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POSSIBILITY OF CEYLON TEA WASTE CONVERSION TO BIOCHAR – A SHORT REVIEW

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Abstract

A few countries fulfil global tea demand, and Sri Lanka, formerly known as Ceylon, is one of the top tea exporters. Tea is Sri Lanka's largest agricultural export, with an annual production of approximately 340 million kg. Consequently, the tea industry generates significant quantities of tea waste. Unfortunately, the Sri Lankan tea industry often ignores proper tea waste management, relying on open dumping and burning, which can harm the environment despite the biodegradable nature of the waste. Among a number of modern waste management methods, pyrolysis is gaining increasing attention as a sustainable waste treatment method as it transforms waste into carbonaceous materials, biofuel and syngas, leaving no waste behind at comparatively lower temperatures (400-600℃). Considering the nature of the Ceylon tea industry, which mainly uses conventional tea production processes, this short review article mainly focused on the effect of tea pyrolysis temperature, derived biochar activation methods, and their uses. Biochar derived from tea waste has demonstrated remarkable utility in various fields. By converting waste into stable carbonaceous materials, it not only mitigates local emissions but also serves as a reliable long-term carbon storage. Moreover, biochar and activated carbon derived from tea waste has proven efficient and cost-effective for removing water, soil, and air contaminants. Industry can obtain financial benefits by introducing derived activated carbon as an adsorbent. These facts highlight the suitability of adopting low-temperature pyrolysis of tea waste and biochar production to the Ceylon tea industry using simple techniques such as double-barrel systems that can be operated with the excess heat produced in boilers.

Keywords: Activated carbon, Biochar, Pyrolysis, Tea waste

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Introduction

Tea is the largest agricultural export from Sri Lanka, providing over 250 million kilograms of Ceylon tea annually to cater to global tea demand (Tea Exporters Association Sri Lanka, 2023). The quantity of tea waste generation also corresponds to the amount of tea manufactured. However, the Sri Lankan tea industries are practising sustainable waste management techniques poorly to treat their waste. Even if it is biodegradable, the improper management of the enormous waste quantity of tea waste leads to both choric and acute environmental issues. Thermal treatment technologies such as incineration, gasification and pyrolysis are evaluated to manage the waste properly. Among these, pyrolysis is a promising sustainable solution as it converts the waste into biochar, biofuel (tar, bio-oil) and syngas (pyrolysis gas), leaving no waste behind. Biochar receives the highest attention among these products due to its versatile properties. As pyrolysis is carried out at comparatively lower temperatures (500-700 ^{0}C), industrial excess heat can be used for pyrolysis. This short review article focuses on the current state and future possibilities of converting tea industry waste into biochar. This overview specifically focused on the impact of pyrolysis temperature, biochar activation methods, and the diverse applications of both biochar and activated carbon. This is because complicated biochar production methods, which can change other operating parameters such as residence time and sweeping gas flow rate, might not be suitable for the Sri Lankan tea industry, which relies on conventional tea processing methods. Around forty (40) research studies focusing on biochar production techniques from tea waste was reviewed for the development of this article. Research articles primarily focused on conventional tea waste management techniques, biochar production from other biomass, and production of other carbonaceous materials from tea waste were excluded from the study. Reviewing and refining the extracted data from studies, the key findings, trends, and advancements in biochar production from tea waste were summarised to present a comprehensive and reliable overview.

Biochar Production

Biochar has been used as an adsorbent since ancient times. Okoli et al. (2020) mentioned the first recorded knowledge from Egyptians on using char for treating the foul odours from festering wounds around 1500 B.C. The study stated that additional developments in the use of char for antiseptics, water purification, bleaching sugar, and odour elimination occurred between the 16th and 19th centuries. It also reported about commercially produced activated carbon in a powdered form as it initially appeared in the 20th century during the First World War.

