Review

Comprehensive Review on Bio-Briquettes Developed from Processed Cashew Nut Shell Wastes

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ABSTRACT

Cashew nut shells (CNS) are the primary waste produced during the processing of cashew nuts; and needs constant attention to handle or valorize these wastes effectively. As a result, these CNS wastes are processed into solid briquettes citing their significant calorific content, thus making them as a promising renewable biofuel for combustion based applications. In most cases, these wastes are pre-treated either through de-oiling or carbonizing prior to compaction, thus removing the harmful hydrocarbons present in them in form of CNS liquids. Presently, this chapter focus on summarising various data related to these CNS wastes and their briquettes in terms of their availability, chemical characteristics, pre-treatment and processing technique, fuel and combustion properties as reported in various literatures. Here, availability depicts the current trend in global consumption of these snack nuts and the proportionate amount of waste shells produced; while, chemical characteristics focused on discussing their anatomy, proximate, lignocellulosic and elemental compositions. Following this, pre-treatment and processing techniques list out the various practises followed to remove CNSL, process de-oiled CNS cakes into bio-char through carbonization, and briquetting of pre-treated CNS wastes along with their compacting techniques prescribed by various researchers. Lastly, fuel and combustion properties briefs out about the fuel traits of developed CNS briquettes along with their burning characteristics; and include parameters like proximate and elemental compositions, density and compressive strength, and results related to their combustion and water boiling tests. Moreover, all the reported results and data in this study were in accordance with the international testing standards; and ranged in between their permissible range.

Keywords: Cashew Nut Shells; Shell Press Cakes; CNS char; Cashew Nut Shell Liquid; CNS Briquettes; Calorific Value

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INTRODUCTION

To begin with, Cashew (*Anacardium occidentale*) is a pseudo-fruit bearing tropical evergreen tree, native to Brazil that was later spread across the globe during late sixteenth century with an intention of conserving soil. This tree is mainly cultivated for its nuts (cashew seed) which grows at the base of its peduncle or pseudocarp (cashew apple); and are consumed as direct snacks, as an ingredient in cuisines, and are even used as the raw material for producing cashew oil and butter (Mgaya et al., 2019). Apart from this, these nuts (either in roasted or dried form) are used for making pastries, confectionaries, ice creams and chocolates (Tuates Jr et al., 2020); and play a vital role in international and foreign exchanges market in many countries (Rabany et al., 2015; Maia et al., 2000). Presently, many countries are cultivating these exotic nuts, with United States and European Union countries being established well in this market (Mubofu & Mgaya, 2018). Infact, India is also a leading contributor in this well established market, and is known to be the largest producer, processor, exporter and second largest consumer of cashew in the world (Sanger et al., 2011).

In general, these nuts are deshelled from their pseudocarp, and are then roasted or dried before consumption; hence, producing a large volume of cashew nut shell wastes (Sanger et al., 2011; Sawadogo et al., 2018). These wastes are usually discarded into the environment; and causes acid pollution to the soil, besides possessing threats in form of fire risks due to their high organic content (Godjo et al., 2015). As a primary waste from cashew nut processing industries, they are often disposed

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quickly at very low prices (Singh et al., 2006; Huko et al., 2015); however, these shells hold certain calorific content, which makes them suitable for energy applications. Infact, these Cashew nut shells (CNS) wastes have been identified as most versatile organic renewable material available in abundance, and are observed as a raw material for numerous renewable energy resources that can replace fossil-based petroleum, value-added chemicals, and polymers (Kimutai & Kimutai, 2019; Mgaya et al., 2019; Pandiyan et al., 2020).

Though, these wastes do not pose any food competition threats, direct use or burning them produces toxic emissions and releases highly corrosive chemicals, which have adverse effect on the boilers, combustors and heating equipments. Hence, these chemicals in form of cashew nut shell liquid (CNSL) must be removed from these CNS, thus leaving behind residual cashew nut shell cakes that can be processed into biofuels (Sawadogo et al., 2018). However, these CNS cakes are low density residues, and occupy large areas during their transportation and storage which increases their handling costs (Chen et al., 2015; Ngusale et al., 2014). As a result, the CNS cakes are compacted into briquettes that introduce their superior energy characteristics like low moisture content, and high density and calorific content (Stolarski et al., 2013). Apart from the de-oiled or pressed cakes, cashew nut shells are also carbonized into bio-chars using pyrolysis or carbonization process, which later on are compacted into charcoal briquettes. These thermochemical treatments vaporise the harmful and volatile hydrocarbons responsible for toxic emissions from these shells, thus leaving behind significant amount of bio-char and mild traces of CNSL, depending upon the process adopted (Ifa, 2019; Sanger et al., 2011). Hence, briquetting of these CNS wastes helps in developing cheap source for clean energy compatible for both domestic and industrial applications, and is seen as an effective solution for disposing these wastes in a sustainable manner (Lubwama and Yiga, 2017; Mousa et al., 2019; Tuates Jr et al., 2020).

In general, these briquettes are priced lower than coals, and are highly renewable than compared to non-renewable fuel resources citing the absence of sulphur content in them, thus contributing very minimal to environmental pollution. Besides, these briquettes report higher calorific values than their raw feedstocks and even other solid fuels, thereby exhibiting better and uniform combustion, and high boiling efficiencies with low ash content. Interestingly, these solid biofuels have good mechanical properties including low moisture content, high density and durability that make them resistant to impacts and microbial activities allowing them to get transported, handled and stored easily (Sharma et al., 2015; Tuates Jr et al., 2020; Chungcharoen & Srisang, 2020; Kathuria & Grover, 2012).

With improvised energy conversion technologies like briquetting, around 36.6 tg/yr of carbon dioxide (CO_2) and 76,000 ha of woodlands can be conserved by 2030, thus saving about 8.1 million tons of woody biomass and even reducing the dependence on them (Huko et al., 2015). Infact, this practise will tend to reduce the pressure on low income countries to rely on firewood or charcoal harvested from local forests; which eventually will mitigate the partial destruction of their forest cover, thereby conserving both environment and climate change from any adverse effects (Mitchel et al., 2007). Besides, demand for energy is also rising steadily citing the modernisation amidst human population and revolutionary industrialisation; thus consuming more fossil fuel every day, only to release increased CO_2 emission, resulting in global warming and climate change (Srinivasan et al., 2020; Srinivasan & Jambulingam, 2018). Hence, identifying an ideal source of energy to meet this energy demand renewably, to avoid any further damage to the environment is highly appreciated.

