{-1} of biochar)		3 (i*)	(2–4) x 10^{-2} (r*)	(1.3–5) x10^{-1} (d*)	2.2–2.9 × 10^{-1} (q*)
Pyrolysis temperature (°C)		200–500 (k)	502 (m)	750–850 (d)	600 ± 200 (l*)
Efficiency (%)	Dry weight basis (%)	10–15 (j)	<15 (b)	22–28 (c, t)	16 ± 4 (l*, o)
	Thermal efficiency (%)	–	–	–	–
	Carbon content (%)	–	31–44 (c)	40 ± 11 % (c)	32–42 (c)
Degree of control	Pyrolysis conditions	No control	No control	No control	No control (h)
	Quenching/snuffing	Water and soil (i)	Soil and water	Water and lid cover (i)	Water
Emission levels	CO_2	1689–1785 g kg^{-1}B (n)	3800 ± 1300 g kg^{-1}C (c)	2300 ± 800 (c)	4700 ± 800 (c)
	CO	29–82 g kg^{-1}B (i)	51 ± 39 g kg^{-1}B (s)	54 ± 35 g kg^{-1}C (i)	73 ± 31 g kg^{-1}C (c)
	NO_2	148 ± 64 g kg^{-1} B (i)	–	0.4 ± 0.3 g kg^{-1} B (i)	–
	CH_4	1.1–5.7 g kg^{-1}B (n)	32 ± 44 g kg^{-1}C (c)	30 ± 60 g kg^{-1}C (c)	36 ± 70 g kg^{-1}C (c)
	$PM_{2.5}$	4.5–18 g kg^{-1} B (n)	31 ± 29 g kg^{-1} B (s)	11 ± 15 g kg^{-1}C (c)	12.8 ± 1 g kg^{-1} B (o*)
Biochar quality	Homogeneity of biochar	Highly heterogeneous	Highly heterogeneous	Heterogeneous	Heterogeneous
	Fixed Carbon (%)	28 (j)	46 ± 1 (m)	75.5 ± 9 (c)	65 ± 30 (l*)
	Hydrogen content (%)	–	2 ± 1 (c)	1.85 ± 0.5 (c)	1.3–2.2 (c)
	Volatile matter (%)	–	39 ± 1 (m)	–	16 ± 10 (l*)
	Nitrogen content (%)	0.22 (j)	1 ± 0.5 (c)	0.69 ± 0.2 (c)	0.6–1.2 (c)
	pH	–	–	9 ± 0.3 (e)	7 ± 3 (l)
	Calorific value (MJ kg^{-1})	–	–	27.3 (f)	–
	Ash Content (%)	–	14 ± 1 (m)	–	4 ± 2 (m)
Applicability		Farm/individual and small group level	Farm/individual and small group level	Individual/farm level (d)	Individual/farm level
Production co-products/services		None	None	None	None

Sources: (a) Smebye et al. (2017), (b) Gray (2022), (c) Cornelissen et al. (2016), (d) Schmidt and Taylor (2014), (e) Pandit et al. (2017), (f) Fuentes et al. (2020), (g) Landell Mills Ltd (2016), (h) Hedley et al. (2020), (i) Hoffman-Krull (2018), (j) Page-Dumroese et al. (2017), (k) Hubbert et al. (2015), (l) Inoue et al. (2011), (m) Anika et al. (2022), (n) Aurell et al. (1994), (o) Puettmann et al. (2018), (p) Baltar (2018), (q) Wilson (2019), (r) Brown (2009), (s) Sharma and Ghimire (2017), (t) Cornelissen et al. (2023).
Note: 1) * indicates that values were calculated/converted or derived based on figures/numbers provided by the author represented by the alphabet.
2). (−) Means the values are not available, either they are yet to be determined, or difficult to find.
3). g kg^{-1} B = grams per kilogram of initial biomass.

Oregon in the USA, where the cost of labour is high, before being promoted in other countries including low to middle income countries.

Because they are partially or fully open, flame curtain kilns cannot produce co-products, such as wood vinegar or useful heat, and Wilson (2015) refers to this as a lost opportunity. They allow little control of the pyrolysis process and are strongly influenced by wind strength and direction, making it impossible to achieve complete and homogeneous pyrolysis within the kiln (Hadden and Switzer, 2020). It is also difficult to reduce emissions as some volatiles escape into the atmosphere before they ignite to drive the pyrolysis reaction, leading to air pollution (Kong and Sii, 2020). Controlling pyrolysis through "fluffing up" at the bottom to reduce incomplete carbonization is also difficult due to the intense heat (Baltar, 2018). Snuffing of the kiln can be achieved using soil or water (Nobert and Bruton, 2019). However, use of soil is highly discouraged because it increases impurities in biochar, making it unsuitable for briquetting or adsorption purposes due to the high ash content (Anika et al., 2022). Use of water is not feasible in areas that experience water shortages because 1 m^3 of biochar requires over 50 gallons (190 l) of water for quenching (Amonette et al., 2021).

2.2. Drum kilns

Drum kilns can be fabricated by modifying a used oil-drum or by riveting a steel sheet into a cylinder or rectangular box with incorporation of a chimney, firing point and air inlets (Oduor et al., 2006; Venkatesh et al., 2015). In drum kilns, pyrolysis heat is transferred through a combination of conduction, convectional and radiation mechanisms (Suzuki et al., 2008). Conduction occurs through direct contact among materials being carbonized, and a close contact of materials and steel sheet kiln walls (Sucahyo and Mustaqimah, 2019; Suzuki et al., 2008). Convectional heat transfer occurs as hot flue gases move within the kiln before exiting through the chimney (Levenspiel, 2014). Due to the presence of the kiln wall, convectional heat transfer is more effective than in flame curtain kilns.

Common design features of drum kilns include a perforated base (Fig. 3a), bottomless drum (Fig. 3b), horizontal drum (Fig. 3c) and horizontal rotary drum kiln (Fig. 3d) (Mandal et al., 2022; Moser et al., 2023; Yadav et al., 2023). All drum kilns are suitable for small-scale use by low-income famers as they can be made from locally available

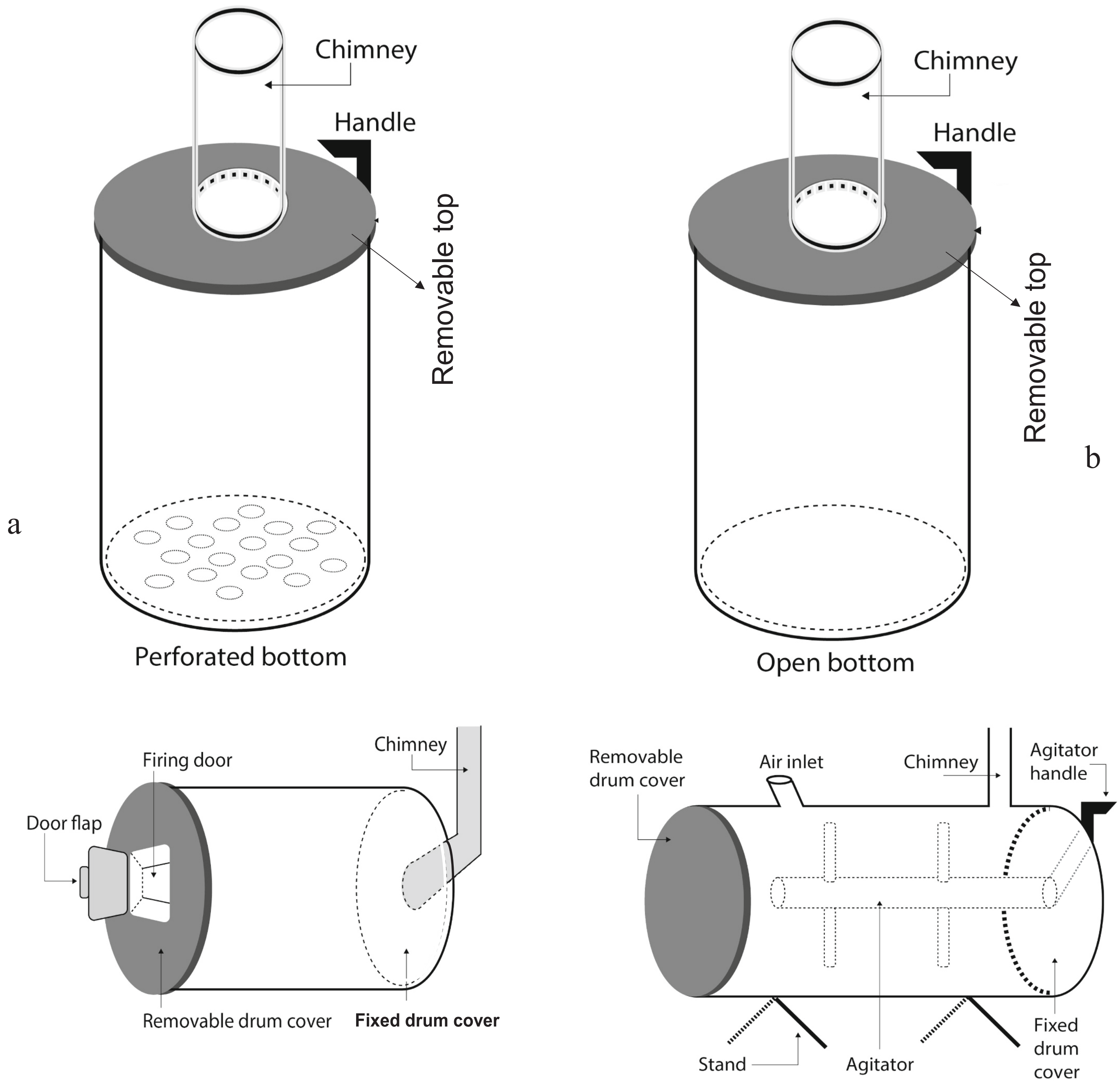

Fig. 3. Schematic diagrams of drum kilns (a) perforated drum kiln modified from Venkatesh et al. (2015), (b) bottomless drum kiln modified from Tintner et al. (2020), (c) Horizontal drum kiln modified from Oduor et al. (2006), (d) horizontal with agitator modified from Mandal et al. (2022).

materials, such as used oil-drums, and can be used to carbonize almost all biomass materials produced on the farm (Table 2), including elephant grass, corn stalks, rice husks, sugarcane bagasse, leaves, coffee pulp, bamboo and low diameter feedstocks in the form of branches and withies (Hansson et al., 2021; Khawkomol et al., 2021; Tesfaye et al., 2022). Kilns can be purchased from specialized artisans, typically for US $ 13–100, depending on size, design and geographical location (Burnette, 2013; Venkatesh et al., 2013). The operation of a drum kiln is simple, requiring only informal training by peers or fabricators on optimal moisture content of the feedstock, loading and pyrolysis monitoring, with white dense smoke indicating the drying phase, thin and light smoke signifying carbonization, and clear blue smoke indicating complete carbonization (Oduor et al., 2006; Oduor et al., 2015).