1.1. Pyrolysis Process

Biochar is produced using pyrolysis, a well-known simple method of converting biomasses into stable carbonaceous materials. The pyrolysis process is conducted by heating feedstocks to a higher temperature in a low or O_2-free environment. According to Ahmad et al. (2014), pyrolysis methods can be divided into a few categories according to the residence time and heating rate: fast, intermediate, and slow. Slow or intermediate pyrolysis methods promote biochar production with a residence time of up to several hours, while past pyrolysis is used to extract higher bio oil contents. According to the study of Chen et al. (2015), the pyrolysis process can be generally expressed as $C_XH_YO_Z + Q \rightarrow$ Biochar + Bio-oil + Syngas + H_2O while Q represents the input heat (Fig. 1). Bhadha et al. (2014) conducted a pyrolysis process and discovered that temperature causes the breakdown of the cellulose and lignin products of the biomass and produces combustible H_2 rich gases and biochar with high carbon content. Biochar can be identified as the main product among these products due to its versatile applications. Biochar can be used as a soil amendment, carbon sequestration agent, fuel source, and to derive activated carbon (Kane et al., 2016; Lamichhane et al., 2023; Stéphanie et al., 2022). Activated carbon is commonly used in water treatment processes, decolourisation and deodorisation applications, gold recovery processes, contaminated site recoveries and even medical industries for the treatment of poisons and overdosing (Anish & Indira, 2022; Bonilla-Velez et al., 2017; Jackson, 2020; Soleimani & Kaghazchi, 2008; Vasilyeva et al., 2007). Due to electric conductivity and higher surface area, activated carbon is also used in super-capacitor development (Peng et al., 2013).

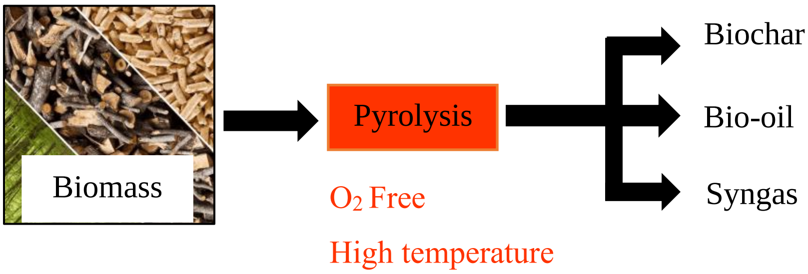

Figure 1: Products from Pyrolysis of Biomass

1.2. Impact of Pyrolysis Conditions on Biochar Characteristics

Feedstock type, pyrolysis temperature, residence time, and heating rate directly affect the quantity and quality of the biochar produced. Ahmad et al. (2014) showed that feedstock types with high inorganic constituents, such as animal litter and solid waste, favour high yields of biochar compared to crop and wood. It also stated that higher levels of potassium (K) and zinc (Zn) containing feedstock such as rice husk, coir pith, wheat straw, and groundnut shells promote high biochar yields. Other studies show that feedstocks with high amounts of cellulose (>60%) might not be suitable for producing good-quality biochar (Pollnow, 2014). The initial moisture content of the feedstock is also not favourable for biochar production due to the high heat demand for moisture removal (Chen et al., 2015).

Many studies confirmed that pyrolysis temperature is the major parameter affecting biochar characteristics. An increase in temperature causes an increase in the carbon content of the biochar and a decrease in oxygen and hydrogen contents despite the increase in surface area in most cases (Ahmad et al., 2014). Further increase in temperature above 700°C sometimes decreases the surface area of the biochar as the enriched inorganic compounds block the developed pores. Char yield decreases with the increase in temperature due to extended organic degradation at higher temperatures (Chen et al., 2015). The study of Janu et al. (2021) reported a loss of functional groups of biochar with increasing temperature.

The study of Chen et al. (2015) discussed the influence of the particle size of the feedstocks on the pyrolysis process because it determines the rate at which a particle heats up and the removal of volatiles. According to the study, smaller particle pyrolysis will expose a larger surface area in a short period. This results in higher yields of liquid or gas products. On the other hand, coarser particles require more time to complete the process. However, once high temperatures are reached, product yield differences become smaller because the increased heat transfer through radiation balances the slower heating rate of coarser particles.