Summing up, it is fairly evident that these cashew nut shell wastes are seen as high potential feedstock for making briquettes, which in turn are regarded as suitable alternative or additive for the existing solid fossil fuels. Taking this into account, this present chapter will focus on briefing enriched information about the availability of these wastes, the anatomy of these shells and nuts, the chemistry involved in these wastes, pre-treatment techniques (de-oiling and carbonizing) followed, briquetting methods practised, and the fuel and combustion characteristics of these CNS briquettes in a consolidated manner.

AVAILABILITY OF CNS WASTES

As mentioned earlier, this cashew tree (*Anacardium occidentale*) is indigenous to South America, and has been cultivated predominantly in northeast Brazil, East-west Africa, South East Asia and southern Indonesia after being introduced by Portuguese during 1500's (Dendena & Corsi, 2014). Though edible, these trees have been mainly planted for reforestation purposes since 1970s citing their adaptability to harsh terrain and climatic conditions (Tinlot, 2010). Besides reforestation, these trees were also planted for conserving soil. About their continental distribution, these trees are primarily grown in continents of Asia, Africa and South America; with India, Vietnam and western African countries being the leading producers for past 5 years (Mgaya et al., 2019). Table 1 list out the countries prominently known for cultivating these cashew nut trees.

Insert Table 1 here

Looking into their annual production rate (in Figure 1), the overall production of these nuts (in shells) grew from 3.99 million tonnes to 4.18 million tonnes between 2010 and 2020; however, there were significant fluctuations in the production rate ranging between 3.18 and 4.41 million tonnes (Shahbandeh, 2022). Previously, the overall annual production rate of these nuts was estimated to be only 3.21 million tonnes during 2005 (Mubofu & Mgaya, 2018). Besides, the global production rate of these exotic nuts (in kernel) was estimated to be 0.79 million tonnes during 2017-18, which grew by 32% than compared to the production rate during 2007-08. Figure 2 illustrates the country wise distribution of production rate (in kernel) for the cultivation season 2017-18 (Mgaya et al., 2019). As far as India is concerned, overall productivity area was estimated to be in between 6,66,000-8,54,000 hectares, with an annual production rate ranging between 0.47-0.62 million tonnes/year, and with highest productivity contributed by the states of Tamil Nadu, Maharashtra, Kerala, and Karnataka (Singh et al., 2006; Sanger et al., 2011). In recent times, the net production rate increased from 0.70 million tonnes to 0.77 million tonnes during the cultivation season 2019-20 and 2021-22.

Insert Figure 1 here

Insert Figure 2 here

With increasing rate of production and consumption, the amount of waste generated from these nuts will also increase equally; and on average, each raw cashew nut fruit will generate wastes upto 70% of its weight, in form of shell wastes. Inevitably, this explains the surplus availability of these wastes globally, and can be found in abundance in countries primarily associated with cashew cultivation and processing. To illustrate this, districts of Kollam and Thiruvananthapuram in Kerala, India alone generates almost 75,000–80,000 tonnes of these wastes, while Konkan region at India's western coast generates as much as 20,000 tonnes of these shell wastes during de-shelling of cashew kernels (Singh et al., 2006; Sanger et al., 2011). Meanwhile, nearly 2.26-3.09 Million tonnes of shell wastes would have been generated during the cultivation year between 2010 and 2020, as per the estimated annual production rate (in shells).

Fairly evident, these data ensures sufficient availability of these shell wastes, with promising potential for supply chain in briquette production; however, geographical distribution of these trees makes their availability uneven. Yet, these challenges can be overcome by strategically planned shipping and handling.

CHEMICAL CHARACTERISTICS OF CNS WASTES

Looking into their anatomy, these cashew fruits comprise of an apple and a nut enclosed inside a shell and skin, commonly known as cashew testa; and falls off from the tree when they ripen (Sawadogo et al., 2018; Singh et al., 2006). Furthermore, these nuts consists of kidney shaped kernel constituting upto 35-45 % of its raw weight; and are enveloped inside its shell that contributes to the remaining weight, and comprises of 15–35 % cashew nut shell liquid, a dark reddish brown viscous liquid deposited in their honeycomb structure (Mubofu & Mgaya, 2018). In general, processing of these nuts involves roasting them, which releases the kernels from their hard shells; and results in generating large volume of these shells, CNS liquid, cashew testa and even press cakes depending upon the process undertaken and scale of the processing units (Agyemang et al., 2016).

To begin with, cashew shells have always been seen as a potential fuel for domestic and small to medium scale energy applications owing to their high fixed carbon and calorific content. Based on their proximate composition, waste CNS reported its moisture content, volatile matter, fixed carbon, ash content, and calorific value as 7.8%, 80.8%, 16.7%, 2.5%, and 21.58 MJ/kg, respectively; and its elemental composition as follows- carbon: 59.06%, hydrogen: 6-7%, nitrogen: 0.43 % and oxygen: 29-33.52% (Sanger et al., 2011; Himbane et al., 2018). Accounting this, they are widely used in boilers replacing fossil fuel, thus ensuring high renewability and sustainability. However, direct combustion of these wastes simultaneously produces carcinogenic smoke and releases phenolic lipids, which normally corrodes the boiler components (Sawadogo et al., 2018). This can be explained by the presence of cashew nut shell liquid (CNSL), which comprises of unsaturated phenolic compounds namely anacardic acid, cardanol, cardol and mild traces of 2-methyl cardol (Quirino et al., 2014; Tyman, 1977; Gandhi et al., 2012; Rodrigues et al., 2011; Subbarao et al., 2011; Mubofu & Mgaya, 2018; Srinivasan et al., 2022).