Drum kilns provide moderate control of pyrolysis conditions, especially in terms of air flow (Table 2). A metal or wooden rod may be held vertically in the centre of the kiln during loading and then removed to create a central vent for adequate airflow (Venkatesh et al., 2015). When the kiln is lit, it is fully covered and all air leaks are sealed using readily available materials, such as mud or soil (Oduor et al., 2006). A bottomless drum can be placed on a flat surface and the air supply is then controlled by digging small tunnels under the drum base (Tintner et al., 2020). In a perforated bottom kiln, air is supplied by placing the kiln on raised stones (Venkatesh et al., 2015). An optimal pyrolysis temperature can be maintained by opening and closing of air vents, such as the chimney and air inlets (Abdelhafez et al., 2016). However, knowing when to open and close the air vents and for how long is a challenge, making it difficult to replicate the process, leading to inconsistency in biochar quality and emissions regardless of feedstock types (Masek

Table 2
Performance of Different Designs of Drum Kilns.

		Bottomless Drum kiln	Drum kiln with perforated bottom	Horizontal drum kilns	Drum Kiln with manual rotation
Feedstock		Solid organic residues, bamboo and low diameter feedstock	Solid organic residues, bamboo and low diameter feedstock	Solid organic residues, bamboo and low diameter feedstock	All solid organic residue, bamboo and low diameter feedstock
Construction materials		Mild steel and used-oil-drum	Mild steel and used-oil-drum	Mild steel and used-oil-drum	Mild steel, used-oil drum, fan
Portability		Portable	Portable	Portable	Portable
Source of heat		Partial oxidation	Partial oxidation	Partial oxidation	Partial oxidation
Labour requirements		Semi-skilled monitoring labour	Semi-skilled monitoring labour	Semi-skilled monitoring labour	Semi-skilled monitoring labour
Provider		Specialized manufacturer	Specialized manufacturer	Specialized manufacturer	Specialized manufacturer
Simplicity		Requires simple formal training	Requires simple informal training	Requires simple informal training	Requires simple informal training
Initial investment cost (US$)		50–100 (k*)	15 (a*, e*)	28 (j*)	–
Residence and cooling time (Hours)		–	1–4 (c)	1–12 (h)	3–5 (i*)
Pyrolysis rate (m^3 hr^{-1} of biochar)		(3–12) x10^{-2} (m*)	(3–12) x10^{-2} (c*)	(2–20) x10^{-2} (h*)	(2–5) x10^{-2} (i*)
Pyrolysis temperature (°C)		346–765 (k)	300–800 (b, e)	150–700 (h)	535–581 °C (i)
Heating rate (°C/min)		2–4 (p*)	–	–	3.5–37 (i)
Efficiency (%)	Dry weight basis (%)	23–27 (g)	22–25 (c)	10–34 (h)	24–39 (i)
	Thermal efficiency (%)	22–44 (n, p)	–	–	–
	Carbon content (%)	56–83 (p)	–	–	–
Controllability	Pyrolysis conditions	Slightly controllable	Slightly controllable	Slightly controllable	Controllable
	Quenching/ snuffing	Natural cooling and water	Natural cooling and water	Natural cooling and water	Natural cooling (r)
Emission levels	CO_2	434 (g kg^{-1} B) (n)	< 2 vol% (d)	–	–
	CO	98 (g kg^{-1} B (n)	500 ppm (d)	–	–
	NO_2	–	40 ppm (d)	–	–
	CH_4	16 (g kg^{-1} B) (n)	–	–	–
	$PM_{2.5}$	4.19 ppm (n)	4–48 μg m^{-3} (d)	–	–
Biochar quality	Homogeneity of biochar	Slightly heterogeneous (k)	Slightly heterogeneous	Slightly heterogeneous	Homogeneous
	Fixed Carbon (%)	45–58 (l)	40–72 (a, c)	26–84 (h)	66–81 (i)
	Hydrogen content (%)	–	–	–	2–5 (i)
	Volatile matter (%)	12–23 (p)	7–16 (e)	5–49 (h)	17–39 (i)
	Nitrogen content (%)	0.8–2 (l)	0.09–0.14 (a)	0.2–0.9 (h)	1–5 (i)
	pH	8–10 (l)	6.9–10.0 (b)	8–10 (h)	8–9 (i)
	Calorific value (MJ kg^{-1})	35–40 (p)	< 30 (f)	14–24 (h)	24–30 (i)
	Ash Content (%)	> 6 (k)	16.2 ± 0.04 (c)	4–35 (h)	5–8 (i)
Applicability		Family and small community groups	Family and small community groups	Family and small community groups	Family and small community groups
Production co-products/services		Wood vinegar	Wood vinegar	Wood vinegar	Wood vinegar

Sources: (a) Venkatesh et al. (2015), (b) Mashad et al. (2022), (c) Nataraja et al., 2021), (d) Schweikle et al., 2015), (e) Venkatesh et al. (2013), (f) Tesfaye et al. (2022), (g) Srinivasarao et al. (2013), (h) Khawkomol et al. (2021), (i) Mandal et al. (2022), (j) Burnette (2013), (k) Tintner et al. (2020), (l) Rahman et al. (2022), (m) Oduor et al. (2006), (n) Smith et al. (1999), (o) Manatura (2021), (p) Saravanakumar and Haridasan (2013).
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2). (−) Means the values are not available, either they are yet to be determined, or difficult to find.
3). % vol, g kg^{-1} B and ppm means percent volume of flue gas, grams per kg of charcoal/biochar produced and parts per million.

et al., 2018). A forced draft kiln uses a fan to improve control of the rate of air flow; Mandal et al. (2022) described how pyrolysis temperature (535–581 °C) and heating rate (3.5–37 °C min-1) could be controlled by regulating air flow rates to 40–50 m^3 hr^{-1} using a fan. Maintaining the required pyrolysis temperature affects emissions during pyrolysis, quality and yield of biochar, so forced draft kilns can greatly improve the efficiency and reduce the environmental impact of the process (Sangsuk et al., 2023; Wystalska and Kwarciak-Kozłowska, 2021).

The kiln can be quenched and cooled by closing the small tunnels dug in the case of bottomless kilns or removing the kiln from the raised stones and placing it on a flat surface and closing the kiln with a lid (Hammed and Sridhar, 2014; Venkatesh et al., 2015). However, this may take a long time, increasing the production cycle period per batch (Sangsuk et al., 2020). Therefore, water may also be used to snuff the kiln, although this can reduce the lifespan of the kiln through corrosion and abrupt contraction of the construction material (Kong and Sii, 2020).

Modifications to the design of drum kilns have been proposed to achieve improved heat distribution to ensure more homogeneous carbonization and to reduce residence times by ensuring high and more uniform temperatures (Sangsuk et al., 2023; Sucahyo and Mustaqimah, 2019). Agitation, rotation, partitioning of the kiln or placing a pipe in the centre of the kiln can be used to improve heat distribution (Table 2) (Manatura, 2021; Mandal et al., 2022; Sangsuk et al., 2020). Temperatures can be increased by insulating the drum with materials such as silica, vermiculite, or fibre glass (Wamalwa, 2018). Variations in drum kiln design and performance occur due to lack of standardization, such as insulation thickness, or optimisation of the size, number and shape of air inlet holes (Hadden and Switzer, 2020; Himbane et al., 2017; Manatura, 2021). Kiln designs with the ability to reach very high temperatures have reduced efficiency but produce biochar characterized by high carbon content (Ippolito et al., 2020; Wystalska and Kwarciak-

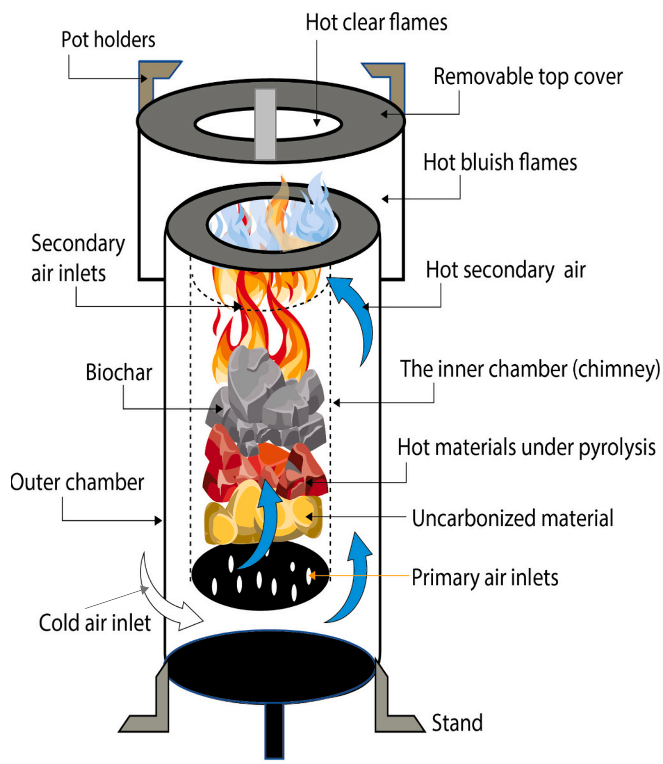

Fig. 4. Schematic structure of a non-insulated natural draft pyrolytic TLUD cookstove (Modified from Lotter et al. (2015)).
Note: when i). a fan or blower is placed at the air entrance, the design becomes a forced draft.
ii). the outer chamber is insulated, it becomes an insulated TLUD cookstove.

