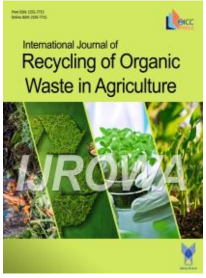

Int. J. Recycl. Org. Waste Agric., 2026; 15(2): 209-227

International Journal of Recycling of Organic Waste in Agriculture (IJROWA)

https://doi.org/10.57647/ijrowa.2026.7968

Research Article

Characterization of Biochar Produced from Cacao Pod Husk with Smallholder Farmers in Farm-Scale Reactors

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Article History:

Received:
22 November 2024

Revised:
01 December 2024

Accepted:
21 December 2025

Published Online:
02 January 2026

Published in Issue:
30 June 2026

Abstract

Purpose: Cacao pod husks, comprising 70% of the crop weight, are usually discarded back on the plot representing a waste stream, even though it could be used to produce biochar, a valuable soil amendment. Biochar is usually produced in large-scale reactors; however, producing it in farm-scale reactors could be more affordable and socially equitable for the farmers, and more sustainable. Here, we investigate whether cacao husk biochar can be produced using farm-scale reactors and has properties suitable for use as soil amendment.

Method: With Malaysian cacao farmers, we fabricated two reactor setups operating under pyrolysis and gasification. We characterized its properties according to International Biochar Initiative standards and compared the two production processes.

Results: Both reactor setups reliably converted cacao husks into biochar. The biochars passed all toxicology tests. Gasifier biochar largely contained more nutrients (total P, K, Ca, Mg, and S) and volatile matter than retort biochar, likely because gasification required quenching before complete thermochemical conversion to preserve yield. As quenching induces thermal shock, gasifier biochar had higher pore volumes (0.02 vs. 0.002 cm^3/g), pore sizes (20.08 vs. 9.61 nm), and surface areas (48.58 vs. 8.34 m^2/g) relative to retort biochar. The gasifier reactor also required less setup time (30 vs. 120 mins) and capital cost, but had longer post-processing times, lower yields (13% vs. 33% feedstock weight), and lower pyrolysis temperatures.

Conclusion: The production of cacao husk biochar with small-scale reactors proved successful and cost-efficient, and could be used to produce biochar locally at the waste source.

Keywords: Cacao pod husk, Biochar characterization, Farm-scale reactors, Pyrolysis and gasification, Smallholder agriculture

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Cite this article: Hamzah, L., Geng Ong, N., Nayak, A., Luby, S. & Vindušková, O., (2026). Characterization of Biochar Produced from Cacao Pod Husk with Smallholder Farmers in Farm-Scale Reactors, *International Journal of Recycling of Organic Waste in Agriculture,* 15(2), 209-227. https://doi.org/10.57647/ijrowa.2026.7968

1. Introduction

At present, only the cacao pulp and bean, which constitute ~30% of cacao pod weight, are productively used in the chocolate industry, while the husk, representing the remaining ~70%, is considered waste. As part of the chocolate production process, especially on small farms, the cacao pulp and bean are fermented and dried on site. This allows the husks to be discarded back onto the plot to decay and potentially fertilize the soil (Lu et al., 2018). However, natural decomposition processes may not make substantial or reliable improvements to soil fertility because decay rates vary substantially depending on soil quality, shade regimes, litter nitrogen content, and carbon / lignin ratios, among other factors (Bonanomi et al., 2017; Ofori-Frimpong et al., 2007). One potential solution is to thermochemically convert the husks into value-added products, e.g., biogas, bio-oils, and biochar.

With cacao husks, biofuel and bioactive compound production have often been prioritized due to their higher value (Adjin-Tetteh et al., 2018; Belwal et al., 2022; Londoño-Larrea et al., 2022); however, biochar also has many interesting and unique properties (de Paula Protásio et al., 2022; Pinzon-Nuñez et al., 2022). It has been studied as an adsorbent to remediate contamination (Abbey et al., 2022; Bednárek et al., 2022; Córdova et al., 2020; Eduah et al., 2020; Lang et al., 2021; Najafabadi et al., 2020; W.-T. Tsai et al., 2020), as a fuel or energy storage (Lang et al., 2021; Milian Luperón et al., 2020; C.-H. Tsai et al., 2018), and as a soil amendment in agriculture (Ogunlade et al., 2016; Pinzon-Nuñez et al., 2022). When used as a soil amendment, biochar can improve soil performance, fertility, and yield, remediate contamination, and sustainably sequester carbon (Ahmad et al., 2014; Guo et al., 2020; Qambrani et al., 2017; Verheijen et al., 2010; J. Wang et al., 2016).

Biomass can be thermochemically converted into biochar in a reactor via pyrolysis (fast or slow), hydrothermal carbonization, gasification, torrefaction, and flash carbonization (D. Wang et al., 2020; Yaashikaa et al., 2020; Zhang et al., 2019). Although there are many commercially available reactors, their capacities far exceed farmers' production: a typical farmer earns ~US$500/year from producing 750kg of wet weight cacao beans, whereas the smallest field scale reactors cost ~US$4,000 with a 10,000L capacity (Garcia-Nunez et al., 2017; Woolf et al., 2017). Larger facilities benefit from efficiencies of scale and have the production volume and capital necessary to engage in more complex engineering to produce higher value products, but they also require large amounts of feedstock, with farmers sending them their raw material input. However, most cacao is produced on small farms. For example, 98% of land cultivated for cacao in Malaysia are smallholdings, each less than a hectare (Government of Malaysia, 2022; Motolani et al., 2017). In this context, centralized large-scale production is neither logistically practical nor socially equitable because the small-scale and relatively intermittent nature of production means that the unit transportation costs of shipping raw material would be high and compensation to the farmers meager. Additionally, the high moisture content of the cacao husks would result in high levels of spoilage during the transportation process in ambient conditions. An alternative is for smallholder farmers to produce their own biochar on-site with an affordable, appropriately sized reactor (Nsamba et al. 2015a). This would simplify the logistics of production and consumption, increasing its sustainability, while allowing farmers to retain control over their product. They could produce biochar intended for agricultural use, unlike many commercially-produced biochars (Promraksa & Rakmak, 2020). For this they would require a small-scale reactor that produces a competitive yield of good quality biochar (International Biochar Initiative, 2015) with low capital and operating costs and limited additional training and manpower needs. There is a need to develop mobile but economical technologies that can be adopted by small-scale farmers and to understand how a particular biochar technology impacts biochar properties as well as the production costs (Nsamba et al. 2015b). Two types of reactors can be easily and affordably fabricated for small-scale use, operating by: i) slow pyrolysis ('retort') (Ighalo et al., 2021; Living Web Farms, n.d.), and ii) gasification ('gasifier') (Kim et al., 2016; Rogers & Augustine, 2011; Taupe et al., 2016). However, differences between these production methods in terms of yield and quality of biochar at this scale remain unexplored. Furthermore, the development and optimization of these reactors should be informed by input from farmers as potential future users. Finally, the produced biochar should be benchmarked against objective international standards to reliably assess the success and feasibility of the designed method.