Eventually, this can be overcome by removing these harmful shell liquids from these shells using suitable extraction techniques, which would leave behind residual press cakes. Like CNS, even de-oiled press cakes have also been identified as ideal raw material for fuelling boilers and furnaces, besides being used as primary ingredient for briquetting. This was supported by their proximate composition, which reported their moisture content, volatile matter, fixed carbon, ash content, and calorific value as follows: 9.72%, 77.81%, 19.14%, 3.05%, and 20.78 MJ/kg (Sawadogo et al., 2018). Inevitably, there was a slight yet significant reduction in the calorific value upon de-oiling the waste shells, which raised concerns over this energy loss; however, this can be addressed by carbonizing these shells (raw or de-oiled) using pyrolysis or carbonization into bio-chars. On average, pyrolysis of these waste CNS yields about 41% of biochar, 39.3% of volatile liquids smokes, and rest as gas (Ifa et al., 2020); whereas, carbonization of these shells produce 21.1-23.8% of oil content, 18.3-21.04% of char content, and 1.27-3.34% of ash content depending upon the method followed (direct or indirect carbonization) (Sanger et al., 2011). Interestingly, these CNS bio-char exhibited superior fuel characteristics and promising combustion behaviour. Supporting this, these biochar reported its proximate and elemental composition as follows: volatile matter: 8.93-29.65%, fixed carbon: 64.55-78.02%, ash content: 5.8-13.05%, and calorific value: 27.31-27.73 MJ/kg, respectively; carbon content: 73-78.27%, hydrogen content: 1.24-5%, nitrogen content: 1-2% and oxygen content: 13-19% (Sanger et al., 2011; Himbane et al., 2018). Lastly, liquids derived from cashew testae have good potential as leather tannin in tanning industries as they contain about 25% and 11% of tannin and non-tannin materials, respectively (Singh et al., 2006).

Fairly evident, these wastes can be valorised into numerous energy products or as raw materials for producing numerous commercial chemical products like varnishes and paints. However, waste cashew shells are of prime interest for this present study as they are primarily involved in briquette production. On the other hand, no detailed focus have been given for cashew testae liquid or shell liquid as they don't play any significant contribution in briquetting process.

PREPARATION AND PROCESSING OF CNS WASTES

In general, these shell wastes needs to undergo certain pre-treatments and pre-processing prior densifying them into briquettes; that includes roasting, de-oiling, drying, pyrolysing and carbonizing, and milling and sieving (Bellamy et al., 1984; Njenga et al., 2014). It is worth mentioning that many biomasses do not need any carbonizing and milling prior to briquetting; however, cashew shell wastes needs to undergo both of these pre-treatment methods in order to produce high quality CNS briquettes (Sawadogo et al., 2018).

Roasting of Cashew nuts

As mentioned earlier, edible cashew kernels are enveloped inside their nut shell, and are cracked open by roasting them using heat, that make these shells turn brittle, and less corrosive, thus allowing them to be handled easily. Traditionally, these nuts are roasted directly on an open pan under continuous heating and stirring (to avoid scorching), followed by throwing them into sand to extinguish the fire, and ensure slow heat loss. On the other hand, modernised large scale cashew industries used hot oil bath for roasting these nuts at 192 °C for about 90 seconds; however, roasting temperature and time duration were dependent on the size of the nuts roasted (Mubofu & Mgaya, 2018).

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De-oiling of CNS wastes

De-oiling of these CNS ensures the removal of CNSL from them and is regarded as an essential step in the briquetting process as it helps in isolating the harmful chemicals from these wastes. In general, this de-oiling can be carried out in numerous methods; however, the most commonly preferred methods include mechanical extraction, thermal extraction, solvent extraction and pyrolysis method (Mgaya et al., 2019). Table 2 consolidates the detailed description of the most commonly practised de-oiling techniques (Mubofu and Mgaya, 2018).

Insert Table 2 here

Drying of CNS wastes

In case of mechanical or manual extraction, these nuts do not undergo any heat treatment, and are cracked open using external force. As a result, they carry some residual moisture content along with them, and needs to be removed before processing further. In relevance to that, these waste shells are dried under direct sun light or in open dry air to reduce their moisture content; and have been proven to the most economical way for pre-processing these wastes (FAO, 1985). On average, these shells are dried under sun between 1 and 4 days; and are very effective in bringing down their moisture content below 10% with minimal energy and cost (Ifa et al., 2020; Kimutai, 2021). Likewise, even de-oiled and solvent treated CNS also report upto 13% of moisture content, and needs to be sun dried for 3 to 5 days in order to reduce it below 7% (Tuates Jr et al., 2020). In fact, even briquettes are also dried in similar manner; and supporting this, Sawekwiharee et al. (2015) reported the average weight of the sun dried CNS briquettes, with dimension of 5×4.5 cm as 42.49 g (Sawekwiharee et al., 2015). Moreover, any foreign particles like stones and metal pieces must be removed from these shells prior drying them (Kimutai & Kimutai, 2019).

Pyrolysis and Carbonizing of CNS wastes

In most cases, these waste shells cannot be directly compacted into briquettes, due to their minimal lignin content, and residues of CNSL which are carcinogenic during its combustion. In order to overcome these challenges, these waste shells are carbonized into biochar in an inert atmosphere through pyrolysis, which increases the concentration of carbon compounds having high activation energy (Sanger et al., 2011). Following this, waste CNS are thermally degraded in absence of air or oxygen, and produce solid bio-char, liquid smoke, and tar depending upon the reaction parameters of pyrolysis. This can be explained by the breaking down of the aromatic hydrocarbons (anacardic acid, cardol, and cardanol) into by-products with relatively smaller molecules (Basu, 2018). In general, pyrolysis of these waste CNS are carried out in between 250 and 400 °C (Huko et al., 2015; Kimutai & Kimutai, 2019; Kimutai, 2021; Gimba & Turoti, 2008); however, the most promising yields are reported at an optimum temperature of 350 ^{0}C producing about 41% of biochar, 39.3% of liquid smoke and 19.7% of gas upon pyrolysing CNS (Ifa et al., 2020; Sawadogo et al., 2018). In most cases, pyrolysis of CNS at lab scale using muffle furnace last long upto 60 minutes; but prolongs beyond that during commercial processing (Ifa, 2019). Other works include burning of CNS (1 kg) in muffle furnace at 600 ^{0}C for 60 minutes; burning in open air for 75 minutes, followed by closed combustion in absence of oxygen for another 30 minutes (Sawekwiharee et al., 2015), burning in developed prototype kiln (capacity of 5 kg) using direct carbonization at 452.2 ^{0}C, and indirect carbonization at 458.8 ^{0}C (Sanger et al., 2011). Besides, these shells can also be carbonized in customised metal box, maintained at 250 °C for 3 hours (Sen et al., 2016; Sanger et al., 2011); and a drum type carbonizer operated at 250-350 °C (Tuates Jr et al., 2020). Eventually, carbonizing these wastes into biochar enhances their overall combustion efficiency and eases the briquetting process (Sanger et al., 2011).