Kozłowska, 2021). Therefore, there is a need for research to determine the optimum design of kiln to meet different design constraints, such as cost, efficiency or quantity and quality of biochar.

The type of feedstock and their characteristics such as moisture content and particle size also affect residence time, recovery rates, quality of biochar and emissions (Cornelissen et al., 2023; FAO, 2017; Sangsuk et al., 2023). Himbane et al. (2017) used a drum kiln to carbonize different feedstocks and recorded efficiencies of 34 % for peanut shells and millet stalks, but only 23 % for cashew shells. Residence times vary according to feedstock type and quantity; using the same equipment and procedures, millet stalks were carbonized in 42 min and peanut shells in 89 min, while cashew shells required as long as 230 min (Himbane et al., 2017). Different qualities of biochar (ash and carbon content) were produced using a similar perforated bottom drum kiln when the feedstock was pigeon pea or cotton residues (Nataraja et al., 2021), or almond shells (Mashad et al., 2022). Materials with a high silica content, such as rice straw, tend to produce biochar with high ash and low carbon contents, and low calorific values (Khawkomol et al., 2021).

Unlike flame curtain kilns, drum kilns have the potential to produce co-products, such as wood vinegar, generated through condensation of flue gases in the exhaust chimney (Manatura, 2021). Condensation of exhaust smoke into wood vinegar is important in reducing emissions during pyrolysis while also providing an additional product that can be sold or used on farms to improve their productivity and income (Mopoung and Udeye, 2017; Zhu et al., 2021).

2.3. Pyrolytic top-lit updraft cookstoves

Pyrolytic top-lit updraft (TLUD) cookstoves are designed to generate biochar instead of ash while also using produced heat for cooking and heating (Cornelissen et al., 2016). The cookstoves can be fabricated using concentric containers from readily available and recyclable materials, such as paint tins and tomato cans (Birzer et al., 2013). Holes are made in the base of the outer tin to act as the main air inlet, primary air enters through the perforated bottom of the inner tin and secondary air enters through holes at the upper end of the inner tin to ensure complete combustion of flue gases (Birzer et al., 2013). The upper part of the kiln is covered with a removable lid to allow loading, lighting, and offloading (Fig. 4). Heat transfer in pyrolytic TLUD cookstoves is through conduction, convection and radiation similar to the drum kilns described in section 2.2. There are three main designs of pyrolytic TLUD cookstoves with varying pyrolysis performances (Table 3): non-insulated with natural draft, insulated with natural draft and TLUDs with forced draft.

Regardless of the design, pyrolytic TLUD cookstoves can use a variety of small-sized traditional biomass resources, such as withies, cuttings, husks, nuts, shavings, sawdust and pellets, to produce useful heat and biochar, and they have low emissions compared to conventional biomass cookstoves (Hansson et al., 2021). Using readily available small-sized fuels to cook increases the flexibility of fuel use (Lotter et al., 2015). This is important in mitigating deforestation and forest degradation as it reduces the demand for woodfuel, which accounts for about 70 % of deforestation in Sub-Saharan Africa (Subedi et al., 2014). Compared to other improved cookstoves, pyrolytic TLUD cookstoves have low emissions because most pyrolytic gases are combusted in the flame front of the chimney as they react with hot secondary air introduced at the top part of the kiln, hence reducing carbon monoxide, methane and $PM_{2.5}$ emissions by over 75 % compared to traditional cookstoves (Cornelissen et al., 2016). Therefore, TLUDs are ideal for poor households in rural and urban areas for production of both biochar and useful heat (Birzer et al., 2013).

Natural draft pyrolytic TLUD cookstoves operate at a steady state supply of air of 300–1250 % over the stochiometric requirements (Prapas et al., 2014). However, modern insulated TLUDs have been designed to operate with a forced draft generated using a fan (Kirch et al., 2016). As indicated in Table 3, forced draft TLUDs have higher thermal efficiency, lower pyrolysis residence time, lower emissions and produce biochar of better quality than natural draft TLUDs. This is because fans ensure steady, accurate and homogeneous distribution of air flows within the stove even in areas that are difficult to be reached by natural convection (Wamalwa, 2018). This is important especially when using fuels, such as husks and nuts, that have high air resistance (Guthapfel and Gutzwiller, 2016). Fans allow control of pyrolysis conditions, such as temperature or operation time, by adjusting the speed of the fan or adjusting the air control meter (Kirch et al., 2016). This is important because optimal pyrolysis conditions vary among feedstocks and affect the physical, chemical and mechanical properties of the biochar (Kalina et al., 2022). Insulation also helps in heat conservation by reducing heat loss to the environment (Kirch et al., 2016). For uninsulated kilns, part of the heat is radiated to the environment and therefore does not contribute to pyrolysis. Under insulated conditions, heat radiation within the kiln is maximized by minimizing heat emitted to the outside environment through kiln walls (Charvet et al., 2022; Rodrigues and Junior, 2019). The thickness and thermal properties of the insulating material controls the effectiveness of insulation; thicker insulators increase conduction resistance, while reducing convection resistance of the system because of increased outer surface area and vice versa (Memon et al., 2020; Rodrigues and Junior, 2019; Wamalwa, 2018). Therefore, the appropriate insulation thickness can be estimated from the ratio of the thermal conductivity and its convective heat transfer coefficient (Wamalwa, 2018). However, adding a fan, air control meter and insulation materials, such as fibre glass, makes TLUD stoves expensive (up to US$ 150 in Kenya), and potentially unaffordable for small-scale farmers in low to middle income countries where over 40 % of the population live in extreme poverty (Agayi and Karakayaci, 2022; Ehrensperger et al., 2017). Nevertheless, the costs can be contained by optimizing the size of the fan used and avoiding those that are unnecessarily large and costly (Wamalwa, 2018). Ehrensperger et al.

Table 3
Performance comparison of different designs of pyrolytic TLUD cookstoves.

		Non-insulated TLUDs (with natural draft)	Insulated TLUDs with natural draft	Insulated TLUDs with forced draft
Feedstock		Pellets, low diameter feedstock, cobs, wood chips, husks nuts and briquettes (a, c, e)	Pellets, low diameter feedstock, cobs, wood chips, husks nuts and briquettes (a, c, e)	Pellets, low diameter feedstock, cobs, wood chips, husks nuts and briquettes (a, c, e)
Construction materials		Waste tins, stainless steel, and iron sheet	Waste tins, stainless steel, and iron sheet. (Insulation materials include clay soil/ ceramic, silica, vermiculite (a)	Waste tins, stainless steel, and iron sheet. Insulation materials include clay soil/ceramic, silica, vermiculite, fan, source of power
Portability		Portable	Portable	Portable
Source of heat		Partial oxidation, flue gases	Partial oxidation, flue gases	Partial oxidation, flue gases
Labour requirements		Formal training on operation	Formal training on operation	Formal training on operation
Provider		Specialized artisan	Specialized artisan	Specialized artisan
Simplicity		Requires medium level informal training (b, c)	Requires medium level informal training (b, c)	Requires medium level informal training (b, c)
Initial investment cost (US$)		25–50 (o)	50–125 (d, e, o)	≤150 (o)
Residence and cooling time (hours)		2 (j)	0.5–1.5 (r*)	0.5–1(s*)
Pyrolysis rate (m^3 hr^{-1} of biochar)		–	–	–
Pyrolysis temperature (°C)		200–950 (j, n)	750–850 (r)	300–1000 (g)
Heating rate (°C hr^{-1})		10–25 (j*)	–	–
Efficiency (%)	Dry weight basis (%)	16–24 (j)	32–37 (e)	–
	Thermal efficiency (%)	7–20 (h, i)	23–35 (e)	32–41 (a, p)
	Carbon content (%)	–	–	–
Controllability	Pyrolysis conditions	Controllable	Controllable	Highly controllable
	Quenching/ snuffing	Soil, water, natural cooling	Soil, water, natural cooling	Soil, water, natural cooling
Emission levels	CO_2	8–19 % vol (q)	27–36 ppm (e)	803–994 ppm (a)
	CO	49–57 ppm (b)	17–18 ppm (e)	18–27 ppm (a)
	NO_2	54–63 ppm (b)	0.2–17 ppm (s)	2.6–5 ppm (s)
	CH_4 (% vol of flue gas)	–	–	1–3 % vol (g)
	$PM_{2.5}$	1000–7000 μg m^{-3} (q*)	–	322 μg m^{-3} (a)
Biochar quality	Homogeneity of biochar	Homogeneous (i)	Homogeneous (i)	Highly homogeneous (i)
	Fixed Carbon (%)	42–84 (j)	87.0 ± 0.8(k)	63–91 (m)
	Hydrogen content (%)	1–3 (j)	1.7 ± 0.2 (k)	0.4–0.9 (m)
	Volatile matter (%)	6.6–9.6 (m)	9.7 ± 0.6 (k)	5–12 (m)
	Nitrogen content (%)	0.2–0.7(j)	0.2–0.6 (m)	0.2–0.5 (m
	pH	6–10 (j)	8.7 ± 0.3 (k)	5–7 (l)
	Calorific value (MJ kg^{-1})	29.1–33.2 (m)	33.7 ± 0.1 (k)	32.1–33.2 (m)
	Ash Content (%)	1–36 (j)	3.3 ± 0.7 (k)	–
Applicability		Family level	Family level	Family level
Production of co-products/services		Useful heat	Useful heat	Useful heat