Although some studies reported that heating rate is the least affecting factor for biochar yield, other studies showed that a higher heating rate could lead to a higher tar or gas yield and lower char yields (Ahmad et al., 2014; Qari et al., 2005; Safdari et al., 2019). According to Singh Karam et al. (2022), an increase in heating rate decreases the biochar yield. Longer residence time promotes higher syngas yields while improving the quality of the bio-oil product as it allows further decomposition of longer hydrocarbons. It also noted that temperatures above 700℃ with low residence time produce biochar with low surface area due to deformation, cracks, and blockages of pores (J Bhadha et al., 2014).

1.3. Waste derived biochar

Biochar production from waste has become a popular method to treat waste sustainably. All the studies mentioned in Section 1.2 have used different types of waste biomass as feedstock for the pyrolysis process. Among them, Chen et al. (2015) used municipal solid waste in biochar production and concluded it as a promising method to manage solid waste. Pyrolysis is also evaluated for different types of waste, such as agricultural waste, wastewater sludge, plastic, polythene and even for hazardous waste containing heavy metals (Adeniyi et al., 2023; Chen et al., 2015; Ghani et al., 2013; Gopinath et al., 2021; Nam et al., 2018; Singh Karam et al., 2022). The reason for using waste materials for biochar production is that the world has a vision of achieving a carbon-neutral life. The conversion of waste into stable carbon helps with carbon sequestration. Therefore, industries focus on converting waste into carbonaceous materials such as biochar using simple, cost-effective, and sustainable methods like pyrolysis as it converts waste into stable carbon.

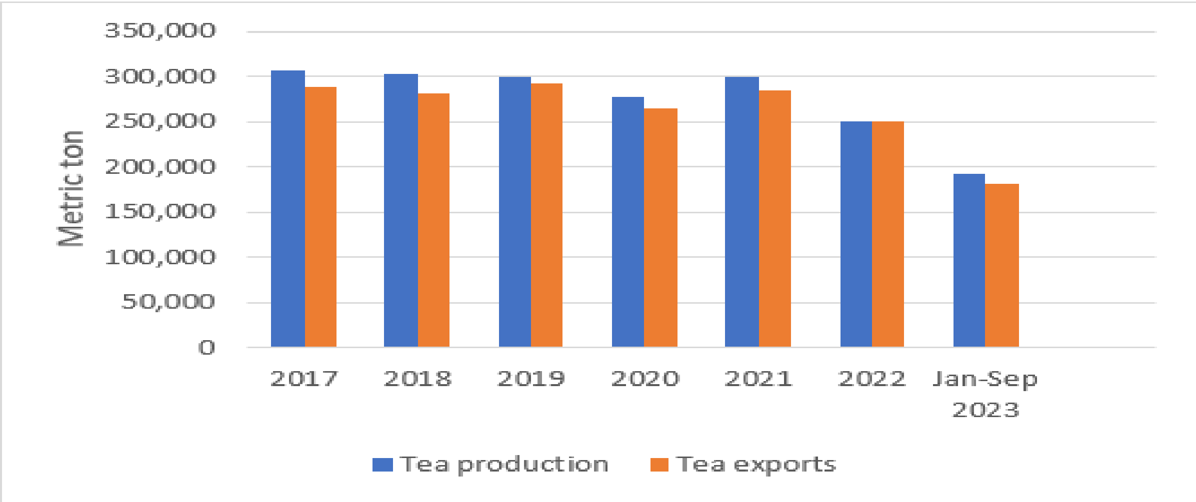

Figure 2: Ceylon Tea Production and Exports (Tea Exporters Association Sri Lanka, 2023)