Milling and Sieving of CNS Char

Post carbonizing, these CNS char were milled into fine powder until the particle size reached below 2 mm; and in general, are milled using traditional tools like manual grinders, electrical blenders, and even milling machines (Ifa et al., 2020; Kimutai & Kimutai, 2019). In practise, these pulverised CNS char are differentiated either based on their particle size or on the mesh size of the sieve used. In first

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case, these CNS char are pulverised into fine powder having particle sizes of 0.5mm, 1.0mm and 2.0mm; whereas in second case, they are sieved in 70, 140, and 200 mesh sizes (Kimutai & Kimutai, 2019; Ifa, 2019). Supporting this, Sawadogo et al. (2018) used char particles of carbonised CNS press cake with grain size of 0.5 mm; and developed briquettes with high durability and superior fuel efficiency (Sawadogo et al., 2018). However, any residual particles bigger than 2.0 mm or that could not pass through any of these sieves were pulverised and milled again (Ifa et al., 2020; Ifa, 2019; Kimutai, 2021; Kimutai & Kimutai, 2019). Apart from this, different set of sieve mesh sizes namely U.S. sieve No. 3/8 (particle size of 9.51 mm), No. 4 (particle size of 4.76 mm), and No. 8 (particle size of 2.38 mm); and particle sizes namely 3mm, 5mm, 7mm and 10mm were followed in differentiating the pulverised CNS char (Chungcharoen & Srisang, 2020; Zhang et al., 2012). Moreover, Sawekwiharee et al. (2015) estimated the overall time duration of the milling process as 1 hour, as it was fairly enough to produce fine powdered char particles (Sawekwiharee et al., 2015).

BRIQUETTING OF CNS BRIQUETTES

To begin with, CNS is valorised by compacting them into briquettes; Recollecting from earlier facts, raw CNS contain harmful hydrocarbons that are carcinogenic in nature, hence must be processed by removing their shell liquids before densification. Thus, only de-oiled or carbonised CNS wastes are used in the production of briquettes. In general, an ideal briquette requires a potential biomass as feedstock having appropriate particle size and moisture content, a binder with high starch content and good adhesive property that does not affect the overall renewability, an additive with similar fuel characteristics of feedstock used, and appropriate compaction pressure and temperature, to induce proper binding among these particles. In common practise, these compaction are performed using different techniques that includes direct compacting or ramming, and are carried out using numerous tools and machinery like screw press, hydraulic and pneumatic press, manual compaction tool, briquetting machines. In fact, quality of these briquettes depends on dosage of the binder and compaction technique; and also varies with the feedstock used (Chen et al., 2015; Kaliyan & Morey, 2009; Roy & Corscadden, 2012). Following this, numerous researchers have carried out detailed study on compacting these processed CNS wastes into CNS briquettes; and works related to their briquetting have been tabulated in table 3, comprising details related to briquette type, additive and binder added, compaction technique and conditions, and key highlights in their work.

Insert Table 3 here

FUEL AND BURNING CHARACTERISTICS OF CNS BRIQUETTES

All produced CNS briquettes needs to be evaluated for their fuel characteristics, to ensure their suitability for commercial applications. Generally, these briquettes are assessed following the international testing standards, as par with ASTM standards (moisture content: ASTM D3173; ash content: ASTM D3174; volatile matter: ASTM D3175; fixed carbon: by difference; calorific value: ASTM D5865; Compressive strength: ASTM D 2166-85; density: ASAE S269.4) (Huko et al., 2015). Table 4 summarises and compares the elemental composition of CNS wastes, CNS bio-char and CNS bio-char briquettes (Himbane et al., 2018).

Insert Table 4 here

Firstly, moisture content of CNS briquettes, post drying were estimated to be less than 10% (Ifa et al., 2020); while, moisture content of fresh CNS briquettes reached upto 72% (Sawadogo et al., 2018; Sawekwiharee et al., 2015). Here, high water content in fresh briquettes were explained by their necessity during briquetting of CNS wastes, in order to avoid formation of cracks and resist compression (Sawadogo et al., 2018). However, CNS briquettes, upon drying reported very low moisture content than compared to other biomass briquettes (Ifa et al., 2020), and were deeply influence by the method of drying and particle size. Explaining this, many studies suggested drying these briquettes at 105 ^{0}C for 24 hours, either using hot air oven or dryers (Ifa et al., 2020; Ifa, 2019; Sawekwiharee et al., 2015; Sawadogo et al., 2018); yet, certain studies recommended sun drying during summer (@ 34-36 ^{0}C for 7 days) as an effective, simple and low-cost method, especially duirng large scale production (Chungcharoen & Srisang, 2020). Next up, increase in particle size reduced the moisture content; and according, Huko et al. (2015) noted reduction in moisture content from 7.56% to 6.88%, as particle size increased from 3mm to 11mm (Huko et al., 2015). On the other hand, CNS char briquettes reported their moisture content in between 5-7%; and presence of moisture content in these char particles were explained by the difficulty in vaporisation of absorbed water, post carbonization, that are trapped in their small pores. Eventually, absorption of these wasters can be rectified by adding binders (Kimutai & Kimutai, 2019; Ifa, 2019; Tuates Jr. et al., 2020).

Moving on, ash content of these CNS briquettes defines the amount of burnt resudes left behind after their combustion (Huko et al., 2015; Tamilvanan, 2013; Abdillahi et al., 2017; Ujjinappa & Sreepathi, 2018; Ifa et al., 2020; Sawekwiharee et al., 2015; Glushankova et al., 2018); and in general, ranges between 2-5% citing the presence of numerous minerals, which don't oxidise with oxygen and remain in their solid form even after burning (Olanders & Steenari, 1995; Zhu et al., 2011; Tamilvanan, 2013; Ujjinappa & Krishnamurthy, 2018; Tuates Jr. et al., 2020). Supporting this, only 4.3% of ash content were noted upon combusting these CNS briquettes at 750℃ at 6 hours; and were recorded for the particle size of 200 mesh, thus claiming that ash content reduces with increasing particle size (Sawekwiharee et al., 2015; Huko et al., 2015; Chungcharoen & Srisang, 2020). Moreover, CNS char briquettes reported higher ash content than its raw counterpart; but, still remained below 8% as prescribed by fuel standards (SNI 016235-2000) meant for bio-char briquettes (Ifa, 2019). Most importantly, these ash content have adverse effect on both environment and calorific value of these briquettes, and on environment, through harmful emissions (Sawadogo et al., 2018; Akowuah et al., 2012; Onchieku et al., 2012; Onukak et al., 2017).