Sources: (a) Wamalwa (2018), (b) Birzer et al. (2013), (c) Hailu (2022), (d) Guthapfel and Gutzwiller (2016), (e) Punin (2020), (f) Ahmad et al. (2019), (g) Mehta and Richards (2017), (h) Obi et al. (2016b), (i) Shackley and Carter (2014), (j) Masís-Meléndez et al. (2020), (k) Sundberg et al. (2020), (l) Swaminathan and Amupolo (2014), (m) James et al. (2016), (n) Kirch et al. (2016), (o) Ehrensperger et al. (2017), (p) Scharler et al. (2021), (q) Krüger and Mutlu (2021), (r) Shimabuku et al. (2019), (s) Ndindeng et al. (2019).

Note: 1) * indicates that values were calculated/converted or derived based on figures/numbers provided by the author represented by the alphabet.
2). (−) Means the values are not available, either they are yet to be determined, or difficult to find.

(2017) suggested that adoption of costly cookstoves requires potential users to be correctly identified, recovery of upfront costs through reduced fuel consumption to be quantified, maintenance services to be made available, health benefits from reduced indoor air pollution to be identified and flexible financing models to be provided.

Users of all pyrolytic TLUD cookstove designs need to be trained in their operation to obtain optimal results. Operating pyrolytic cookstoves may be a challenge especially in terms of assessing fuel size as improperly prepared fuels lead to high emissions, low efficiencies and low biochar quality (Ehrensperger et al., 2017). Smaller pieces of fuel can block the primary air flow pathways and hinder pyrolysis, while larger pieces may not be pyrolyzed to their core (Birzer et al., 2013). The stove efficiency, usually 30–45 % higher than a traditional cookstove, relies on optimized ratios of fuel to airflow (Cornelissen et al., 2016); a high air flow rate cools the pyrolysis chamber while a low air flow leads to incomplete pyrolysis (Birzer et al., 2013).

Although pyrolytic TLUD cookstoves can be used at household or family level (Table 3), the reality is that producing enough biochar for soil amendment or briquetting using pyrolytic TLUD cookstoves is time consuming and sometimes impractical (Pandit et al., 2017). Most common TLUDs used for domestic cooking in low to middle income countries are small, and so generate very little biochar (0.3–1 kg per run); this compares to the more expensive and larger TLUDs that may generate over 10 kg per run (Cornelissen et al., 2016; Pandit et al., 2017; Torres-Rojas et al., 2011). In addition, the challenge is that quenching the stove after every cycle to recharge it with biomass may be time-consuming and impractical (Cornelissen et al., 2016). Therefore, biochar production using pyrolytic TLUD cookstoves is only practical for small-scale uses.

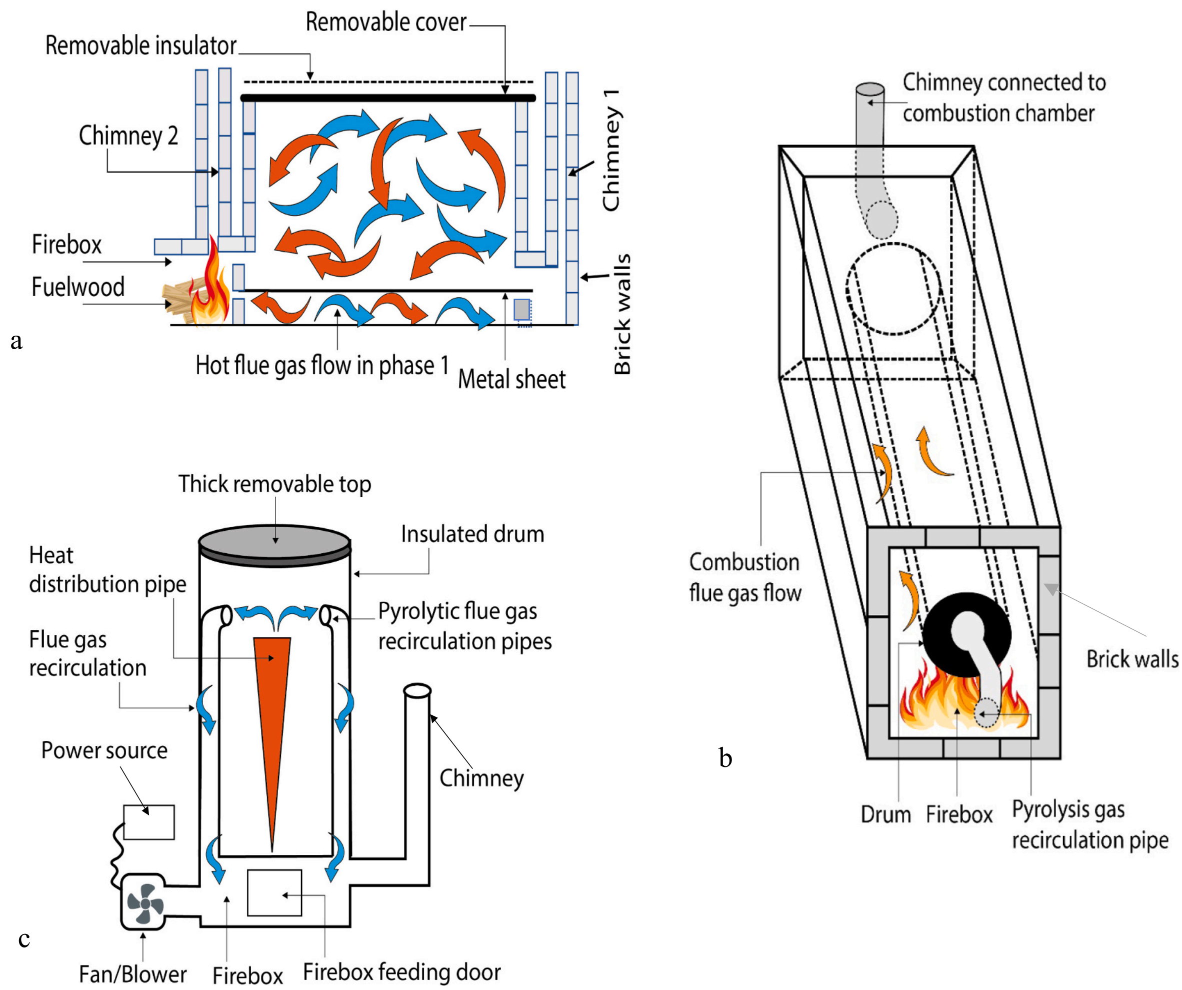

Fig. 5. Schematic diagrams of retort kilns (a) Brick retort modified from Adam (2009), (b) brick-drum retort modified from Kong and Sii (2020), (c) insulated forced draft kiln modified from Manatura (2021).

2.4. Retort kilns

Retort kilns are advanced biochar producing kilns that operate on a two-chamber principle (Adam, 2009; Ilankoon et al., 2023). The first chamber is a firebox while the second chamber is the pyrolysis chamber (Ighalo et al., 2022; Kong and Sii, 2020). Prior to ignition, the firebox chamber is filled with combustible materials, such as firewood or organic residues, while the pyrolysis chamber is filled with materials to be carbonized. Retort kiln designs can be categorized into natural draft retorts made entirely from bricks (Fig. 5a), natural draft retorts using a drum inside a brick firebox (Fig. 5b), natural draft uninsulated drum retorts, natural draft insulated drum retorts and forced draft retorts (uninsulated/insulated) (Fig. 5c).

Regardless of the design, retort kilns operate by igniting an external firebox to produce heat that is directed to the pyrolysis chamber to start pyrolysis (Adam, 2009; Ankona et al., 2022). Therefore, heat is transferred from the firebox to the pyrolysis chamber through conduction via a heat conducting metal sheet separating the firebox and the pyrolysis chamber (Suzuki et al., 2008). In the pyrolysis chamber, the metal sheet conducts and/or radiates heat to materials in contact or close to it (Suzuki et al., 2008). The heated materials start emitting hot flue gases containing methane, carbon dioxide, hydrogen, carbon monoxide and $PM_{2.5}$ among other combustible compounds that move within the kiln towards the recirculation pipes, and in so doing, they transfer part of the heat to the cold materials they encounter as they move to the firebox for complete combustion and heat generation (Adam, 2009). Depending on the position of the circulation pipe (inside or outside the kiln), the flue gases may either gain or lose heat as they are recirculated to the firebox (Manatura, 2021). When the recirculation pipes are placed inside the kiln (Fig. 5a), the flue gases gain heat as they move towards the firebox through the hot pyrolysis chamber, while those outside tend to lose heat to the environment unless they are insulated.