Gasification has typically been used to produce synthesis gas (Klinghoffer et al., 2015; D. Wang et al., 2020; Yaashikaa et al., 2020), while farm scale technologies to pyrolyze biomass have focused on energy provision and cleaner cooking (Scholz et al., 2014; Sundberg et al., 2020). Producing cacao husk biochar at the farm scale for use as a soil amendment is therefore novel, although bench-scale studies have been reported (Rozita et al., 2022). As biochar characteristics can vary substantially based on the original feedstock and production techniques (Ippolito et al., 2020; Yaashikaa et al., 2020), it is not known *a priori* what characteristics will result from each production method (D. Wang et al., 2020). Additionally, optimizing each reactor to a cacao husk feedstock requires tuning the airflow rate, moisture content, feedstock size, and capacity. The aims of this project were three-fold: i) to convert cacao husks into soil amendment biochar using farm-scale reactors and characterize its properties, ii) to fabricate and compare the reactors with input from farmers, and iii) to compare the biochar produced from two types of small-scale reactors operating under different principles. The primary novel aspects of our study are exploring the use of farm-scale reactors for biochar production from cacao husks and involving farmers in the reactor design process.

2. Materials and methods

2.1. Study site and reactor design

The cacao husks used for the production of biochar in this study came from a subset of smallholder farmer suppliers of Chocolate Concierge in Peninsula Malaysia, predominantly located in the central and western states of Melaka, Selangor, and Pahang. Reactor prototypes were tested, iterated, and optimized at a Chocolate Concierge farm in Pahang with farmer input. The sizes and material of the prototypes were determined both by farmers' yields and budgets, and manufactured with material that was readily available locally. Biochar reactors were sized to fit approximately one batch of harvested cacao husks. Each small-scale farmer harvests approximately 100 kg of fresh pods at a time (equivalent to ~10 kg of dry husk). Given the average fresh pod weight (180 g) (Meza-Sepúlveda et al., 2021), 100 kg represents ~550 pods (Caputo & Mašek, 2021). There were two readily available materials that could serve as candidates for the main reactor body - cylindrical stainless-steel drums of either 100L or 200L volume. We chose to use a 100L drum for the retort reactor nested within a larger 200L drum that contained fuel, and selected a 200L for the main gasifier reactor body. Diagrams of both reactors including photos when assembled and disassembled are shown in Figure 1 and their technical drawings in Figures SM.1 and SM.2 (Supplementary material). Cacao pod husks contain 20-26% cellulose, 9-13% hemicellulose, and 14-28% lignin (Lu et al., 2018). Cellulose pyrolyzes at approximately 320-365°C, hemicellulose at 270-310°C, and lignin over a wider range that peaks around 375°C with long Gaussian tails stretching from 145°C to 635°C (Cai et al., 2013). The retort reactor separates the flame from the feedstock whereas the gasifier reactor does not (Figure 1). Given the broad distribution of temperatures over which lignin decomposes, the temperature of the inner drum of the retort reactor must reach at least ~425°C (one standard deviation away from the peak) to decompose 84% of the lignin. Considering that i) the pyrolysis of wood begins around 300°C (Koraïem & Assanis, 2021), ii) pyrolysis is an initial step of the combustion process, iii) temperatures of up to and beyond 800°C are required to completely combust the volatile gases emitted and gasified biochar produced (Koraïem & Assanis, 2021), and iv) the gasifier biochar production process here relies on an open, combustion flame, we can assume that our minimum temperature requirement of 425°C will be met in the gasifier reactor setup since the combustion of gases would take the process temperature far beyond the required minimum. Projecting a biochar yield of between 30-40% (Caputo & Mašek, 2021), each batch would produce roughly 5 kg of biochar.

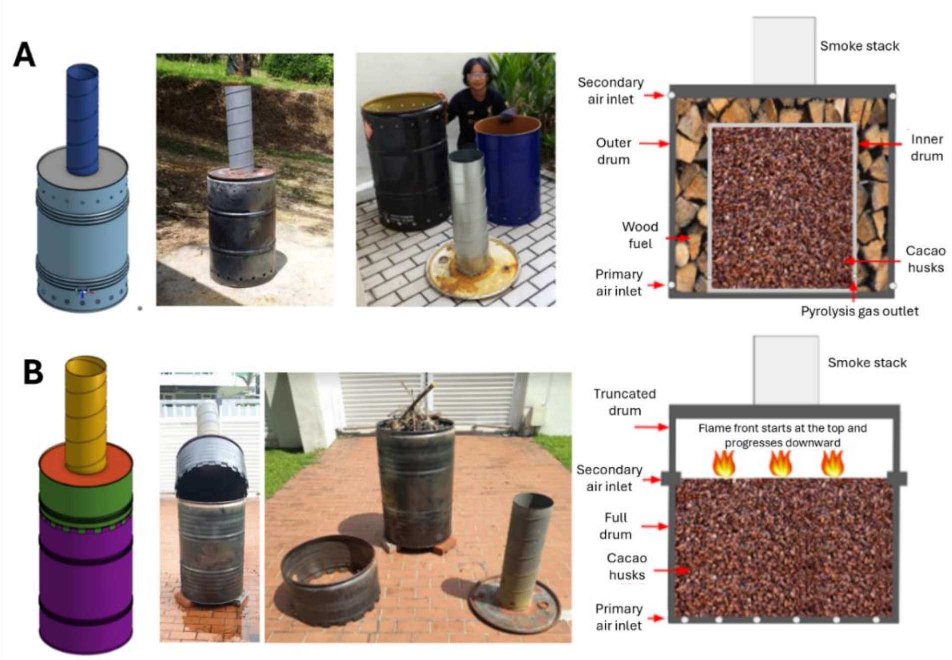

Figure 1. Diagrams and photographs of both assembled and disassembled retort reactor (A) and gasifier *reactor* (B)

2.2. Biochar production method

The cacao husks were first dried. This was done in ambient conditions and resulted in husks of ~20% moisture, hard and unyielding under pressure, that sounded percussive when flicked together. On the farms, the harvested cacao seeds and pulp were first fermented in barrels for about 5 days before being dried on drying tables set up in a greenhouse. Given that the cacao pods were also harvested in batches, the farmers suggested this could be a convenient logistical arrangement as the husks could be dried on the same tables during the fermentation process. Enough cacao husks were dried and accumulated to provide the feedstock necessary for at least 5 runs in each reactor. The husks were then thoroughly mixed to ensure that the two reactors received husks of similar composition. To start the pyrolysis process, both the retort and gasifier reactors required kindling. Farmers suggested bamboo from the farms, which they harvested, dried, and prepared, as well as dried leaves / twigs / sticks. These were lit with a lighter with the smoke stack detached. Once the flame was established, the smoke stack was placed on top of the setup. On brief occasions where the emissions from the smoke stack were not completely clear, indicating incomplete combustion, cracking open the smoke stack to allow greater airflow (and therefore oxygen) remedied the situation.