Following this, volatile and fixed carbon content in these CNS briquettes was reported in between 65 to 80%, and 17 to 20% (Sanger et al., 2011; Sawadogo et al., 2018; Chungcharoen & Srisang, 2020); and varied inversely for CNS bio-char briquettes, thus reporting only 25-30% of volatile content, 70-80% of fixed carbon content (Ifa, 2019; Sawekwiharee et al., 2015; Sanger et al., 2011; Tamilvanan, 2013; Ujjinappa & Krishnamurthy, 2018). Illustrating this, the fixed carbon and volatile content in the raw CNS briquettes were measured as 19.14% and 77.81% (Sawadogo et al., 2018); however, the CNS wastes carbonised at 350 ⁰C, produced bio-char with fixed carbon and volatile content as 71.19-72.62%, and 17.16-19.56% (Ifa, 2019). Here, high volatile content in these raw briquettes tends to reduce the utilization of their calorific content effectively, thus reducing their thermal efficiency and making them slightly uneconomical (Kimutai & Kimutai, 2019; Karunanithy et al., 2012); yet, this can be rectified by carbonizing these wastes prior briquetting, which eliminates their volatile content significantly, thus enhancing their fixed carbon content (Sanger et al., 2011; Sotannde et al, 2010; Zapusek et al, 2003). Besides, addition of binders simultaneously increased the fixed carbon content, and reduced the volatile content of their resultant briquettes, thus favouring their complete combustion (Kimutai & Kimutai, 2019). Moreover, reduction in the particle size of CNS and their char particles increases their fixed carbon content, but again decreases their volatile content (Chungcharoen & Srisang, 2020).

Next up, calorific content of this CNS briquetes estimate their quantity required for producing the desired amount of energy (Sotannde et al, 2010); and generally, is reported in between 18.81-30.5 MJ/kg (Ifa et al., 2020; Ifa, 2019; Kimutai & Kimutai, 2019; Sanger et al., 2011; Chungcharoen & Srisang, 2020). The calorific content of these briquettes are inversely proportional to their volatile content (Suhartini et al., 2011), hence, briquettes developed from carbonised CNS wastes exhibited significant calorific value owing to their high fixed carbon content (Ismaila et al, 2013 ; Sanger et al., 2011). Explaining this, briquettes developed from CNS bio-chars recorded their calorific value in between 28.3 and 29.49 MJ/kg (Kimutai & Kimutai, 2019; Ifa, 2019). Besides, studies have claimed that addition of binders increased the calorific value of these briquettes; and relating this, rise in calorific value from 28.3 MJ/kg to 30.5 MJ/kg upon introducing 30% of cassava starch as binder, with CNS char (Kimutai & Kimutai, 2019). Moreover, no significant variations in calorific values were noticed in these briquettes, with respect to change in their particle size (Huko et al., 2015; Ifa, 2019). For instance, CVs of briquettes from CNS bio-char with particle size of 70 and 140 mesh had minimal difference of 0.04 MJ/kg (Sutrisno et al., 2017).

About their physical characteristics, these CNS briquettes report their density in range of 765-910 kg/m^3 (Tuates Jr. et al., 2020; Sawadogo et al., 2018); and is influenced by compaction pressure and particle size, and plays a crucial role in their combustion (Himbane et al., 2018). To begin with, high compaction pressure established strong inter-particle attraction forces amongst the CNS particles; and maximum pressure was achieved using piston type compaction (Oladeji, 2015). To illustrate this, briquettes developed from mechanical pressed and hexane treated de-oiled CNS reported their as 0.87 g/cm^3, for both cases, upon using piston type briquetting machine for compaction along with 10% binding agent; meanwhile, briquettes compacted using screw type briquetting machines measured only 0.83 g/cm^3, for both samples (Tuates Jr. et al., 2020). With respect to particle size, density of these briquettes reduced with increasing size of CNS particles; and accordingly, Huko et al. (2015) noted significant drop in density of CNS briquettes from 729.08 kg/m^3 to 492.41 kg/m^3, while particle size increased from 3 mm to 11 mm (Huko et al., 2015). This can be explained by the reduced inter- and intra- particle distances between the CNS particles due to their tight packing (Kimutai, 2021). And, addition of binders increased the density of these briquettes, as they induced adhesion and close packing of the CNS particles, post compaction; and was explained when briquettes with 30% binder recorded higher density than briquettes developed using 10% binder content (Kimutai & Kimutai, 2019).

Compressive strength is regarded as an indicator for briquettes' durability (Wilaipon, 2007), and ranges in between 0.04-29.42 MPa (Sawekwiharee et al., 2015; Kimutai & Kimutai, 2019; Sawadogo et al., 2018; Tuates Jr. et al., 2020), depending on their briquette dimension. In general, compressive strength of these briquettes depends directly on compaction pressure and binder concentration, and inversely with their particle size (Kimutai & Kimutai, 2019). Explaining this, high compaction pressure induced effective compaction of the CNS particles into briquettes; and responding to this, Kimutai & Kimutai (2019) noted highest and lowest compressive strength of 7.84 MPa (80 kg/cm^2) and 2.94 MPa (30 kg/cm^2) for a compaction pressure of 300 kg/cm2 and 100kg/cm^2, respectively (Kimutai & Kimutai, 2019). Furthermore, de-oiled CNS briquettes, with 10% of binding agent developed using screw type briquetting machine reported high compressive strength of 101.82 kPa opposed to screw type briquetting machine reporting only 43.97 kPa (Tuates Jr. et al., 2020). Besides, reduced particle size of these CNS particles reduced the formation of voids between them, thus increasing their compressive strength significantly; however, larger particles created voids between them, thereby affecting their strength adversely (Huko et al., 2015). And, increased concentration of binders helps in filling these voids, apart from bridging the CNS particles; thus, producing high quality briquettes (Rahman et al., 2003). Infact, numerous studies have suggested that increased use of binders produced CNS briquettes with high strength and durability (Ifa, 2019; Kimutai & Kimutai, 2019; Tuates Jr. et al., 2020). Eventually, these facts were supported upon noticing a rise in compressive strength from 40 to 60 kg/cm^2, with increase in binder concentration from 10% to 30%, in CNS char briquettes compacted at 200 kg/cm^2 (Kimutai & Kimutai, 2019).