Tea Industry

The Camellia sinensis plant's leaves are used to make tea, and four primary tea types are commonly available: black, green, white, and oolong (M. Ridder, 2022). According to the study by M.Ridder (2022), the leading global tea manufacturer China produces nearly 3.1 million metric tons of tea annually. India is the second largest producer of tea, followed by Kenya, Sri Lanka, and Indonesia. Ceylon Tea has been Sri Lanka's most significant agricultural export, generating close to 1 million jobs directly and indirectly. Approximately 4% of the nation's land area (~203000 hectares) is occupied by tea plantations with annual production of 340 million kg (Harshana et al., 2020). Most of Sri Lanka's tea-growing regions are in the island's southern and central inland regions (Export Development Board (EDB), 2022). Ceylon Black Tea has a large international market, while Ceylon Green Tea also has a similar market around the world. Fig. 2 shows the statistics of tea production and export in Sri Lanka (Tea Exporters Association Sri Lanka, 2023).

1.4. Tea Waste

For this article, tea waste generated in factories is considered as tea waste. This waste category includes tea plant buds, leaves, and tender stems. Fig. 3 shows the flow of tea waste generation.

Figure 3: Tea Waste Generation

These waste can be produced at various stages of tea production. According to Harshana et al. (2020), these stages are the offloading bay, withering, processing, firing, sorting and packaging. Table 1 shows the waste types produced during different stages of the tea processing.

Table 1: Type of the Waste Produced at Each Stage of the Tea Industry (Harshana et al., 2020)

Source	Waste	Waste Type
Leaf collection	Green leaf Gunny bags	Organic-Inorganic
Withering	Green leaf	Organic
Maceration	Green leaf Metal chips	Organic Wastewater
Fermentation	Pekoe dust Heat	Organic Thermal
Drying	Pekoe dust Heat	Organic thermal

According to Kathir et al. (2022), in 2020, tea production in India was up to 1,250 million tons, which grew over 5,66,660 hectares. This massive tea production generated about 0.015 million tons of tea waste. To break it down further, for every 100 kilograms of tea processing from the initial stages to export, a minimum of 2 kilograms of tea waste is produced. As a significant tea exporter, the Ceylon tea industry produces 27 tonnes of tea waste daily (Soysa et al., 2016).

1.5. Tea Waste Management

The Sri Lankan tea industry has faced many challenges and difficulties while managing tea waste. Despite being biologically degradable, improper disposal of tea waste can pollute soil, water, and air. This biodegradable waste generated by the tea factory is often openly dumped and burnt. Factory tea waste is the fibre portion of leaves removed during tea processing. Using factory tea waste directly as animal feed is limited due to presence of tannic acid (Harshana et al., 2020). Some industries purchase a small amount of solid tea waste to extract caffeine for pharmaceutical laboratory use. Decaffeinated Tea Waste contains little tannic acid compared to the original fait, enabling the utilisation of decaffeinated tea waste as animal feed (Harshana et al., 2020). As carbonisation becomes popular, tea waste has been examined for producing carbonaceous materials. Soysa et al. (2016) used Ceylon tea waste to produce bio-crude oil. Some tea reuses their tea waste within the plantation area as fertiliser. However, tea waste can raise soil acidity due to caffeine content. To counter this, tea waste is mixed with urea and cow dung and allowed to decompose into an effective bio-nutrient and bio-fertiliser (Harshana et al., 2020). Fig. 4 summarises the existing tea waste disposal methods.