2.3. Optimization process

Each reactor prototype was optimized with the farmers until they performed reliably and predictably on three consecutive runs of biochar production, with samples and data taken from each successful run used for subsequent analysis. A successful run was an uninterrupted run where the feedstock is completely converted into biochar. The parameters measured included: i) temperature profile through the pyrolysis process at four heights along the external reactor surface as well as the smoke stack, ii) the time taken during preparation, pyrolysis, and post-processing, iii) yield, iv) moisture content, v) feedstock preparation process, and vi) resources required. Farmers were able to independently operate the reactor after approximately 3 hours of training and supervision. Temperature was measured using a TPI 377 infrared temperature gun with sensor emissivity set at 0.99, which was validated by a Red Lion Controls TMPKUT02 K-type thermocouple. The moisture content of the husks was measured using an Extech MO55 moisture meter, which was subsequently validated by oven drying a subset of cacao husk samples at 105°C for 48 hours. The moisture content of the produced biochar was measured by oven drying at the same conditions.

2.4. Biochar quality assessment

The biochar produced by each optimized process was characterized and assessed based on utility and toxicology properties published by the International Biochar Initiative (International Biochar Initiative, 2015). Before subsampling, both produced biochars were homogenized by grinding (applying the same effort) which is a common approach (Thomas 2021). The tests were conducted at commercial labs run by ALS Technichem (M) Sdn. Bhd. and the Forest Research Institute of Malaysia. Measurements of exchangeable Na, K, Ca, and Mg, mineral NH_4^+ and NO_3^-, and available P were made following Page et al. (Page et al., 1982). Measurements of liming as a percentage of $CaCO_3$, electrical conductivity, moisture content, and pH were conducted as described in (American Public Health Association et al., 1975). Volatile matter was measured following the methods specified in CH17-8 at 104°C, while total N followed the Dumas method (FAO, 2021), total Cl followed EN14582 (European Committee for Standardization, 2016). Hydrogen was measured by elemental analysis using He as carrier gas and infrared detection (LECO CHNS628, LECO, USA). Measurements for dioxins and furans were made following the methods specified in USEPA 1613 (USEPA, 1994a), with slight modifications, total organic carbon was measured following USEPA 9060 (USEPA, 2004), total As, Cd, Co, Cu, Pb, Mo, Ni, Se, Zn, B, Na, P, K, Ca, Mg, and S all followed USEPA 6010B (USEPA, 1996a), Hg followed USEPA 7471A (USEPA, 1994b), while polycyclic aromatic hydrocarbons and polychlorinated biphenyls following USEPA 8270C (USEPA, 1996b). Particle size distribution was measured on a shaker with sieves of differently sized meshes, while the total surface area, pore size, and pore volume were measured using an accelerated surface area analyzer/BET process, having first degassed the samples at 300°C for 48 hours. A composite sample was assessed for each pyrolysis process by taking a 300 g sample from each of three reliably optimized runs per reactor. The analytical results provided by ALS Technichem (M) Sdn. Bhd. were ensured by analyses of certified reference material under conditions of internal reproducibility.

3. Results and discussion

3.1. Characterization of biochar produced from cacao husk in farm-scale reactors

The properties of biochar produced from cacao husk in each reactor type are shown in Table 1. Although pyrolysis conditions can contribute to higher levels of toxicants (Verheijen et al., 2010) , both biochars met all Category B toxicant standards and are therefore safe to use as a soil amendment given current guidelines. The original cacao husk feedstock also met these toxicant standards, as shown in Table SM.1 (Supplementary material). Even though dioxins and furans were detected in the samples (Table 1), the measured levels were well within the ranges reported for other biochars, which have also been deemed to be safe for soil amendment use (Sobol et al., 2023). The two biochars showed many similar properties in Category A (basic utility properties) and some in Category C (advanced analysis) (Table 1). Of these characteristics, both biochars fell within the properties reported for the other cacao husk biochars for organic carbon, total ash, and total nitrogen content, as well as electrical conductivity (Table 1). The hydrogen to organic carbon ratio ($H:C_{org}$) of both of the produced biochars was slightly higher but close to the upper range reported in the literature. Both biochars also had substantially higher liming potential than other cacao husk biochars, which were reflected in their higher pH. In terms of the nutrients covered in category C advanced analysis, the produced biochars seemed to differ from some of the reported values of other cacao husk biochars. However, relatively fewer studies reported these data making the comparisons only indicative. From those parameters where more data was reported, the produced biochars seemed to have lower exchangeable Ca and available P, and higher exchangeable K than other cacao husk biochars.

There are two main categories of biochar: woody and non-woody, with non-woody biochars further subdivided into crop- and grass-based, animal waste, and solid waste biochar (Ippolito et al., 2020; Tomczyk et al., 2020). Cacao husk biochar originates from a crop-based, non-woody biochar. The ash content of our biochars produced from cacao husk was ~28%, which falls within the reported values from other cacao husk biochars (19% – 29%) and is in line with observations that the ash content of crop-based biochars typically falls between that of woody biochars (<7%) and animal-waste based biochars (>50%) (Cornelissen et al., 2018; Gamboa-Herrera et al., 2021; Martinsen et al., 2015; Mukome et al., 2013; Pouangam Ngalani, Dzemze Kagho, et al., 2023). Plant-based biomass generally have higher lignin contents than animal waste, which increases both biochar carbon content and ash content (S. Wang et al., 2015). Both ash and carbon contents can increase with increasing temperature due to losses by volatilization of other elements (Enders et al., 2012; Gamboa-Herrera et al., 2021; Ippolito et al., 2020; Pouangam Ngalani, Dzemze Kagho, et al., 2023; Tomczyk et al., 2020). However, the maximum organic carbon content is naturally limited by the fraction remaining after the ash content has been considered. Correspondingly, the carbon content of crop-based biochars also falls between that of animal-waste based biochars (18-28%) and woody biochars (up to 98%), with crop-based biochars such as orange pomace yielding a carbon content of 68% (Jiang et al., 2013; Tag et al., 2016; Tomczyk et al., 2020; Zielińska et al., 2015). The carbon content of a biochar is a direct reflection of the proportion of other elements (e.g., N, S, P, K, Ca, and P) that exist in the original feedstock; e.g., woody biochars have high C content due to a smaller C-dilution effect owing to lower quantities of other elements present (Ippolito et al., 2020). This is reflected in the organic carbon content of our cacao husk biochars at nearly 60%. This was similar to the majority of other cacao husk biochars of 54% – 76% (Cornelissen et al., 2018; Gamboa-Herrera et al., 2021; Martinsen et al., 2015; Obia et al., 2015; Oluleye et al., 2023; Pouangam Ngalani, Dzemze Kagho, et al., 2023), although there were also a few others that reported organic carbon contents of 11% – 35% (Jubaedah et al., 2021; Pouangam Ngalani, Dzemze Kagho, et al., 2023; Sam et al., 2017; Yeboah et al., 2016). The produced cacao husk biochar was highly alkaline, with a pH value of about 11. This appears to be on the more alkaline part of the range reported for biochars, even for crop-based biochars (Ippolito et al., 2020; Tomczyk et al., 2020), although most other cacao husk biochars were only slightly less alkaline with pH values of between 9.5 and 10.8 (Cornelissen et al., 2018; Gamboa-Herrera et al., 2021; Jubaedah et al., 2021; Martinsen et al., 2015; Obia et al., 2015; Pouangam Ngalani, Dzemze Kagho, et al., 2023; Quansah, 2021; Sam et al., 2017; Yeboah et al., 2016). This could be a function of pyrolysis temperature, as increasing pyrolysis temperatures are correlated with higher pH values (Ding et al., 2016; Gamboa-Herrera et al., 2021; Pouangam Ngalani, Dzemze Kagho, et al., 2023). Although crop-based (including cacao husk) biochars produced at lower temperatures of ~300°C had pH values ranging between 7.7 and 9.5 (Pouangam Ngalani, Dzemze Kagho, et al., 2023; Yuan et al., 2011), the temperatures that the biochars produced in this study reached were generally higher. Additionally, crop-based biochars have higher pH values than woody biochars by between 2 and 3.4 units (Mukome et al., 2013; Tag et al., 2016). This is likely due to the higher ash and salt contents in crop-based biochars relative to woody ones (Ippolito et al., 2020; Montes-Morán et al., 2004). If used as an agricultural soil amendment, the high pH of the cacao husk biochar could be helpful in remediating acidic soils (Cornelissen et al., 2018; Dai et al., 2017; Gul et al., 2015; Martinsen et al., 2015; Obia et al., 2015; Pouangam Ngalani, Dzemze Kagho, et al., 2023; Pouangam Ngalani, Ondo, et al., 2023), although it could also elevate the soil pH above optimum levels for nutrient availability in less acidic soils (Adam et al., 2020; Bahrun et al., 2018; Quansah, 2021; Weil & Brady, 2017).