About their burning characteristics (from table 5), CNS briquettes reported their average burning rate and heat utilization efficiency as 11.90 g/min and 18.01%, respectively; with a weight loss rate of 61.9-62.5%, thus exhibiting burning characteristics equivalent to firewood or fuel (Sawekwiharee et al., 2015). On the other hand, water boiling tests on these briquettes, as tabulated in Table 6, showcased combustion performance similar to that of wood charcoal (Sawadogo et al., 2018). Moreover, CNS briquettes with adequate binder concentration ignited faster and combusted rapidly than compared to raw CNS briquettes (Kimutai & Kimutai, 2019). Relating these facts, briquettes developed using CNS bio-char with 35% of moisture content and 10% of binder dosage exhibited favourable burning characteristics; and following were the parameters deduced from their water boiling test: Boiling duration- 47 mins, firepower- 1.34 kW, thermal efficiency- 33.9%, specific fuel consumption- 131.09 KJ/L/min (Sawadogo et al., 2018). Lastly, studies reported that CNS briquettes underwent burned well without any cracks; and produced similar results of wood or char biomass, in terms of their combustion and emission (fumes and soot) (Sawekwiharee et al., 2015).

Insert Table 5 here

Insert Table 6 here

CONCLUSION

Hence, the reported set of data related to availability, chemical characteristics, pre-treatment and processing technique, fuel and combustion properties of the CNS briquettes have been successfully complied into a comprehensive review; and following were the key conclusions deduced from this study:

I. CNS wastes have been proven to be an ideal choice as the raw material for producing briquettes, available abundantly with zero food vs. fuel conflict issues.
II. Citing their high aromatic hydrocarbons, it is highly recommended to pre-treat these wastes by de-oiling them, followed by carbonising for producing high quality briquettes with minimal emission levels.
III. With respect to densification, these processed wastes can be briquetted directly with or without additives, and requires only very minimal binder dosage in case of de-oiled CNS wastes.
IV. Looking into their fuel properties, increase in binder dosage and reduction in particle size enhanced the overall properties of these CNS briquettes.
V. Explaining this, increase in binder dosage and reduction in particle size increased their moisture content, ash content, fixed carbon content, density and compressive strength. Worth mentioning, calorific content of these briquettes remained same inspite of increase in their particle size.
VI. Adequate amount of volatile matter and fixed carbon content ensured the stable combustion of these CNS briquettes; and also produced burning characteristics similar to that of wood biomass.

Summing up, it is fairly evident that these briquettes serves well as a feasible supplement or alternative for fossil coal; and is seen as the most effective in handling the increasing volume of the CNS wastes. Moreover, this chapter sheds light on enriching the knowledge related to the life cycle of these CNS briquettes, guide the consumers in choosing their right application and handling techniques, and hinting individuals in identifying the possible opportunities for generating revenues, employment opportunities and trading. Ultimately, it can be deduced that usage of these renewable briquettes satisfies the energy demand renewably and help develop sustainably.

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LIST OF TABLES

Table 1: List of countries cultivating cashew nuts (continent wise) (Mubofu and Mgaya, 2018; Mgaya et al., 2019; Sawekwiharee et al., 2015)

Continent	Countries
Asia	India, Vietnam, Indonesia, Philippines, Malaysia, Thailand (Southern Thailand), Sri-Lanka
Africa	Côte d'Ivoire, Nigeria, Tanzania, Mozambique, Kenya (Kwale, Mombasa, Kilifi, Lamu, Tana River, and Taita Taveta counties), Benin, Guinea-Bissau, Mozambique, Ghana, Senegal, Madagascar
South America	Brazil, Columbia, Costa Rica, Honduras, El Salvador

Table 2: Detailed description of the most commonly practised de-oiling techniques (Mubofu and Mgaya, 2018).

De-oiling Technique	Approach	Comment
Solvent extraction (Suitable when CNSL is rich in anacardic acid) (Mubofu and Mgaya, 2018)	Static Solvent* Extraction (Tyman et al., 1989), Soxhlet Extraction (Senthil kumar et al., 2009; Idah et al., 2014); Ultrasonic Extraction, Two-Step Extraction (Yuliana et al., 2012), Subcritical Water (SCW) Extraction (Yuliana et al., 2012), and Supercritical Carbon Dioxide (Patel et al., 2006; Smith et al., 2003)	Dissolves all aromatic lipids and leaves behind non-lipid residues
Thermal extraction (Suitable if end product needed is cardanol-rich CNSL, as anacardic acid is decarboxylated into cardanol at higher temperatures)	Open Pan Roasting, Drum Roasting and Hot Oil Roasting (Mubofu and Mgaya, 2018)	Imparts embrittlement to the shells by forcing out the oil from their cells
Mechanical extraction (Suitable when CNSL is rich in anacardic acid) (Rodrigues et al., 2011; Himabindu et al., 2015)	Screw Press Method (Tapered Compression Screw)	Exert high pressure on shells, which helps in release of CNSL from them
*Petroleum ether, Carbon tetrachloride, Hexane, Cyclohexane, Diethyl ether, Xylene, Ethyl acetate, Toluene, Ethanol, Methanol, Acetone, Polar solvents (Gandhi et al., 2013)		

Table 3: Tabulated summary of briquette type, additive and binder added, compaction technique and parameters, and key highlights of different studies reported in the literature related to CNS briquettes

Briquette type	Feedstock	Additive	Binder	Briquetting technique	Briquetting conditions	Remarks	Reference
Homogeneous	CNS biochar	50% ethanol,	8-12 % of	Bio-briquettes press	Compaction pressure- 29.4 MPa	• Briquette shape: Hollow cylinder • Mesh sizes used: 70,140, 200 mesh	Ifa et al., 2020; Ifa, 2019