Advanced retort kilns have been developed that carbonize a wide range of feedstocks, including forest and agricultural residues, grasses, bamboo and other low diameter feedstocks (Adeniyi et al., 2019; Emrich, 1985; Kalenda et al., n.d.). They are either portable or stationary depending on the construction materials. Larger retort kilns constructed from bricks or a combination of bricks and drums, such as the Adam's retort, are stationary structures, while retort kilns constructed from used oil-drums or steel sheets can be portable on a trolley, truck or can be pushed on removable wheels (Table 4) (Sangsuk et al., 2020; Shepard, 2011). Portable retort kilns have the advantage of reducing the cost of transporting feedstock from production to the central processing sites, which contributes significantly to the total cost of producing biochar and charcoal (Murcia and Plains, 2002). Stationary retort kilns are most suitable for large-scale biochar production and when feedstock is readily available within a short radius (Kalenda et al., n.d).

Retort kilns have low emissions, generate more thermal energy and have a shorter production cycle compared to other kilns (Ayass et al., 2018; Ighalo et al., 2022; Manatura, 2021). Recirculation of pyrolytic flue gases in the firebox ensures complete combustion and generates

Table 4
comparisons of Retort kilns.

		Natural draft brick retorts like Adams	Natural draft drum-brick retorts	Natural draft non-insulated drum retorts	Natural draft insulated drum retorts	Forced draft retorts (non-insulated/ Insulated)
Feedstock		Wood materials with diameter up to 18 cm, bamboo, bundled agricultural residues (a, b, f)	Medium to low diameter wood, bamboo, agricultural and forest residues	Low diameter wood, bamboo, forest and agricultural residues	Low diameter wood, bamboo, forest and agricultural residues	Low diameter wood, bamboo, forest and agricultural residues
Construction materials		Bricks, sand, cement, steel	Used oil drums, mild steel, bricks, clay, cement (g)	Used oil drum, mild steel metal sheets	Used oil drum, mild steel metal sheets	Used oil drum, mild steel metal sheets, fan, battery
Portability		Stationary	Stationary	Portable	Portable	Portable
Source of heat		External heat from burning wood in the combustion chamber, recycled pyrolysis gases (c)	External heat, recirculation pyrolysis gases	External heat, recirculation pyrolysis gases	External heat, recirculation pyrolysis gases	External heat, recirculation pyrolysis gases
Labour requirements		Require loading and monitoring labour	Require loading and monitoring labour	Require monitoring labour but loading is simple	Require monitoring labour but loading is simple	Require monitoring, loading is simple
Provider		Specialized and skilled mason	Specialized and skilled mason	Specialized and skilled artisan	Specialized and skilled artisan	Specialized and skilled artisan
Simplicity		Require skilled and experienced operator	Require medium level informal training	Require medium level informal training	Require medium level informal training	Require medium level informal training
Initial investment cost (US$)		300–500 (c, d)	350–500 for a single drum (g*, i*)	–	–	–
Residence and cooling time (Hours)		24–48 (d)	10–15 (g)	1–3 (k*, l*)	2–6 (r*)	1–6 (q*)
Pyrolysis rate (m^3 hr^{-1})		(3.5–7) x 10^{-3} (f*, d*)	–	–	(3–9) x 10^{-2} (r*)	–
Pyrolysis temperature (°C)		400–850 (f, i)	>450 (g, i)	300–700 (*k*,*l*,n)	350–450 (r)	550–900 (q)
Heating rate (°C/min)		40 (f)	10 (i)		4 ± 1 (r*)	
Efficiency (%)	Dry weight basis (%)	30–45 (c, d, e)	25–35 (i*)	14–45 (k, l, P)	38–45 (r)	37–46 (q)
	Thermal efficiency (%)	30–60 (i)	65 ± 2 (i*)	–	56–85 (r)	–
	Carbon content (%)	45–57 (g)	36–40 (g)	–	–	–
Controllability	Pyrolysis conditions	Controllable	Controllable	Controllable	Controllable	Highly controllable (q*)
	Quenching/ snuffing	Natural quenching (c, d)	water and natural quenching (h)	water and natural quenching	water and natural quenching	–
Emission levels	CO_2	3–16 (%vol) (f), 1200–3024 (g kg^{-1}C) (g),	995–4132 (g kg^{-1}C) (g),	–	–	–
	CO	0.2–1 (% vol) (f*) 10 ppm (f), 62–122 (g kg^{-1}C) (g),	78–168 (g kg^{-1}C) (g)	–	–	–
	NO_x	3–164 ppm (f), ≤ 2 (g kg^{-1}C) (g),	≤ 2 (g kg^{-1}C) (g)	–	–	–
	CH_4	0.04–1.42(% vol) (f) 1.9–44 (g kg^{-1}C) (g),	7–84 (g kg^{-1}C) (g)	–	–	–
	$PM_{2.5}$	1–32 (g kg^{-1}C) (g),	1–10 (g kg^{-1}C) (g)	–	–	–
Biochar quality	Homogeneity of biochar	Homogeneous	Homogeneous (o)	Homogeneous	Homogeneous	Highly homogeneous
	Fixed Carbon (%)	72–87 (i)	46–81 (g, o)	51–84 (l, m, P)	61–74 (r)	73–87 (q)
	Hydrogen content (%)	2–6 (i)	< 5 (i*)	3.21 ± 0.04 (j)	–	–
	Volatile matter (%)	3–24 (i)	15–25 (i)	13–41 (m, P)	23–32 (r*)	6–18 (q*)
	Nitrogen content (%)	0.8–1.3 (i)	< 2 (i*)	0.38 ± 0.004 (j)	–	
	pH	–	–	8.72 ± 0.12 (j)	–	–
	Calorific value (MJ kg^{-1})	17–35 (i)	21–29 (o)	–	23–25 (r)	–
	Ash Content (%)	2–8 (i)	6–23 (o)	2–10 (j, m, P)	3–8 (r)	4–5 (q)
Applicability		Community/semi-industrial, industrial	Family, small groups or community level	Family level	Family and small community groups	Family and small community groups
Production co-products/services		Useful heat and bio-oil like vinegar	Useful heat and bio-oil like vinegar	Useful heat and bio-oil like vinegar	Useful heat and bio-oil like vinegar	Useful heat and bio-oil like vinegar

Sources: (a) Emrich (1985), (b) Kalenda et al. (n.d), (c) Adam (2009), (d) Vis (2013), (e) Cornelissen et al. (2016), (f) Adam (2013), (g) Sparrevik et al. (2015), (h) Kong and Sii (2020), (i) Chandrasekaran et al. (2021), (j) Abdelhafez et al. (2016), (k) Adeniyi et al. (2019), (l) Adeniyi et al. (2021), (m) Anika et al. (2022), (n) Chandra and Bhattacharya (2019), (o) Charvet et al. (2022), (P) Gonzaga et al. (2018), (q) Ayass et al. (2018), (r) Manatura (2021).

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2). (–) Means the values are not available, either they are yet to be determined, or difficult to find.

3). % vol, g kg^{-1}C and ppm means percent volume of flue gas, grams per kg of charcoal/biochar produced and parts per million.

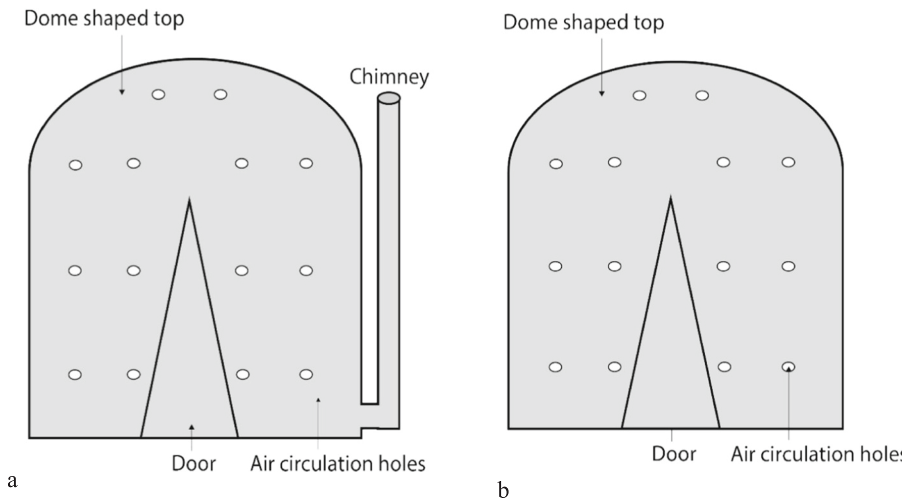

Fig. 6. Schematic diagrams of masonry kilns (a) masonry kilns with chimney, (b) chimneyless kiln (Modified from Rodrigues and Junior (2019)).

more thermal energy that shortens the production cycle and reduces emissions by over 70 % compared to open piles and pit kilns (Chandrasekaran et al., 2021; GIZ and GBEP, 2014; Ighalo et al., 2022). Furthermore, hot flue gases from the firebox can be recirculated to the pyrolysis chamber during start-up to increase initial pyrolysis temperatures and dry the materials, which has the potential of reducing total production time from 10 to six hours due to high pyrolysis and heating rates (Table 4) (Ayass et al., 2018; Sparrevik et al., 2015).

Retort kilns have higher yield efficiency and can produce co-products, such as wood vinegar and useful heat (Manatura, 2021). Yield efficiencies recorded for Kon-tiki cone kilns were 22 ± 5 %, drum kilns with forced draft and manual rotation 24 % – 39 %, and insulated TLUDs with forced draft 32–41 % (Tables 1 – 3), while the thermal efficiency of retort kilns can reach 85 % with a biochar yield of 46 % (Table 4). The high efficiency of retort kilns may be because they use an external heat source for startup and can employ recirculation of pyrolysis flue gases. The inclusion of exhaust vents connected to the firebox enables condensation of flue gases into multipurpose bio-oils such as wood vinegar (Theapparat et al., 2018).