Table 1. Characterization of biochar produced from cacao husk in two types of small-scale reactors (retort and gasifierThe properties characterized are as listed by the International Biochar Initiative (International Biochar Initiative, 2015). Asterisk denotes properties for which the two biochars differed by more than 10%. Where available in the literature, the characteristics of other cacao husk biochars are listed. NA: not available

Parameter	Criteria	Unit	Retort	Gasifier	Other Biochars
Category A: Basic Utility Properties					
Moisture*	Declaration	% dry mass	3.7	37.4	NA
Organic Carbon (C_{org})	10% minimum	% dry mass	59	56.4	17.4 – 76.1[a-g,i,j]
H : C_{org}	0.7 maximum	Molar ratio	0.32	0.34	0.031 – 0.31[b,e]
Total Ash	Declaration	% dry mass	28.6	28.3	18.9 – 29.0[a,b,d,g]
Total Nitrogen*	Declaration	% dry mass	1.3	0.9	0.46 – 1.5[a-f,h-j]
pH	Declaration	pH	11	11.3	7.9 – 10.8[a-j]
Electrical Conductivity	Declaration	dS/m	19.3 at 25°C	19.7 at 25°C	9.08 – 30.5[b,g]
Liming (if pH > 7)*	Declaration	% CaCO3	23.40	59.90	10.1 – 14.2[g]
Particle size distribution*	Declaration	< 0.106mm;	1.69%	1.63%	NA
		0.106-0.212mm;	8.34%	3.30%	NA
		0.212-0.50mm;	10.83%	7.91%	NA
		0.50-1.18mm;	15.85%	13.34%	NA
		1.18-2.36mm;	20.34%	19.24%	NA
		> 2.36mm	41.21%	54.58%	NA
Category B: Toxicant Assessment					
Polycyclic Aromatic Hydrocarbons, total	6 – 300	mg/kg	<0.5	<0.5	NA
Dioxins / Furans*	17	ng/kg I-TEQ	6.1 (max)	9.8 (max)	NA
Polychlorinated Biphenyls	0.2 – 1	mg/kg	<0.1	<0.1	NA
Arsenic	13 – 100		<1	<1	NA
Cadmium	1.4 – 39		<1	<1	NA
Cobalt	93 – 1200		1	<1	NA
Copper*	34 – 100		13	21	NA
Lead	143 – 6000		<1	<1	NA
Mercury	1 – 17		<0.1	<0.1	NA
Molybdenum*	5 – 75		14	<5	NA
Nickel*	47 – 420		2	8	NA
Selenium	2 – 200		<5	<5	NA
Zinc*	416 – 7400		120	172	NA
Boron*			41	47	NA
Total Chlorine*	Declaration		890	740	NA
Sodium (total; exchangeable)*			187; 34.5	535; 50.6	141[f]; 66-990[a,d,e,j]
Category C: Advanced Analysis					
Mineral (available) nitrogen (NH_4^+)*		mg/kg	9.76	1.37	NA
Total phosphorus*		mg/kg	4620	6890	0.5[f]
Total potassium		mg/kg	102000	110000	257[f]
Exchangeable potassium*		mg/kg	80045	66689	5265-49530[a,d,e,h,j]
Available phosphorus*		mg/kg	144.5	67	263-3898[g-j]
Total calcium*		mg/kg	10700	23400	2890[f]
Total magnesium*		mg/kg	4770	9750	NA
Total sulphur*		mg/kg	1820	2180	2500-3200[b]
Exchangeable calcium *		mg/kg	569	1130	7455-40800[a,c-e,h,j]
Exchangeable magnesium*		mg/kg	2360	6700	3087-33900[a,c-e,h,j]
Volatile matter*		% dry mass	3.7	37.4	NA
Total surface area*		m^2/g	8.34	48.58	29-30.9[a,d,e]
Pore size*		nm	9.61	20.08	NA
Pore volume*		cm^3/g	0.002	0.02	NA

a: (Cornelissen et al., 2018); b: (Gamboa-Herrera et al., 2021); c: (Jubaedah et al., 2021); d: (Martinsen et al., 2015); e: (Obia et al., 2015); f: (Oluleye et al., 2023); g: (Pouangam Ngalani, Dzemze Kagho, et al., 2023); h: (Quansah, 2021); i: (Sam et al., 2017); j: (Yeboah et al., 2016)

The H: Corg of the produced cacao husk biochar was ~0.3. Crop-based biochars again have intermediate H:C_{org} ratios relative to wood biochars (low) and animal / solid waste feedstocks (high) (Tomczyk et al., 2020), although the exact values vary substantially depending on temperature, yield, and volatile matter content (Wani et al., 2020). An H:C_{org} ratio of less than 0.7 indicates that a material has been sufficiently thermochemically altered (International Biochar Initiative, 2015; Ippolito et al., 2020) since the biochar production process results in the loss of H and O via water, organic surface functional groups, and tar (Ahmad et al., 2014; Cantrell et al., 2012). Although this was similar to the cacao husk biochar produced by (Obia et al., 2015), it was much higher than the 0.03 – 0.07 reported by (Gamboa-Herrera et al., 2021), which also had significant differences in the production method.

Although the electrical conductivity of our cacao husk biochar (19.3-19.7 dS/m) was higher than reported for the means of most crop-based biochars (5.72+0.67 dS/m) (Ippolito et al., 2020), it does fall within the wide range of values reported for biochars (10^0 to 10^4 dS/m) (Kane et al., 2021; Singh et al., 2017) and was similar to other cacao husk biochars of between 9.1-30.5 dS/m (Gamboa-Herrera et al., 2021; Pouangam Ngalani, Dzemze Kagho, et al., 2023).

Generally, higher electrical conductivity values are seen in biochars with higher lignin content and production temperatures (Kane et al., 2021).

Where cacao husks can have lignin content of between 14-28%, other crop residue feedstocks are much lower, for example orange pomace (3.3+2.3%) and corn straw (7.5+0.4%) (Song et al., 2014). This can be a result of the higher ash content generated, which increases the amount of soluble salts in the biochar which contribute to electrical conductivity (Singh et al., 2017).