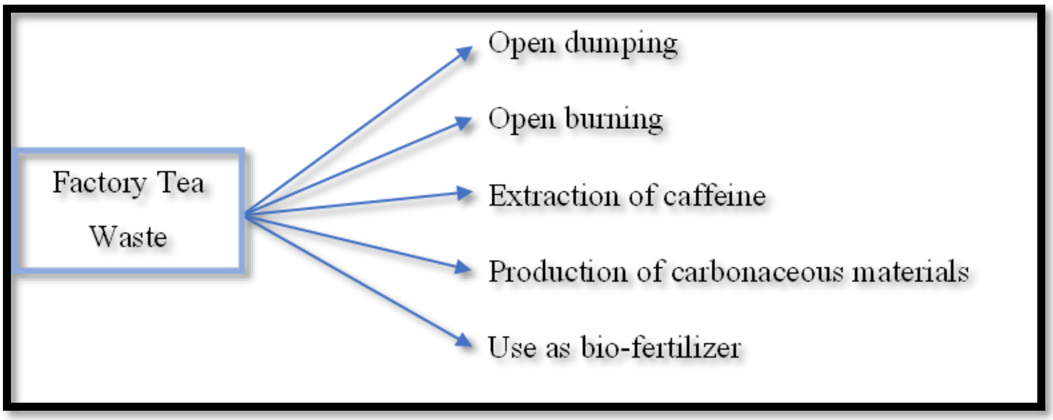

Figure 4: Existing Disposal Methods of The Waste

1.6. Biochar Production from Tea Waste

This short review article mainly focuses on biochar production from tea waste. Many researchers have identified tea waste as a potential feedstock type for biochar production. Studies have used different methods to produce biochar from tea waste. The high content of lignin, cellulose, hemicellulose and other organic compounds favours biochar production with high porous structure and large surface area through pyrolysis.

1.6.1. Temperature Concern in Tea Waste Pyrolysis

The study of Soysa et al. (2016) used the pyrolysis technique to produce carbonaceous materials from Ceylon tea waste. The pyrolysis process was carried out in a fluidised bed reactor which continuously operates under the nitrogen gas flow (N_2). The pyrolysis was carried out at temperatures of 450, 500, 550, and 600 °C, and the resulting biochar yields were 38.5%, 35.7%, 31.8% and 29.0% respectively. This confirmed the decline of biochar yield with increasing temperature. Guo et al. (2021) and Basumatary et al. (2018) also reported similar results.

The carbonised temperature affects the surface area of biochar. Guo et al. (2021) had identified a considerable increase in surface area of tea waste-derived biochar with the increase in temperature. The formed large surface area is typically associated with effective performance of adsorption capacity, water holding ability, remediation efficacy and super-capacitor property. That study also recognised a decline in the surface area of tea waste derived biochar when the temperature increased to 700 °C. That might be due to the collapse of pore structures under high temperature and block the pores.

According to previous studies, a pyrolysis temperature around 500°C can be the ideal temperature to produce biochar from tea waste. However, the temperature should not exceed 700°C to avoid the pore collapse.

1.6.2. Activation of Tea Waste Biochar

Either chemical or physical activation methods can prepare activated carbon. Gundogdu et al. (2013) produced activated carbon from industrial tea waste using Zinc chloride ($ZnCl_2$) as the chemical activation agent, and pyrolysis/activation was conducted at 700 ^{0}C. Mariah et al. (2023) have researched about carbonising of tea waste and the production of activated carbon. In this study, biochar was produced initially at 300°C for 1 h, linked to an activation process. Sulfuric acid (H_2SO_4) was used for the activation. Duran et al. (2011) also used concentrated H_2SO_4 as the activation agent. However, they mixed the acid with tea waste and then pyrolysed the mixture at 200°C. The study of Hossain et al. (2023) researched the production of cost-effective activated carbon from tea waste. Crusted tea was mixed with Potassium hydroxide (KOH) solution in a ratio of 1:1.5 and kept for 2 h. Then, the sample was dried at 85 °C for 6 hours and then pyrolysed under N_2 flow at various temperatures ranging from 200-1000 °C for 2 h. The results showed 89–97% chromium reduction by the activated carbon derived. The tested wastewater also significantly reduced BOD, COD, turbidity, conductivity, and chromium (Cr).

Few studies about the physical activation of tea waste is available to the best of the author's knowledge. Some studies about tea waste activation by physical activation showed the need of high temperature. The study of Zhou et al. (2018) investigated the feasibility of preparing activated carbon from waste tea by physical activation using steam. Initially, tea waste was carbonized at 450 °C, and prepared biochar was activated at 700, 750, 800, 850, and 900 °C using steam. The results showed that more volatiles would be lost with increasing temperature, leading to lower yields of activated carbon. Physical activation methods are not popular as they are complex and expensive. Moreover, compared to chemical activation, physical activation methods have demonstrated low surface roughness, kurtosis, and a low yield of activated carbon (Inbaraj et al., 2021; Zhou et al., 2018).

