Sustainable Applications of Tea Waste: Current Practices and Emerging Trends

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Tea, *Camelia sinensis* (L.) O. Kuntze belongs to family Theaceae and is native to Southern China. It is the second most consumed beverage after packaged drinking water throughout the world and the demand and consumption of tea are increasing all over the world. The top tea producing countries in the world are China, India, Kenya, Indonesia and Sri Lanka, of which China shares around 40% of the total tea production whereas India contributes about 23%. The estimated worldwide daily consumption of tea is around 18–20 billion cups. The worldwide tea consumption in 2020 was approximately 6.3 million metric tonnes and it is expected to rise to 7.4 million metric tonnes by 2025 because of its numerous health benefits as well as for several refreshing effects. Tea is popular for its outstanding health-promoting effects such as anti-inflammatory, cardiovascular preventive, anticancer, antidiabetic, anti-obesity, neuro-protective and antioxidant activities. In order to meet such growing demand, the worldwide tea production is rising drastically which in turn results in the generation of enormous amounts of tea waste. approximately 90% of tea leaves become tea waste after processing and consumption. After utilizing tea, the left-over residue is discarded into the environment without prior treatment. This may cause very harmful effects on humans, soil, water and the environment. The disposal of a large amount of untreated tea waste in the environment affects the pH of soil. The acidic pH in the soil makes it unfertile for farming. Moreover, the bacterial and fungal growth on the tea residue leftover leads to spreading of bad odours into the surroundings. Therefore, to overcome these issues, it is important to reuse or convert waste tea residues into value-added products.

In India, tea cultivation covers an area of about 5,79,000 ha and the approximate annual tea production is 8,57,000 tonnes. Subsequently, the total tea waste produced by the respective factories after processing is around 1,90,400 tonnes Regarding tea production, the Tea Board of India follows the clause no. 8 of the Tea Waste (Control) Order, 1959, which states that the minimum volume of tea waste and made tea should be at a ratio of 2:100 kg, after processing out of the leaves, tender stems and buds of tea plants. Before exporting, selling or holding stock of tea waste, it shall be denatured by the admixture of urea not less than five percent, cow dung, slaked lime or such other denaturants as may be specified by the Tea Board of India. In comparison to the huge quantities of waste generated, the number of buyers for tea waste is less in India. Only a small portion of tea waste is purchased and utilized by some industries for the caffeine extraction or used as animal feed / compost and the rest is disposed of as wastes creating a number of environmental issues. Therefore, the potential and sustainable utilization of tea waste has become a matter of high research priority in the recent times. Tea waste can be divided into two categories according to production and processing methods. The tea stem makes up about 20% of the total weight of tea. The other is the tea residue discharged from the tea beverage factory after processing.

Composition of tea waste

Tea waste is basically a lignocellulosic biomass consisting of cellulose, hemicellulose, lignin, polyphenols, proteins and tannins. Tea waste contains 20.82% crude protein, 5.23% lipid, 4.92% ash, 13.69% moisture, 17.06% crude fiber, 4.58% cellulose, 13.96% hemicellulose, 0.54% calcium, 0.36% phosphorus and 0.18% silica.

Products obtained from tea waste

Tea waste has significant structural and nutritional potential and it can be used in the production of both food and non - food products. Thermochemical and biological conversion of tea wastes generates value-added products. In this regard, several studies reported the utilization of tea waste for the extraction of antioxidant products with medicinal values such as flavanols, catechin, caffeine production of adsorbents for waste water treatment, generation of bioenergy and for several other purposes like fabrication of energy storage devices, reinforcement in polymer composites as well as synthesis of crystalline cellulose derivatives.

Different Methodologies for value-added products from tea waste

Tea waste compounds make it an excellent candidate for generating value-added products such as

bioenergy, functional foods, food additives, compost, packaging materials, silage and adsorbents.