The cacao husk biochars were classified as shown in Table 2. Brief explanations for what a given rating means are described in each table entry, while a full description of the basis, rationale, and calculations for each classification can be found in Camps-Arbestain et al. (2015).

3.1.1. *Effect of small-scale reactor type on biochar properties*

Feedstock type is usually the biggest driver of biochar properties (Ippolito et al., 2020) and the produced biochars did show large similarities in their basic properties.

However, the reactor type in our study (retort vs. gasifier) also produced some differences which we highlight further when the values of the retort and gasifier biochars were not within 10% of each other (Table 1). Given that we use the same feedstock sourced from the same region over the same timeframe to produce both retort and gasifier biochar and analyzed composite samples to reduce the impact of batch-to-batch variability, any differences between the biochars are likely to be explained by variations in production method. In terms of physical properties, quenching the biochar at the end of the gasification process causes a thermal shock to the freshly formed biochar that results in an increase in the total surface area, pore size, and pore volume (Kong & Sii, 2020).

This explains why the gasifier biochar has higher values of all these properties relative to the retort biochar (Table 1).

Quenching also introduces moisture to the biochar that is not fully evaporated during post-pyrolysis drying of the gasifier biochar, whereas the retort biochar had all moisture vaporized at the beginning of the pyrolysis process.

Consequently, gasifier biochar has a substantially higher moisture content than retort biochar (Table 1). The difference in particle size distributions between the biochars were also impacted by their production methods, with the retort biochar having a higher proportion of smaller sized particles compared to the gasifier biochar (Table 1).

This was likely due to the retort biochar was brittle due to its dryness, so was more easily crushed. The gasifier biochar was less brittle, although it had already broken up into smaller pieces during quenching.

Table 2. Classifications of the cacao husk biochars using the International Biochar Initiative's Biochar Classification Tool (Lehmann & Joseph, 2015)

	Retort Biochar	Gasifier Biochar
Carbon Storage Class	3: 400-500 g/kg C_{org} remains in soil after 100 yrs	2: 300-400 g/kg C_{org} remains in soil after 100 yrs
Fertilizer Class	2: sufficient K & Mg (but not P or S)	2: sufficient K & Mg (but not P or S)
Liming Class	3: $CaCO_3^-$ eq > 20%	3: $CaCO_3^-$ eq > 20%
Particle Size Class	Blended powder	Blended

Based on a meta-analysis, Thomas (2021) suggested that the optimal particle size of biochar for soil amendment use is in the range 0.5–1.0 mm and that smaller particles can negatively affect porosity. From this point of view, retort contained larger proportion of particles smaller than 0.5 mm (20.9%) than gasifier (12.8%) so lower brittleness of gasifier may be advantageous.

Chemically, the gasification process does not allow for full pyrolysis of the entire batch of feedstock. Particularly at the bottom of the reactor, the required high temperatures necessary to maximally decompose organic matter by volatilization and thermal degradation were not reached (Tomczyk et al., 2020).

This is because quenching occurs as the flame front reaches the bottom, where temperatures have reached the more than 250°C necessary for pyrolysis (Tomczyk et al., 2020) but before we risk complete combustion and the attendant reduction in yield. This can explain why gasifier biochar contains higher levels of volatile matter than retort biochar, which leads to correspondingly higher levels of associated nutrients like total N/P/Ca/Mg/S and exchangeable Ca/Mg, in addition to greater liming potential. However, retort biochar contained higher levels of other nutrients, such as exchangeable K, available P, and mineral nitrogen, relative to gasifier biochar. Given that these are all labile and partly soluble nutrients; it is possible that some of these nutrients were leached from the gasifier biochar during the quenching process.

3.1.2. *Potential use of the produced biochars as soil amendment*

Biochars have a range of proposed uses, such as to remediate contamination, improve soil fertility, and sequester carbon (Ahmad et al., 2014; Guo et al., 2020; Qambrani et al., 2017; Verheijen et al., 2010; J. Wang et al., 2016). Since we produced cacao husk biochar to investigate the possibility that it could benefit the cacao crop, we focus here on its potential impacts as a soil amendment.

The high pH of our biochars make them particularly suited to remediating acidic soils (Guo et al., 2020), while their low $H:C_{org}$ ratio makes them effective at mitigating against N_2O pollution (Ippolito et al., 2020). Given that $H:C_{org}$ ratios are positively correlated with O:C ratios, it is therefore also likely that our biochars will have a correspondingly long half-life of more than 1000 years, making them good candidates to sequester carbon (Ippolito et al., 2020; Spokas, 2010). Their high ash content is likely to result in increased hydrophobicity in soils to which they are applied (Kookana et al., 2011), leading to greater retention of hydrophobic agrochemicals such as herbicides (Sopeña et al., 2012). Although this increased hydrophobicity could result in lower water retention levels in soils, the high organic carbon content of our biochars increases the specific surface area of soils, negating the hydrophobic effects by providing additional surface area that leads to better water sorption (Tomczyk et al., 2020).

The other impact of high ash content is high electrical conductivity, which implies higher levels of soluble salts in our biochars (Singh et al., 2017). With this, the existing soil salinity as well as salt-sensitivity of cacao should be taken into account (Singh et al., 2017).

There were also differences in the biochars produced in the two different reactors, indicating they may have different effects as soil amendments. Biochars with a high volatile matter (>20%) content can inhibit growth due the priming effect and increased microbial activity in at least the short term, which increases soil respiration and immobilizes inorganic N pools (Deenik et al., 2009). This suggests that gasifier biochar may not be a promising soil amendment, especially since its mineral nitrogen pools are already lower than those of retort biochar. However, the gasifier biochar also had greater concentrations of most nutrients relative to the retort biochar, which may be compensatory depending on the soil properties to which the biochar is added and how this relates to the needs of the cacao plant. In addition, the gasifier biochar also had a greater total surface area, pore size, and pore volume than the retort biochar. Greater porosity and surface area could improve soil quality by providing habitats for symbiotic microbes, allowing greater air movement through soil for microbes and roots, and adsorbing any fertilizer that may be applied to counteract the nutrient deficiencies caused by priming (Tomczyk et al., 2020).

As other studies have noted, the effect of biochar in soil is time-dependent, especially in a one-time application. However, the degree of this impact depends on the application rate, soil type, and other factors. One study noted that although there was a decreased impact over time of biochar on soil pH, the highest application rate still showed significantly increased soil pH after 9 years (Šimanský & Juriga, 2025).

Two other studies found that microbial activity remained substantially changed in amended soils 2.5 years later (Xia et al., 2022) but that enzymatic activity decreased across a 6-year period, with reapplication recommended for consideration (Futa et al., 2020). A fourth study showed that more total carbon and nitrogen was retained in soil 13 years after amendment but that the impacts on pH and electrical conductivity were less persistent (Apostolović et al., 2024). Given these varied effects, the comparison of the overall performance of the two biochars as soil amendments would therefore need to be directly tested, preferably in a long-term trial.