Retort kins have better control of pyrolysis conditions than other designs that results in improved biochar characteristics (such as high carbon and low ash content) and low emissions (Table 4) (Chandra and Bhattacharya, 2019). Some designs have air vents at the bottom of the kiln to enable temperature control by closing and opening the vents (Abdelhafez et al., 2016). Insulation materials help in controlling heat losses to the environment, which also allow the kiln to reach the required pyrolysis temperature within a short time. Pyrolysis temperatures may also be controlled by regulating the fuel supply to the firebox, and the amount of flue gases directed to the firebox by opening and closing pipe valves (Ankona et al., 2022; GIZ and GBEP, 2014; Manatura, 2021). However, this optimisation requires calibration using digital thermometers to indicate how to adjust the air holes, fuel and pipe valves. Regulating fuel supply may also be impractical as it requires the hot firebox to be opened to remove or add fuel which may result in significant risk of burns, feedstock burn-off, reduction in efficiency and an increase in ash content. Ayass et al. (2018) suggested that forced draft convection can be used to improve control by providing the right amount of air at different parts of the firebox to ensure complete combustion and enough draft for recirculation of flue gases.

In some retort designs, a heat distribution pipe may be installed to either aid heat transfer from the firebox to the upper part of the kiln (Sangsuk et al., 2020; Sangsuk et al., 2023), or as a chimney from the firebox passing through the middle of the pyrolysis chamber to transfer heat in combustion flue gases to the pyrolysis chamber before they are exhausted to the environment (Manatura, 2021). The heat distribution pipes increase the surface area in the kiln to increase heat transfer through conduction and radiation. To produce more heat, the firebox needs to burn fuel at higher temperatures (Adam, 2013). However, the temperatures in the firebox may be greatly influenced by the temperature of the incoming primary air. This is supported by Ayass et al. (2018), who found that introducing primary air at an ambient temperature (26 °C) lowers the temperature in the combustion chamber especially at the point of air entrance. Lower temperatures lead to incomplete combustion and additional energy use for pre-heating the incoming cold air, leading to lower efficiency and higher emissions as more fuel will be required (Suresh et al., 2015).

The earliest designs of retort kilns, such as the Adams kiln, are relatively sophisticated and require substantial capital investments, specialized expertise and an experienced operator, which restricts their adoption at domestic scale (Eltigani et al., 2022; Shepard, 2011). However, simple and affordable designs have been developed (Adeniyi et al., 2019). In addition, financial mechanisms have been set up to assist biochar producers to adopt these efficient and effective retort kilns, including financial incentives (such as loan guarantees) and subsidies (Pourhashem et al., 2018). Other measures to encourage uptake include education of consumers to expand markets, contributions from self-help groups and provision of seed capital through project grants (Atieno, 2017; Pourhashem et al., 2018).

2.5. Masonry kilns

Masonry kilns are fixed (permanent) kilns made from bricks and clay with additives such as sodium silicate to prevent cracking during the expansion and contraction cycles (Kalenda et al., n.d; Rodrigues and Junior, 2019). The construction and operation of various masonry kilns, including the arrangement of feedstock and methods for lighting have been described in previous publications (Oduor et al., 2015; Rodrigues and Junior, 2019). All masonry kilns have equi-spaced air inlet holes around the kilns at different height levels (bottom, middle and top) (Rodrigues and Junior, 2019). Some designs, such as the Argentine masonry kilns, have no chimney, while others (such as the beehive kiln) have chimneys (Rodrigues and Junior, 2019). Masonry kilns also differ in terms of source of heat with the Adam kiln operating on a retort principle (see section 2.4) while others use partial combustion of the feedstock for startup heat. Therefore, masonry kilns can be categorized into kilns with chimneys (Fig. 6a), those without chimneys (Fig. 6b) and those following the principles of retort kilns.

Masonry kilns are mainly constructed to carbonize large diameter wood to charcoal but are increasingly also being used to carbonize smaller-sized residues, such as sawmill residues, small diameter withies,

Table 5
Performance comparison of different designs of masonry kilns.

		Masonry kilns without chimney	Masonry kilns with chimneys
Feedstock		Large wood, Saw-mill residues, low diameter stems, twigs and branches, and bamboo (a, b, c, d, h)	Large wood, Saw-mill residues, low diameter stems, twigs and branches, and bamboo (a, b, c, d, h)
Construction materials		Bricks, cement, steel, clay, concrete, noble additives (sugar or sodium silicate) (c)	Bricks, cement, steel, clay, concrete, noble additives (sugar or sodium silicate) (c)
Portability		Stationary	Stationary
Source of heat		Partial combustion of feedstock	Partial combustion of feedstock
Labour requirements		Loading and monitoring labour	Loading and monitoring labour
Provider		Highly trained masonry specialist (f)	Highly trained masonry specialist (f)
Simplicity		Require medium level informal training	Require medium level informal training
Initial investment cost (US$)		500–800 (e)	500–800 (e)
Residence and cooling time (hours)		120–170 (d)	94–167 (d)
Pyrolysis rate (m^3 hr^{-1} of biochar)		(3–4) x 10^{-2} (d*)	(5–9) x 10^{-2} (d*)
Pyrolysis temperature (°C)		400–600 (d)	400–600 (d)
Heating rate (°C hr^{-1})		0.06–0.15 (d*)	0.02–0.2 (d*)
Efficiency (%)	Dry weight basis (%)	27–35 (c, b)	25–34 (c*)
	Thermal efficiency (%)	–	–
	Carbon content (%)	–	–
Controllability	Pyrolysis conditions	Slightly controllable	Slightly controllable
	Quenching/ snuffing	Natural snuffing and water (d)	Natural snuffing and water (d)
Emission levels	CO_2 (g kg^{-1} B)	–	155 (g*)
	CO (g kg^{-1} B)	–	8 5 (g*)
	NO_2 (g kg^{-1} B)	–	–
	CH_4 (g kg^{-1} B)	–	6.1 (g*)
	$PM_{2.5}$ (μg m^{-3})	–	–
	PM_{10} (μg m^{-3})		–
Biochar quality	Homogeneity of biochar	Heterogeneous	Homogeneous (c)
	Fixed Carbon (%)	69–83 (d*)	74–85 (d*)
	Hydrogen content (%)	–	–
	Volatile matter (%)	10–25 (d*)	7–17 (d*)
	Nitrogen content (%)	–	–
	pH	–	–
	Calorific value (MJ kg^{-1})	28–33 (d*)	27–32 (d*)
	Ash Content (%)	3–7 (d*)	5–11 (d*)
Applicability		Community, semi-industrial and industrial level	Community, semi-industrial and industrial level
Production of co-products/ services		None	Wood vinegar

Sources: (a). Kalenda et al. (n.d), (b) Oduor et al. (2015), (c) Rodrigues and Junior (2019), (d) García-Quezada et al. (2023), (e) UNDP (2009), (f) Practical Action (n.d), (g) Santos et al. (2017), (h) Charvet et al. (2022).
Note: g kg^{-1} B means grams per kg of initial biomass.

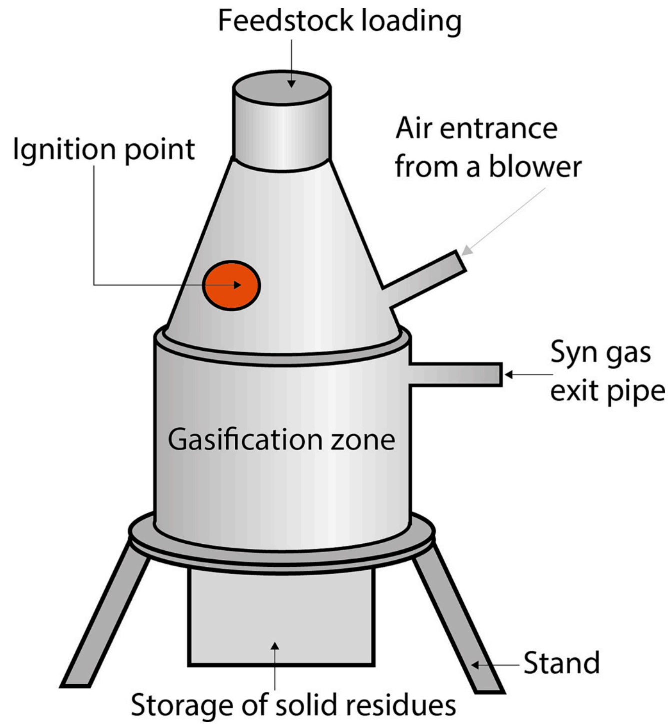

Fig. 7. Schematic diagram of a downdraft gasifier modified from Colantoni et al. (2015).

twigs and branches from shrubs such as *Tarchonanthus camphoratus*, Prosopis and bamboo to charcoal and biochar (Kalenda et al., n.d; Oduor et al., 2015). This shift may be attributed to the increasing scarcity of large diameter wood in areas where masonry kilns have been installed, and the increasing demand for biochar from other feedstocks for purposes such as briquetting and soil amendment. This switch of feedstock may affect the performance of masonry kilns in terms of efficiency, quality of charcoal and biochar produced, and emissions (FAO, 2017; Yaashikaa et al., 2020). Therefore, in addition to kiln design, feedstock characteristics may explain the variations in kiln performance shown in Table 5 (Charvet et al., 2022).

Controlling pyrolysis conditions in masonry kilns is not easy because adjusting temperature is slow due to the heavy brick insulation and the large size of the kilns (García-Quezada et al., 2023; Oduor et al., 2015). In the process over 20 % of the feedstock can be combusted to ash (Rodrigues and Junior, 2019). Difficulties in raising and lowering temperatures, especially during the startup and cooling phases, could contribute to the long ignition time (over 4 h), slow heating rate ($<$ 0.2 °C hr^{-1}) and longer cooling time (over two days), bringing the total carbonization cycle to over 120 h (Table 5) (Oduor et al., 2015; Charvet et al., 2022; García-Quezada et al., 2023).