The discussion shows that the biochar derived from tea waste can be activated using different techniques, even at lower temperatures, especially by using chemical activation techniques.

1.6.3. Applications of Biochar and Activated Carbon of Tea Waste

According to Nan et al. (2021), transforming biomass waste through pyrolysis to derive biochar, followed by its application as a soil amendment, represents a promising strategy with various environmental advantages. These benefits encompass soil contamination remediation, soil quality improvement, and carbon sequestration. The study of Pröll et al. (2017) investigated reduced local emissions and long-term carbon storage through the pyrolysis of agricultural waste and the application of biochar to soil. Direct storage of biologically stable biochar in soils has been discussed as a low-tech zero emission technology option with positive side effects (Pröll et al., 2017).

Shirvanimoghaddam et al. (2021) discovered tea waste biochar utilisation for adsorption as a cost-effective, simple and efficient approach for pollutant removal from wastewater. The study of Pal & Maiti (2019) was based on investigating the effectiveness of tea waste biochar on-site sequestration of cadmium (Cd). The results showed a promising cadmium (Cd) removal performance and observed a high removal with increased dosage.

Activated carbon is a proven adsorbent in contaminant removal from the environment. Many previous studies have researched various contaminant removal from tea waste activated carbon. The study of Duran et al. (2011) investigated the application of tea-industry waste-activated carbon for chromium (Cr) removal. The results showed that it can successfully be applied for the separation, preconcentration and speciation of chromium (Cr) in environmental water and environmental solid samples. An inexpensive and effective adsorbent was developed by Mondal (2009) from waste tea. It performed as an excellent adsorbent in the removal of lead (Pb (II)) ions from aqueous solution, which is suitable for repeated use without noticeable loss of capacity. Ahmaruzzaman and Gayatri (2010) worked to determine the potential of activated carbon in the removal of p-nitrophenol (p-NP) from wastewater. The results indicated the efficiency of activated tea waste as a low-cost adsorbent to remove p-nitrophenol (p-NP) from aqua solutions. Peng et al. (2013) investigated the application of activated carbon derived from tea waste in high-performance super-capacitors electrodes. Activated tea waste has shown excellent electrochemical cycle stability and has discovered desirable capacitive performances that can act as a new biomass source of carbonaceous materials for high-performance super-capacitors and low-cost energy storage devices.

From the discussion, it is evident that the tea waste-based biochar and activated carbon have promising benefits and can be easily commercialised in different ranges of industries.

Perspectives of Ceylon Tea Waste Conversion to Biochar

The literature review has discussed many previous studies, and it is evident that tea waste is a promising material in producing biochar and activated carbon. They can be used for many applications in various fields. Biochar production from waste is correlated with carbon sequestration. Biochar and activated carbon have been recognised as simple, low-cost, and efficient adsorption materials. However, the energy consumption for the pyrolysis process might be higher due to high heat requirements. Therefore, there is a need for cost benefit analysis of the pyrolysis process and biochar production from tea waste and activation.

Most tea factories in Sri Lanka use conventional techniques to produce tea. Therefore, the biochar production reactor should not be complicated and easily adaptable. In this regard, the double barrel carbonisation technique can be recognised as a simple and sustainable mechanism that industries can easily apply to convert waste into char (Gunther, 2015; Pollnow, 2014). In addition to that, this kind of setup can be used inside conventional biomass boilers in tea factories. In that case, waste or excess heat from the boilers can be used to convert tea waste into biochar or even be activated especially using chemical activation methods. Therefore, this technique can be easily adapted to the Sri Lankan tea industry as it is cost effective. The production of biochar and activated carbon can be economically and environmentally beneficial, and it will help to reach net zero emissions, encouraging the circular economy.

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