3.2. Biochar production in small-scale reactors

Both the optimized retort and gasifier reactor prototypes reliably produced biochar in a batch process. There were notable differences in their operation. As a system where the feedstock was directly burned, the gasifier biochar production process was taken to be complete when the temperature at the primary air inlet reached ~250°C. This indicated that the flame front was approaching the bottom of the reactor, which was then quenched to ensure that the combustion process was stopped before the biochar fully combusted to ash. Full temperature profiles of the process are shown in Figure SM.3 (Supplementary material), which took approximately one hour per batch and reached a maximum temperature on the external surface of the reactor of ~430°C. The burn appeared completely clean, producing no visible smoke or particulates throughout. After quenching, the biochar was then dried in ambient conditions for easier handling.

On the other hand, the retort biochar production process was self-limiting as the fuel and flame was separated from the feedstock, which resulted in a gentler taper of the temperature plot indicative of when the fuel has been exhausted. Each batch took approximately two hours to complete, reaching a maximum temperature on the external surface of the reactor of ~500°C. On some runs, the burn produced some visible smoke in 3 to 5-minute spurts once or twice per burn, which was reduced if the smoke stack was opened to allow greater airflow. However, the process could still proceed without issue if no action was taken. An additional precaution was not to open the inner drum too soon after each batch was complete, as any smoldering biochar could completely combust into ash in the presence of additional oxygen or ignite into a burn, jeopardizing the whole batch. A summary comparison between the pyrolysis process of each system and their relative advantages/disadvantages are described in Table 3.

Table 3. Summary of comparisons between the retort and gasifier biochar production processes when pyrolyzing cacao husks for biochar production

	Retort Reactor	Gasifier Reactor
Preparation time	~2 hours	~30 minutes
Post-processing time	Overnight (inactive)	1-2 days (to dry quenched biochar)
Feedstock Mass	~11kg per batch	~20kg per batch
Yield	~35% of feedstock weight	~40% of feedstock weight
Biochar moisture content	~7% of yield	~67% of yield
Dry Weight Yield	~33% of feedstock weight	~13% of feedstock weight
Fuel Mass	~11kg	None
Batch preparation	Fuel must be of the same wood throughout the interstitial space and be cut to the reactor height.	None
Resources required	None	Quenching water
Biochar yield	(+) Higher/maximized as feedstock not directly burned	(-) Lower as part of feedstock used as fuel
Oversight required	(+) Self-limiting process that extinguishes once fuel exhausted	(-) Process requires monitoring and quenching when complete
Fuel requirements	(-) Additional fuel required of specific size, shape, and type, with associated preparation	(+) No additional fuel required beyond starter and kindling
Feedstock density	(-) Cannot be too densely packed because heat conduction/radiation from outer drum means inner most feedstock pyrolyzes last	(+) Feedstock can be packed as densely as possible
Feedstock shape	(+) Feedstock of any shape or size is acceptable as long as there are no nested husks	(-) Requires feedstock of relatively even shape and size to pyrolyze evenly
Fabrication	(-) Requires smaller inner drum that is more difficult to obtain	(+) All materials are easily sourced locally
Post-pyrolysis processing	(+) None	(-) Requires drying time and space after quenching

For the retort reactor, packing the fuel as tightly as possible in the interstitial space was critical to a successful burn as it ensured strong connectivity around the entire reactor for a reliable burn and temperature profile across the reactor. Once the flame front had progressed further down the reactor, it was also helpful to push the coals from the top of the inner drum into the interstitial space to further kindle any fuel.

Although the gasifier reactor appears to produce a higher yield of biochar after drying at ambient conditions, it retains a higher moisture content relative to the retort biochar. Once both biochars are dried at 105°C for 48 hours, the gasifier reactor yields a lower fraction of biochar than the retort reactor. The difference between the yield fractions corresponds to the amount of feedstock combusted to fuel the gasification process in the reactor. However, this difference in yield is not likely to be noticeable in real world situations because processing the biochar at elevated drying temperatures and times is not necessary for its subsequent use, nor is the reactor for doing so widely available to farmers. Consequently, the gasifier reactor may thus provide the benefit of requiring less preparation time and fuel while providing a seemingly higher yield.

The gasifier reactor cost $41.25 to fabricate while the retort reactor cost $95.50 for this pilot study. Scaled production would likely bring unit costs down. The constituent components of each optimized reactor and their material cost are described in Table SM.2 (Supplementary material). This does not include fixed cost items such as tools, which can often be communally sourced, or the transportation of the materials to a given site, which is variable depending on location. It also does not include the cost of starting each pyrolysis cycle. However, the materials, and thus cost, of these are the same and negligible across both reactors. Consequently, it is clear that the price of gasifier biochar production is lower than that of retort biochar. Both reactors are several orders of magnitude more affordable than commercially available field scale reactors (Garcia-Nunez et al., 2017; Woolf et al., 2017).

3.2.1. *Recommendations for the biochar production process*

How beneficial our biochars may be to cacao plants depends on a combination of factors such as soil type, application concentration, and stage of plant growth (Joseph et al., 2021; Schmidt et al., 2021; Tan et al., 2017). As such, we cannot predict biochar performance based on its characteristics alone. However, there are some properties that would broaden the biochar's applicability across regions if tuned via the production process. For example, producing a less alkaline biochar allows it to be applied on a wider variety of soils, not just acidic ones. Similarly, a biochar with lower electrical conductivity could be applied more liberally if needed without risking salt stress in plants. Since both these properties are a function of ash content, which is influenced by the temperature of the production process (Ippolito et al., 2020; Singh et al., 2017; Tomczyk et al., 2020), it could be that reducing the temperature could reduce the ash content, pH, and electrical conductivity of the produced biochars. We could reduce the temperature of our process by reducing the airflow through the reactors, which in practical terms means making the air inlets smaller. However, we would need to ensure that the airflow is still sufficient to result in the complete combustion of fuel so that the burns are clean and toxins do not accumulate. This is an area of suggested future investigation.

It could also be broadly beneficial to increase the surface area, pore size, and pore volume of the biochars as this would allow greater airflow, water retention capacity, and adsorption of nutrients (Tomczyk et al., 2020). Based on the differences between our biochars, a thermal shock may be required to meet this goal. The alternative, an increase in process temperature, would likely go counter to the ash reduction goals previously expressed and hence be undesirable. However, if this thermal shock is achieved by quenching, it could result in the leaching of labile nutrients. Although these could be replenished by fertilization of the soils or conditioning of the biochars before application (Jaiswal et al., 2018), the potential losses of nutrients by leaching risks reducing the agricultural value of the biochar and should be further investigated.

Although a reduction in volatile matter content for the gasifier biochar may also be desirable given its reported inhibitory effects on plant growth (Deenik et al., 2009), this would require ensuring that the flame front progressed further down the reactor, which would have a direct negative impact on yield. An alternative would be to apply the biochar to soils in advance of plants being grown with enough time for the priming effect to stabilize (Deenik et al., 2009). It could also be possible that this may not be as much of an issue with specific combinations of soil, plant, and biochar, although this cannot be established without conducting a growth experiment. Given the correlation between nutrients and volatile matter in gasifier biochar, it is also likely that a reduction in volatile matter content would lead to a corresponding reduction in various nutrients. If these nutrients are required for plant needs, they can subsequently be added via fertilization.