Despite difficulties in controlling pyrolysis conditions, well-monitored kilns have relatively high efficiencies (27 % - 34 %) and produce charcoal of good quality with low emissions compared to open pit kilns (Table 5), but to achieve these benefits, operators of masonry kilns need to acquire a medium level of training on kiln loading and monitoring (Oduor et al., 2015; Rodrigues and Junior, 2019). Accurate monitoring of the smoke, especially in brick kilns with chimneys, enhances efficiency and quality of biochar as it prevents under- or over-carbonization (Rodrigues and Junior, 2019). Insulation improves the thermal balance within the kiln, while chimneys enhance flue gas flow within the kiln to ensure complete and homogeneous carbonization and reduce emissions (Charvet et al., 2022; Rodrigues and Junior, 2019). Natural cooling using mud to seal air inlets to the kiln instead of quenching with soil or water avoids biochar contamination with soil and reduces use of water (García-Quezada et al., 2023).

Regardless of the design, the cost of a masonry kiln is high due to high cost of the construction materials (bricks) and the high level of skilled manpower required in their installation, operation and monitoring (Oduor et al., 2015; Practical Action, n.d). The cost of installing a 900 kg capacity masonry kiln in China was estimated by UNDP (2009) to be over US$ 500, and the current (2023) cost may be even higher.

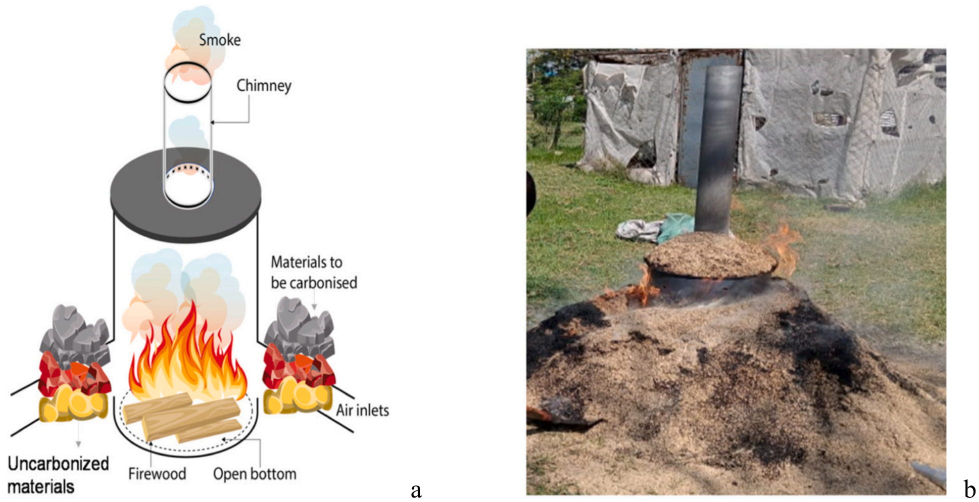

Fig. 8. KEFRI's Cylindrical kiln (a) schematic diagram of the kiln, (b) photo of the kiln taken by author.

Maintenance and operational costs are also high as these kilns require frequent repairs and high manual loading and offloading (Oduor et al., 2015). These factors inhibit widespread adoption of masonry kilns in low to middle income countries.

2.6. Other designs

A number of other biochar production kilns are emerging that have designs tailored to the specific conditions of low to middle income countries. These include downdraft gasifiers and the Kenya Forestry Research Institute (KEFRI)'s cylindrical open carbonizer.

In the downdraft gasifier, fuel is loaded into the top of the reactor, and as the fuel moves downwards, air is introduced by means of a pipe in the central part of the reactor (Fig. 7) (Colantoni et al., 2015; Gandhi et al., 2012). Downdraft gasifiers are uncommon in biochar production because the main product is syn gas, and they have lower efficiency than other designs and produce biochar with a high ash content (Gandhi et al., 2012).

The KEFRI's cylindrical open carbonizer kiln is fabricated by folding a sheet of steel into a cylinder with three pipes at the bottom to act as the air inlet (Fig. 8a). Its operation entails placing pieces of firewood at the fire point, igniting them and then covering them with the cylinder (Fig. 8a and b). The material to be carbonized is then placed around the cylinder while the sideways-facing pipes act as air inlets to the fuel chamber to support fuel combustion. Through conduction, the heat is transferred to the biomass material outside the cylinder which catches

Table 6
Categorization of parameters to Linkert scale.

Parameters			Biochar grading scores 1	2	3	4
Simplicity			Require skilled and experienced operator	Medium level informal training	Require simple informal training	Indigenous knowledge exists
Initial investment Cost (US$)			≥ 500	500 < ≥ 300	300 < ≥100	< 100
Pyrolysis rate (m^3 hr^{-1})			< 0.01	0.01 < 0.1	0.1 < 1	≥ 1
Pyrolysis temperatures (°C)			<550	550 < 750	750 < 1000	≥ 1000
Efficiency	Dry weight (%)		<20	20 < 35	35 < 50	≥ 50
	Thermal (%)		< 30	30 < 40	40 < 50	≥ 50
	Carbon content (%)		< 30	30 < 50	50 < 70	≥ 70
Controllability			No control	Slightly controllable	Controllable	Highly controllable
Emissions	CO_2	g kg^{-1}B	≥ 1500	1500 < ≥1000	1000 < ≥ 500	<500
		g kg^{-1}C	≥3000	3000 < ≥ 2000	2000 < ≥ 1000	<1000
		% vol of flue gases	≥ 15	15 < ≥ 10	10 < ≥ 5	<5
		PPM	≥ 800	800 < ≥ 500	500 < ≥ 200	<200
	CO	g kg^{-1}B	≥ 60	60 < ≥ 35	35 < ≥ 10	<10
		g kg^{-1}C	≥ 100	100 < ≥ 60	60 < ≥ 20	<20
		PPM	≥ 250	250 < ≥ 150	150 < ≥ 50	<50
	NOx	g kg^{-1}B	≥ 90	90 < ≥40	40 < ≥ 10	< 10
		PPM	≥ 50	50 < ≥ 30	30 < ≥ 10	< 10
	CH_4	g kg^{-1}B	≥ 8	8 < ≥ 5	5 < ≥ 3	< 3
		g kg^{-1}C	≥ 50	50 < ≥ 30	30 < ≥ 10	< 10
		% vol of flue gases	≥ 3	3 < ≥ 2	2 < ≥ 1	< 1
	$PM_{2.5}$	g kg^{-1}B	≥ 25	25 < ≥ 15	15 < ≥ 5	< 5
		g kg^{-1}C	≥ 35	35 < ≥ 20	20 < ≥ 5	< 5
		μg m^{-3}	≥ 180	180 < ≥ 100	100 < ≥ 20	< 20
Biochar quality	Biochar homogeneity		Highly heterogeneous	Heterogeneous	Slightly homogeneous	Homogeneous
	Fixed Carbon (FC) (%)		< 25	25 < 50	50 < 75	≥ 75
	Calorific value (MJ kg^{-1})		< 20	20 < 25	25 < 30	≥ 30
	Ash content (%)		≥ 25	25 < ≥ 15	15 < ≥ 5	< 5

Table 7
The Likert grading score of small-scale biochar production kiln designs used in low to middle income countries.

Kiln design	The Likert grading score of different evaluation parameters																		
	SP	IC	P_R	Avg _ a	Temp	Efficiency			Contr	Emission level					Biochar Quality				
						Dw	Tml	C _ Content		CO_2	CO	NO_2	CH_4	$PM_{2.5}$	Homog	FC	CV	AS	Avg _ b
Open pile burning	4	4	4	4	1	1	–	–	1	1	1	1	2	2	1	2	–	–	1.3
Open pit kiln	4	4	2	3.3	1	1	–	2	1	1	2	–	2	1	1	2	–	3	1.5
Kon-Tiki Cone kiln	3	3	3	3	3	4	–	2	1	3	2	4	2	3	2	4	3	–	2.8
Oregon kiln	3	1	3	2.3	2	1	–	2	1	1	1	–	2	3	2	3	–	4	2
Bottomless Drum kiln	3	4	3	3.3	3	2	3	4	2	4	1	–	1	–	2	3	4	2	2.5
Drum with perforated bottom	3	4	3	3.3	3	2	–	–	2	4	1	2	–	3	2	4	3	2	2.6
Horizontal drum kilns	3	4	3	3.3	2	2	–	–	2	–	–	–	–	–	2	4	2	1	2.2
Drum with manual agitator	3	–	2	2.5	2	3	–	–	3	–	–	–	–	–	3	4	4	3	3.1
Natural draft uninsulated TLUDs	2	4	–	3.0	3	2	1	–	3	1	3	1	–	1	3	4	4	1	2.3
Natural draft Insulated TLUDs	2	3	–	2.5	3	3	2	–	3	4	4	3	–	–	3	4	4	4	3.4
Forced draft TLUDs	2	3	–	2.5	4	–	3	–	4	2	4	4	2	3	4	4	4	–	3.5
Natural draft brick retorts	1	1	2	1.3	3	3	4	2	3	1	1	1	3	2	3	4	4	3	2.6
Natural draft drum-brick retorts	2	2	–	2.0	2	3	4	2	2	1	1	2	1	3	3	4	3	2	2.4
Natural draft uninsulated drum retorts	3	–	–	3.0	2	3	–	–	3	–	–	–	–	–	3	4	–	3	3.0
Natural draft insulated drum retorts	3	–	2	2.5	2	3	4	–	3	–	–	–	–	–	3	3	3	3	3.0
Forced draft drum retorts	3	–	–	3.0	3	3	–	–	4	–	–	–	–	–	4	4	–	4	3.7
Masonry kilns without chimney	2	1	2	1.7	2	3	–	–	2	–	–	–	–	–	2	4	4	3	2.9
Masonry kilns with chimneys	2	1	2	1.7	2	2	–	–	2	4	1	–	2	–	3	4	4	3	2.7

Key: SP = simplicity, IC = investment cost, P_R = pyrolysis rate, Avg_ a = average for SP, IC and P_R scores, Temp = Temperate range, Contr = controllability, Dw = dry weight basis, Tml = thermal efficiency, C_Content = Carbon content, CO_2 = carbon dioxide, CO = carbon monoxide, NO_2 = nitrogen dioxide, CH_4 = methane, $PM_{2.5}$ = particulate matter with 2.5 diameter, Homog = homogeneity, FC = fixed carbon, CV = calorific value, AS = ash content, Avg_b = average for Temp, Contr, DW, Tml, C_content, CO_2, CO, NO_2, CH_4, $PM_{2.5}$, Homog, FC, CV, and AS scores.

fire and starts carbonizing. This design is mainly used for materials such as husks and nuts that are difficult to ignite and combust.