		and 50% warm water	tapioca flour	machines (Krisbow hydraulic press floor type 10T)	(300 kgf/cm²); Dwell time- 5 minutes; Mesh size: 200 mesh	• Optimum mesh size: 200 mesh • Briquettes dried in the hot air oven at 50 ^oC for 4–6 hours • binder concentration: 8-12 % of slurry (flour + ethanol + warm water) mix	
Composite/ compound	CNS Char	Mango seed shells (MSS)	50% of banana peel paste	Briquetting press	Compaction pressure- 5 MPa; Compaction temperature: 30-35 ^0C (room temperature)	• CNS wastes sun dried separately to 5% moisture content • carbonization at 400 ^oC for 5 minutes in the muffle furnace • Particle sizes: 3mm, 5mm, 7mm and 10mm • 50g mix of CNS char and MSS • Briquette dimensions: diameter - 50 mm, Length-100 mm	Huko et al., 2015
Composite/ compound	65 wt.% of CNS Char	25 wt.% of Areca nut shells (ANS)	10 wt.% of cassava flour	Electrically operated Screw type press machine	Compressed screw speed: 70-90 RPM	• Semi-carbonized at 300 ^oC • CNS: MC-8%, ANS:MC-12 % • CNS particle size: U.S. sieve No. 3/8 (particle size of 9.51 mm), No. 4 (particle size of 4.76 mm), and No. 8 (particle size of 2.38 mm). • CNS: ANS: Flour (% by weight)-65:25:10 (A), 45:45:10 (B), 25:65:10 (C), 58:22:20 (D), 40:40:20 (E), and 22:58:20 (F). • Briquette dimensions: diameter - 50 mm, Length-100 mm, weight - 210 g • Average production rate: 245 pieces/h (52 kg/h) • Influence of compression speed on production rate was highly significant, especially at 90 RPM	Chungcharoen and Srisang, 2020
Homogeneous	CNS Char	-	10-30% of	Hydraulic press	Compaction parameters varied	• CNS wastes were sun dried under the sunlight for 2–3 days	Kimutai and Kimutai, 2019

			Cassava starch		for optimization purposes; Particle size: 0.5 mm; Dwell time: 120 sec	• Carbonization at 250°C for 3 hours • Particle sizes: 0.5 mm, 1.0 mm and 2.0 mm • Compaction pressures: 100 Kg/cm^2 , 200 Kg/cm^2 and 300 Kg/cm^2 • Binder dosage: 10%, 20% and 30% • Dwelling time: 0 seconds, 60 seconds and 120 seconds • Drying of briquettes: stored at room temperature for 6 to 7 days	
Homogeneous	55% of CNS press cake char	35% of water	10% of Cassava starch	Engine driven conic screw press	Production output: 50 kg/h; compression ratio: 1/45	• CNS press cake was carbonized at 350 °C • Particle size: 0.5 mm • Briquette dimensions: diameter - 50 mm, Length-100 mm • Water content : 25%, 30% and 35% of the total mass (charcoal + starch + water) • Binder concentration: 5%, 10%, 15%, 20% and 25% of the total mass • Drying of briquettes: dried for two weeks at ambient atmosphere (30-31°C), • Final moisture content: 8% (after 2 weeks) • Cassava starch chosen for its physical-chemical properties, low price, easy availability	Sawadogo et al., 2018
Homogeneous	CNS Char	-	Cassava starch	Hydraulic press	Compaction parameters varied for optimization purposes; Optimum	• CNS wastes: sun dried for 2–4 days • Carbonization at 250°C for 3 hours • Particle size: 0.5 mm, 1 mm, and 2 mm	Kimutai, 2021

					particle size: 0.5 mm; Optimum compaction pressure: 29.42 MPa; Optimum dwell time: 120 second (based on highest relaxed density)	• Compaction pressure: 9.81 MPa, 19.6 MPa, and 29.42 MPa • Binder dosage: 10%, 20% and 30% • Dwell time: 0 min, 1 minutes, and 2 minutes • Drying of briquettes: stored at room temperature	
Homogeneous	De-oiled CNS; De-oiled and hexane treated CNS; Carbonized de-oiled CNS char (Sample size: 100 g)	-	4-10% of Starch binder [Screw type: 4%; Piston type: 5-10%]	Piston-type briquetting machine; and Screw-type briquetting machine	-	• De-oiled, De-oiled hexane treated, and Carbonized de-oiled char samples: sun dried for 3 to 5 days (moisture content: 6-8%) • Particle size: reduced to less than 2 mm using commercially available hammer mill. • Binding concentration (piston-type): 0%, 5% and 10% • Binding concentration (screw-type): 0%, 2% and 4% • Briquette dimensions: inner diameter- 16 mm, outer diameter- 50 mm, Length- 50 mm	Tuates Jr. et al., 2020
Homogeneous	1 kg of CNS Char	1L of water	200 g of cassava starch	Briquetting press	-	• Method 1: carbonization at 600°C for 1 hour, then cooled at 5°C/min to room temperature • Method 2: CNS were burnt by open air, using natural firewood for 1.5 hours and sealed to drive out oxygen for 30 minutes • Ground for 1 hour, resulting in a fine powder • Drying of briquettes: sun dried for 3 days	Sawekwiharee et al., 2015

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						• Briquette dimensions: diameter - 45 mm, Length-50 mm, weight - 42.49 g	
Homogeneous	CNS Char	-	Clay and Arabic gum	Manual Briquetting (Hand held hammer)	-	• Carbonization at 250°C for 3 hours • Particle size: 1 mm • Briquette dimensions: diameter-53 mm	Himbane et al., 2018

Table 4: Proximate and elemental composition of CNS wastes, CNS bio-char and CNS bio-char briquettes (Himbane et al., 2018)

Sample	Proximate Composition (dry basis)(in %)				Elemental Composition (dry basis)(in %)				Calorific Value (dry basis) (MJ/kg)
	Moisture content	Volatile matter	Fixed carbon	Ash	Carbon	Hydrogen	Nitrogen	Oxygen	
CNS Wastes	7.8	80.8	16.7	2.5	59.06	6.99	0.43	33.52	21.58
CNS Char	10.6	8.93	78.02	13.05	78.27	1.24	1.14	19.35	27.31
CNS Briquettes	5.43	19.13	62.89	17.98	71.76	2.72	0.95	24.57	26.52

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Table 5: Comparison of results from water boiling test on CNS briquettes and normal firewood (Sawekwiharee et al., 2015)

Parameters	CNS Briquettes	Ordinary Firewood
Weight of water evaporated	804.11 g	824.77 g
Weight of water remaining	695.89 g	701.13 g
Net Weight sample	500 g	500 g
Time of the water boils	12 minutes	14.5 minutes
Total Time	42 minutes	50 minutes
Temperature of the water before the boil	32.5 ^{0}C	32.5 ^{0}C
Heat of Combustion of Fuel	4280 cal/g	4280 cal/g
Works	1.61	1.64
Burning Rate	11.90 g/min	10 g/min
Heat Utilization Efficiency	18.01%	11.65 %
Cracking of Fuel	No	Yes
Combustion Performance	Good	Good
Fume	Low	Low
Soot Formation	Low	Low