Despite determining the standard characteristics of our biochars (Tables 1 and 2) and unique operational advantages and disadvantages of each prototype (Table 3), we cannot determine how to optimize production without a growth experiment. Any suggested production method must account for farmer preferences in operations, logistics, cost, and intended purpose of biochar (e.g., sale versus use). From a crop production and economic perspective, fully converting farmers' cacao husk waste stream into biochar would produce, on average, ~140kg of biochar per season per farmer. This is based on a total harvest of 2,500 kg/year of pods, of which 70% (1,750 kg/year) of the weight is husk. After drying, we would have 350 kg/year of pyrolysis feedstock, which would yield 140 kg/year of biochar in ambient conditions. The 30% of the pod weight currently harvested as pulp and bean (750kg/year) is typically sold for US$0.60/kg for an annual income of $450/year. Given that biochar would be competitively priced at US$1/kg based on their current sales prices on the local market and e-shopping platforms, there may be considerations of its commercial potential in addition to its use as a soil amendment on their own plots. However, these considerations are beyond the scope of this paper.

There remains some uncertainty in this work related to the batch-to-batch variability of the produced biochars. The quality of produced biochars was assessed using a composite sample from three optimized runs for each reactor, therefore the batch-to-batch variability could not be assessed. Future work could include more extensive testing of individual batches to examine how consistent the resultant biochar properties for each method are. However, we believe that analysing a large composite sample (900 g) of biochar for each method provided some confidence about the general characteristics of each method allowing comparisons among the production methods.

Although we have shown that it is possible to produce biochar from cacao husks that is safe for use according to official standards, we cannot make any further statements about how good or effective it will be forfarmers or the cacao crop based on the biochar characteristics alone. To further investigate the feasibility of the cacao husk biochar produced as a soil amendment, growth experiments are needed to examine the performance of the biochars at various concentrations in the context of local soils and the cacao crop. These experiments would highlight the characteristics of biochar that are important within the applied contexts. Analyzing the relevant characteristics in conjunction with the respective operational, logistical, and financial advantages and disadvantages of each reactor would allow us to optimize reactor design for both biochar performance and farmer utility and calculation of the overall profitability. Taken in sum, such factors could influence whether farmers decide whether it is more beneficial to them to, for example, use the biochar themselves or take it to market. Nevertheless, testing of the two production methods and comparison of the produced biochars against international standards represent a first important step in assessing the feasibility of this biochar production approach.

4. Conclusion

Our study shows that it is possible to convert cacao husks into biochar in farm-scale reactors and that the pyrolysis and gasifier reactors we fabricated were appropriately sized for farmers to produce biochar reliably. Importantly, both biochars fulfilled all toxicology requirements, making them safe for potential use as a soil amendment. The produced cacao husk biochars shared some similarities with other crop-based biochars, such as moderately high organic carbon content and low H: Corg ratios. This makes for a stable product that can sequester carbon for long periods.

However, our biochars had higher pH values and electrical conductivity than expected, which may restrict the conditions in which biochar produced using these approaches can be effectively applied to soils that are acidic and of low salinity. Still, the properties of our biochars were within the reported ranges of other cacao husk biochars.

The cacao husk biochars differed from each other in certain aspects. The gasifier biochar had a higher surface area, pore size, and pore volume relative to the retort biochar, potentially providing greater nutrient adsorption, as well as improved air and water retention properties. However, the gasifier biochar also had higher levels of volatile organic matter and most nutrients, which could inhibit plant growth due to greater microbial activity utilizing available nutrients, competition with plants.

This study also demonstrates the importance of local collaboration in designing practical small-scale biochar reactors. The farmers' knowledge was vital to optimizing the fabrication process, from appropriate design, use, setup, and material acquisition for on-site use. Both reactors aimed to meet local constraints related to pricing, and practical use on a smallholding cacao farm.

Although there could be ways to optimize our production methods to adjust these parameters, it is premature to do so without growth experiments that examine the relationship between soil, crop, and biochar concentrations. Such experiments, as future work, would investigate the impact of biochar on soil properties and plant growth, highlighting particularly important characteristics. When examined in conjunction with the logistical, operational, and financial considerations, the production process could be optimized for biochar performance and farmer utility.

Funding

Partial financial support was received from Stanford University's Center for African Studies, Haas Center for Public Service, the Stanford Chapter of Engineers for a Sustainable World, and the Stanford Graduate Fellowship. O.V. has been supported by Charles University Research Centre program No. UNCE/24/SCI/006.

Authors Contribution

All authors contributed to the study conception and design. Material was prepared by Latifah Hamzah and Ning-Geng Ong, data collected by Latifah Hamzah, and analysis performed by Latifah Hamzah and Olga Vindušková. The first draft of the manuscript was written by Latifah Hamzah and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