3. Comparison of small-scale biochar production kiln designs used in low to middle income countries

There are several challenges in comparing the performance of small-scale biochar production kilns used in low to middle income countries. Data on costs and operational variables, such as efficiency and emissions, are missing for many groups, making it difficult to compare across the different kilns directly and accurately. In addition, authors of different studies use different measurement units, making conversion to a general unit for comparison difficult without additional information, such as volumes of initial feedstock, quantity of biochar produced, or volume of flue gases exhausted. For example, when reporting emissions of $PM_{2.5}$, Adam (2013) used g kg^{-1} of biochar produced while Wamalwa (2018) used µg m^{-3} of air in the exhaust vent. Moreover, most studies use only one or two materials to test efficiencies and quality of biochar produced by a single type of kiln. This may lead to inaccurate comparison of kilns because feedstock type affects the quality of biochar, heating rate, residence time and kiln efficiency (FAO, 2017). Despite these challenges, available data can be synthesized to provide a preliminary qualitative comparison of kiln designs using the likert grading score of 1 (worst), 2 (fair), 3 (good) and 4 (best), based on the quality of biochar, pyrolysis rate, investment costs, controllability, temperature ranges, emissions, and simplicity (Table 6). Table 7 indicates the results of likert grading score of small-scale biochar production kiln designs used in low to middle income countries.

The average scores in Table 7 can be used to generate a qualitative schematic comparison of small-scale biochar production kilns used in low to middle income countries (Fig. 9).

Fig. 9 indicates that selection of any kiln design for biochar production from agricultural and forest residues in low to middle income countries has an opportunity cost that reflects a general trade-off between cost and system performance. While open pile burning technique scores are comparatively better (grade score of 4) in terms of simplicity, investment cost and pyrolysis rate, the technique is worst in terms of controllability of pyrolysis conditions leading to high emissions that may be detrimental to the environment, low efficiency that translates to high input but low output, and low biochar quality that affects their effectiveness in some applications. (Table 7; Fig. 9). Apart from the Oregon kiln, which has a score of 3 for simplicity and pyrolysis rate, those with the potential to produce a large volume of biochar per batch, such as the Adams kiln and masonry kilns with or without a chimney, have a lower pyrolysis rate (pyrolysis rate of 3.5×10^{-3} - 9×10^{-2}) (Tables 1, 4, 5), are complex to operate and require high investment costs to install and maintain; hence they are considered to be less suitable for adoption in low to middle income countries.

The natural draft insulated and forced draft TLUD cookstoves produce quality biochar at higher efficiency and lower emissions than open pile burning, open pit, horizontal drum, perforated drum, bottomless drum, Kon-tiki and Oregon kiln designs, but they cost up to US$ 150 in

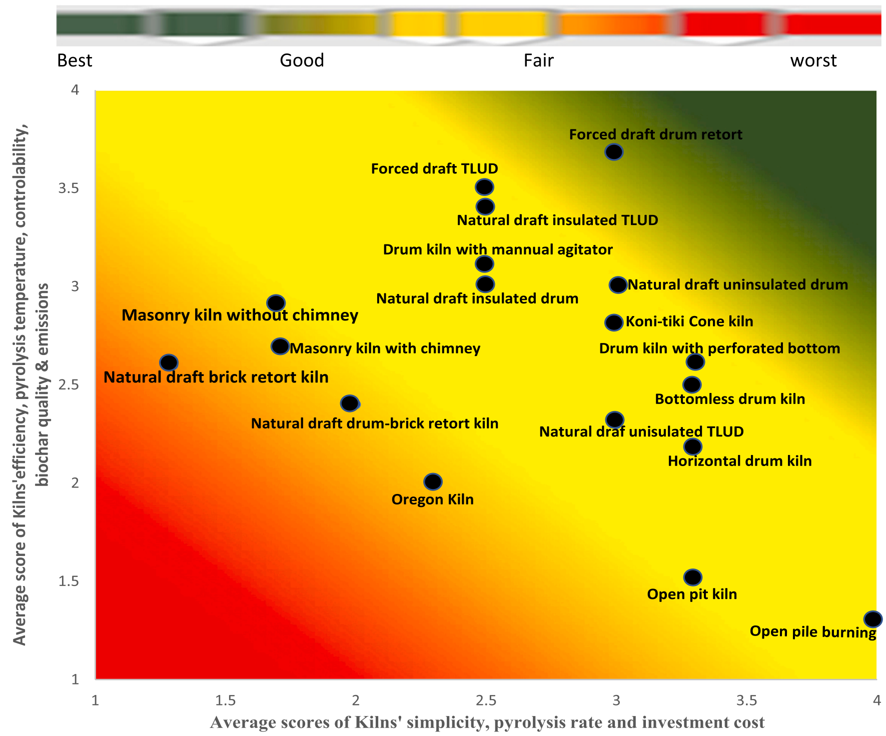

Fig. 9. schematic diagram comparing small-scale biochar production kilns in low to middle income countries.

Kenya and can only produce 0.3–1 kg of biochar per run (Cornelissen et al., 2016; Pandit et al., 2017). Therefore, TLUD cookstoves are generally unsuitable for biochar production in low to middle income countries as they are impractical for applications requiring processing of large amounts of organic residues. On the other hand, while drum kiln designs have the potential to produce co-products, they have only moderate control of pyrolysis conditions, resulting in heterogeneous pyrolysis conditions within the kiln that lowers the quality of biochar and increases emissions. Drum retort kilns, especially those with forced draft, have high real time control of pyrolysis conditions resulting in a more homogeneous pyrolysis, higher quality biochar, higher efficiency and lower emissions. However, they are considered a good option rather than best case because they are relatively complicated to use, requiring operators to be trained to monitor the pyrolysis process and control the airflow.

4. Future research on improving biochar production kilns in low to middle income countries

Rapid, sustainable and cost-effective production of high-quality biochar to meet increasing demand and enhance biochar certification for carbon credits by small-holder producers in low to middle income countries requires improvement of kilns in terms of costs, simplicity, controllability and performance. Instead of incurring the high costs of large masonry kilns or an Adams retort, which are mainly installed for charcoal production from large diameter pieces of wood, small-holder biochar producers processing agricultural and forest residues may benefit from using drum retort kilns that are portable, relatively inexpensive, less complex, and allow high controllability whilst enabling a pyrolysis rate of $(3-12) \times 10^{-2}$ m^3 of biochar hr^{-1} (Tables 2, 4; Fig. 9). However, drum retort kilns with forced draft and insulation may be further improved by combining appropriate design features from different kilns, such as recirculation of hot firebox flue gases into the pyrolysis chamber during the initial stages of pyrolysis, installing a heat distribution pipe in the form of a chimney from the firebox to the exhaust and introducing hot air into the firebox at an optimized flow rate within a specified time frame. These features may help to deliver incremental improvements in drum retort kilns and allow them to approach the theoretical maximum efficiency of 50 % to 80 % with production of high biochar quality, low emissions and without inflating costs or losing simplicity. The new kiln design should then be tested using a variety of feedstocks, to provide a standard set of kiln operations for different feedstocks and characterize emissions and quality of biochar produced from such materials. This is important as different agricultural and forest residues are obtained in different seasons of the year, so having a kiln that can carbonize a wide range of residues will mean continuous processing at all times of year by avoiding feedstock supply uncertainty (Okafor et al., 2022). Further research should also be conducted to establish the economically viable distance that either feedstock can be transported to the central processing site, or that biochar can be transported to the end-user to ensure optimized costs of biochar production.

5. Conclusions

Different kiln designs make use of different heat transfer mechanisms (conduction, convection, or radiation) during pyrolysis with some promoting a combination of all three. Comparison of small-scale biochar production kiln designs used in low to middle income countries is challenging because data are missing for some parameters, there is a lack of uniform measurement units and testing of most kilns has used only one or two feedstock types. Selection of any biochar production kiln design is based on a general trade-off between cost and system performance. However, drum retort kilns are suitable for adoption as they are portable, relatively inexpensive, less complex, highly controllable and produce high quality biochar with low emissions. Future research should focus on designing an inexpensive, efficient, simple and highly controllable kiln that recirculates hot firebox flue gases into the pyrolysis chamber at some pyrolysis stages, uses hot primary air and possesses a heat distribution pipe.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

No data was used for the research described in the article.

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