Table 6: Water boiling test (WBT) for CNS briquettes with varying concentration of binders (Kimutai and Kimutai, 2019)

Briquette sample	Weight (g)	Time duration* (minutes)	Burning rate (g/min)
CNS wastes+ 30% binder	168.7	4	9.42
CNS wastes+ 20% binder	168.2	4.88	8.82
CNS wastes+ 10% binder	168.3	6.03	7.44
*For boiling 100 cm^3 of water			

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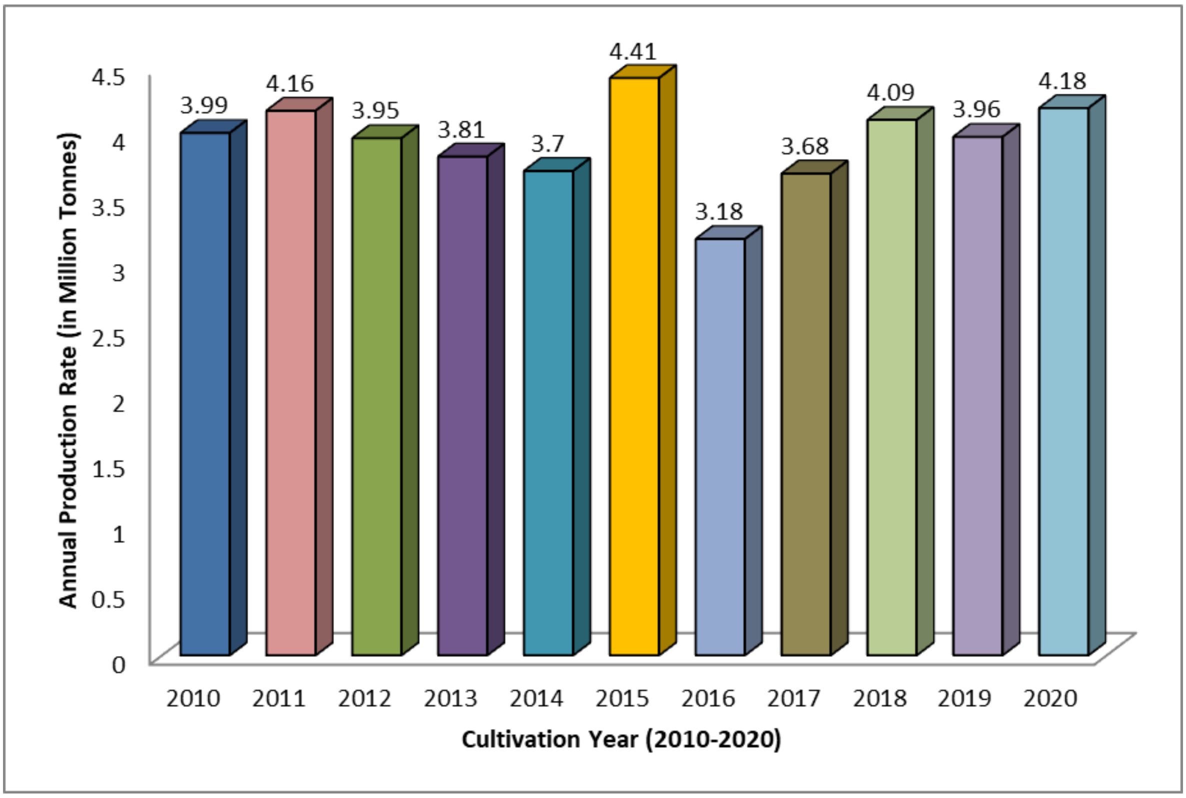

Figure 1: Annual production rate of cashew nuts (in million tonnes) between 2010 and 2020 (Shahbandeh, 2022)

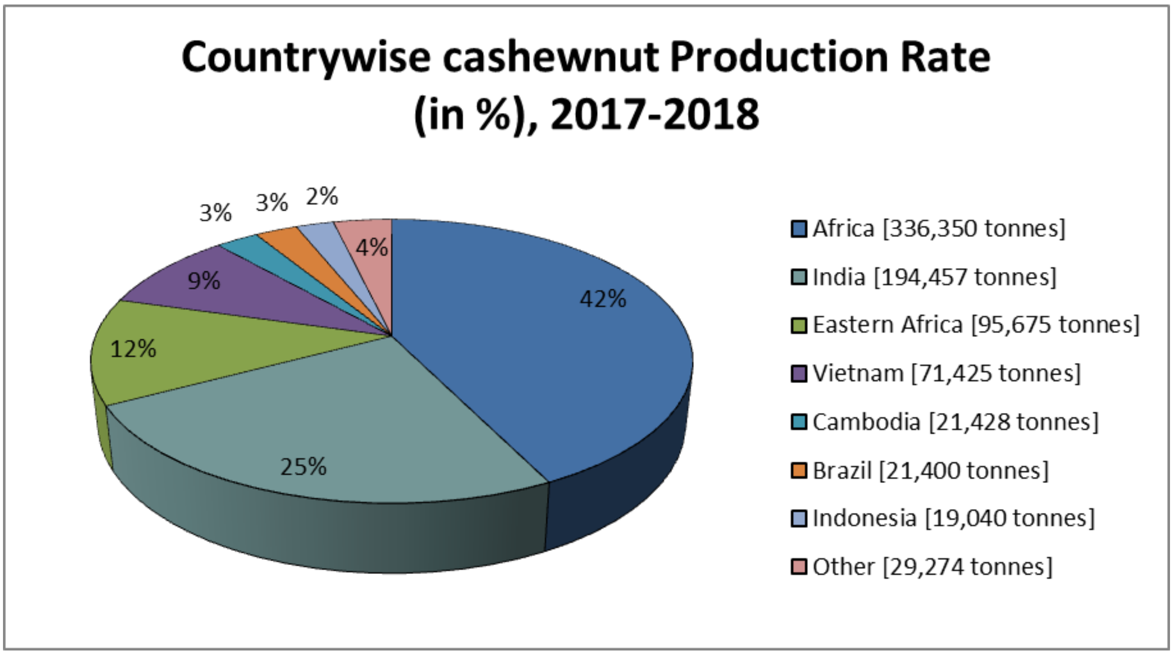

Figure 2: country wise distribution of production rate of cashew nuts (in kernels) during 2017-2018 (Mgaya et al., 2019)