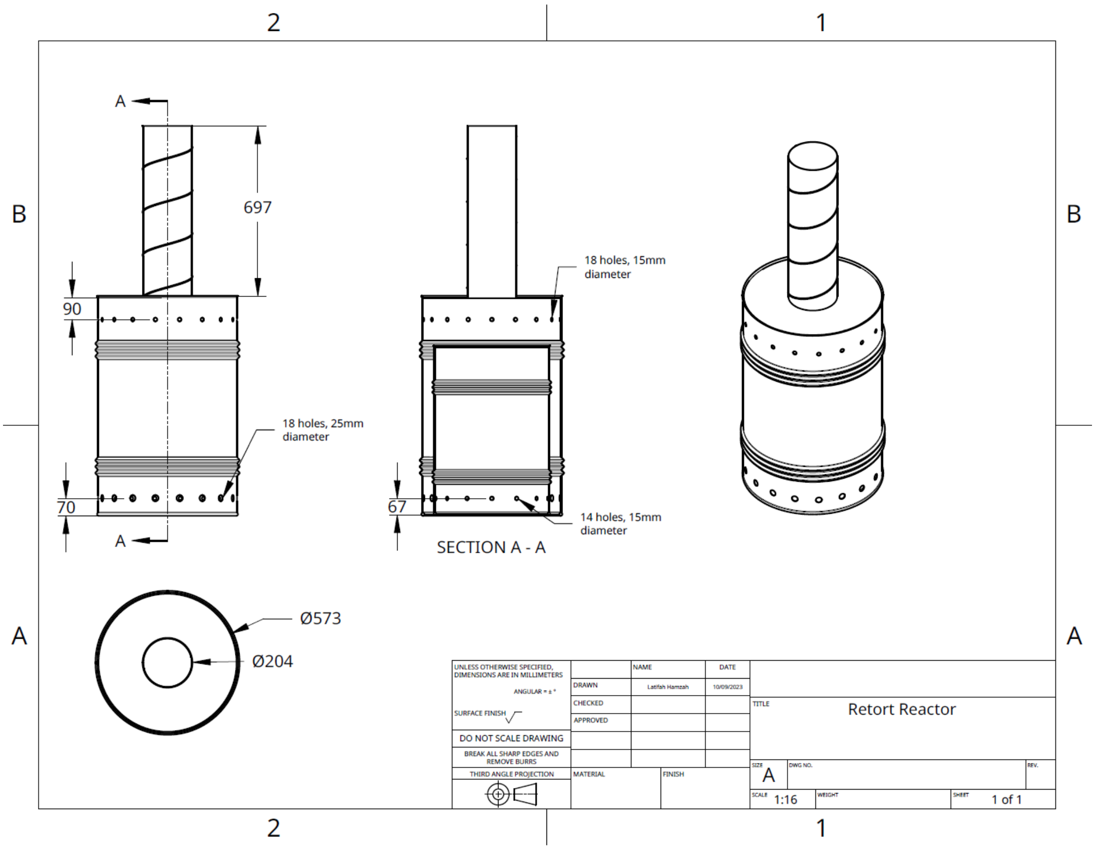

Figure SM.1. Technical drawing of retort reactor

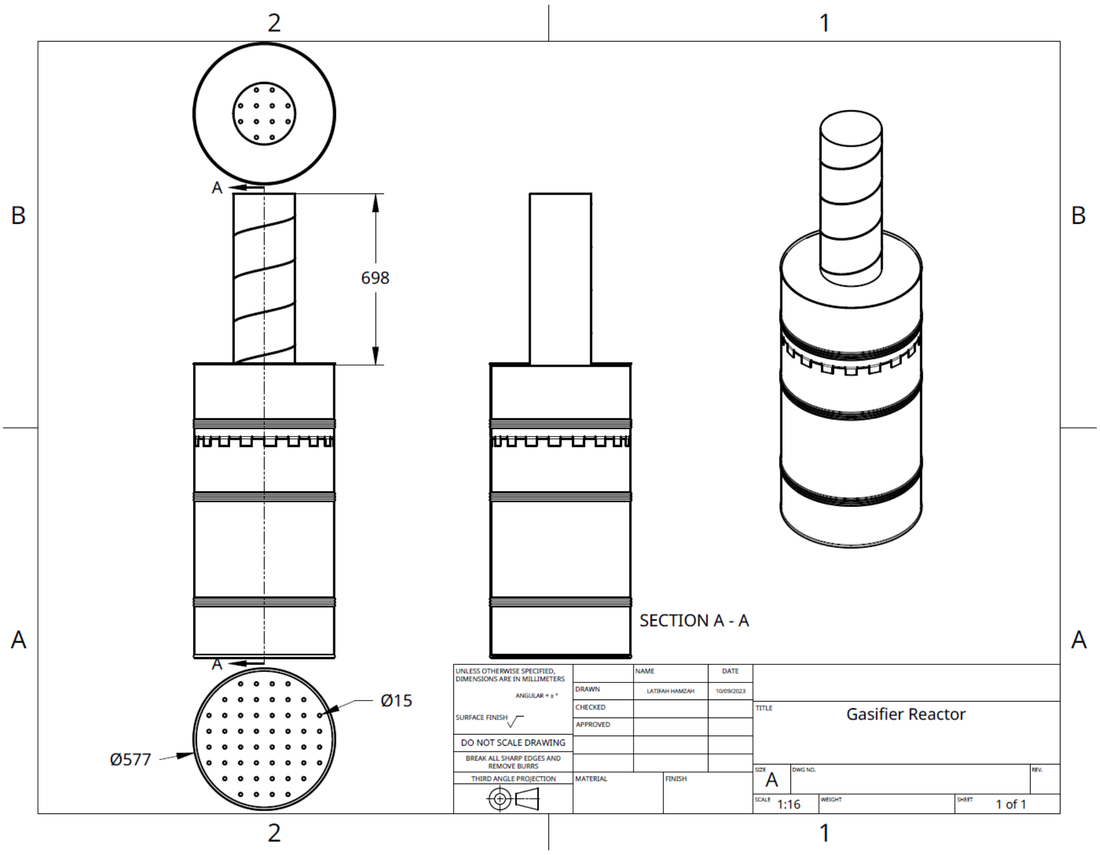

Figure SM.2. Technical drawing of gasifier reactor

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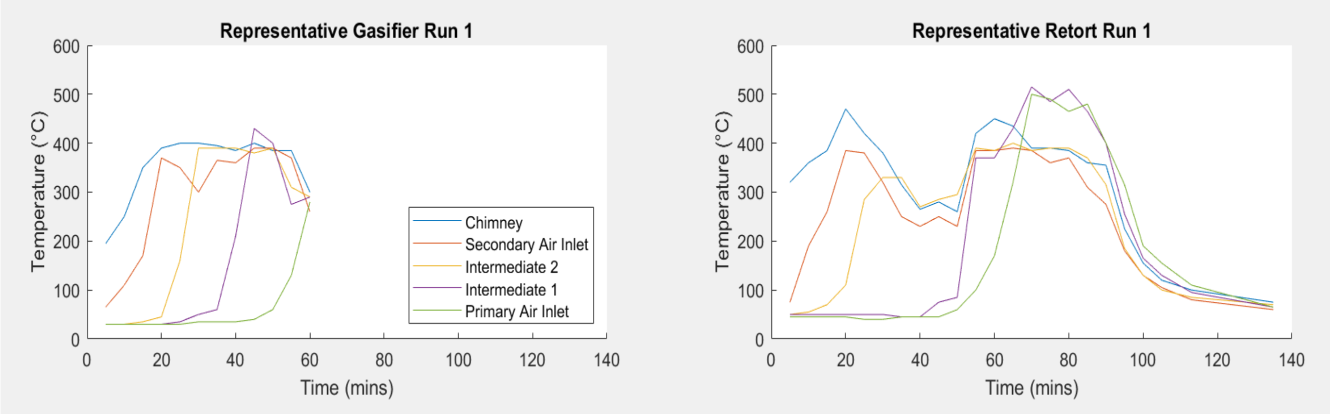

Figure SM.3. Plots of a representative pyrolysis run for the gasifier (left) and retort (right) reactor prototypes. These demonstrate longer processing times and higher peak temperatures for the retort reactor relative to the gasifier reactor. Intermediate 1 and intermediate 2 are points along the external reactor surface that are 1/3 and 2/3 of the way between the primary and secondary air inlets respectively

Table SM.1. Selected pesticide and heavy metal testing of cacao. Tests were conducted by direct sampling on 100g samples of cacao beans submitted to Regulatory and Quality Control Department of the Malaysian Cocoa Board. N.D. indicates that a parameter was not detected at a detection limit of 0.005ppm

		Heavy Metal mg/kg (ppm)				
Farm Location	Pesticides Residue (ppm)	Arsenic	Cadmium	Antimony	Mercury	Lead
Raub	Chlorpyrifos: 0.02 Cypermethrin I: 0.03 Cypermethrin II, III, IV: 0.03	0.03	0.39	0.01	0.01	0.84
Sinderut	N.D.	0.02	0.15	N.D.	0.01	0.75
Machang	Metalaxyl: 0.02	0.20	0.34	N.D.	0.01	0.66
Bera	Chlorpyrifos: 0.02	0.22	0.86	N.D.	0.01	0.13

Table SM.2. Cost per unit of each optimized reactor. The conversion rate used was 1 USD = 4 MYR

	Cost (USD)	
Material	Retort Reactor	Gasifier Reactor
200L drum (used)	10	20 (two required)
100L drum (new)	65	N/A
Smoke stack duct	12.50	12.50
Welding	7.50	7.50
Consumables	0.50	1.25
Total	95.50	41.25