Formation of biogas

Biogas is a renewable fuel source produced via anaerobic digestion of various agricultural, industrial and municipal feedstocks. Co digestion of spent tea waste (25%) with cow manure (75%) in anaerobic digestion reactor provides high yield of biogas containing methane as much as 70% with high energy content and heating value of 5.1–5.7 kW/m3 and 26.4 MJ/kg.High nitrogen content of the tea waste powder significantly increases the biomethane yield.

Production of Manure

Vermicompost tea (VCT), the aqueous extract of Vermicompost presents itself as an opportunity to modern urban agriculture. The spent tea waste was vermicomposted for 60 days using *Eudrilus eugeniae*. It requires a relatively small number of earthworms to cover a large production area while extracting all the desirable biochemical properties of solid vermicompost. It has been shown that vermicompost tea also contains microorganisms, nutrients and plant growth promoters that are beneficial to plants by foliar application or by adding it to the soil. Applications of vermicompost tea have been shown to overcome nutritional deficiencies in high yielding intensive crop production where organic materials are the sole nutrient source as evidenced by enhanced seed germination, plant growth, increased yield and suppression of plant diseases by inducing plant resistance to pathogens, or producing direct toxicity to plant pathogens .The use of vermicompost tea as a pest-resistant agent in hydroponically grown plants reduces the residue of chemical compost in the environment.

Production of Ensilage

It is also possible to use tea waste in animal feed since tea leaves contain many active ingredients, such as proteins, polyphenols and minerals and it has been observed that some insoluble active ingredients are abundant in the tea residues left behind after the extraction process. Tea waste as a ruminant feed is, therefore, a good supplement because it reinforces protein, minerals, fiber and secondary metabolites. As a result of the addition of green tea waste to the silage, the fermentation efficiency was found to be affected positively for the growth of lactic acid bacteria. In another study with goats, the effect of green tea waste addition on the nutritional value of silage was investigated. For this purpose, green tea waste, from a local beverage company, was added to whole grain oat silage and stored in silos for 50 days. As a result, the addition of green tea waste increased the lactic acid concentrations after fermentation. Furthermore, dense tannin and crude protein contents in the silage were found to be higher with this treatment.

Biofuel production

Bioethanol is a biofuel which can considerably decrease the use of petroleum-based fuels in transportation sector. Spent tea waste, being lignocellulosic in nature have great potential to be used as feedstock for bioethanol formation with lower greenhouse gas emissions. It can be seen that the hydrolysis of dried tea waste using H_2SO_4 followed by fermentation with *Saccharomyces cerevisiae* and distillation were able to produce alcohol containing 8.2% of bioethanol. Tea waste is a good carbon source containing glucose, maltose, xylose, mannose, galactose, arabinose and other sugars, which can be converted into bioethanol by fermentation and near to the theoretical yield

Tea waste can be employed as catalyst for the effective esterification of oil into biodiesel. Sulfonated tea waste catalyst synthesized from waste black tea leaves showed excellent performance in the esterification of free fatty acids present in the palm fatty acid distillate. The catalyst exhibited porous structure, good thermal properties and reusability up to 5 cycles. Thus, the minimum temperature requirement, low-cost and reusability for multiple times make the tea waste catalyst efficient and feasible for commercial scale biodiesel production.

Formation of biochar

Tea waste can be converted into biochar through pyrolysis, a process that involves heating organic material in the absence of oxygen. Biochar is highly porous carbon rich material that serves as a soil amendment enhancing soil fertility, water retention, nutrient availability and also helps in sequestering carbon in the soil, mitigating greenhouse gas emission thus improving soil health.Activation with $KHCO_3$ increased the BET surface area of the biochar samples by nearly 280 times and subsequently their adsorption capacities for tetracycline were also improved by 40 times (425.2 and 451.5 mg/g for KBC and KHBC, respectively) as compared to the untreated hydrochar. The characterization of the prepared biochar samples revealed that carbonization considerably effected the

chemical composition, morphology, functional groups and carbon structures.

Production of Bioactive compounds

The polyphenolic compounds extracted from tea waste have antioxidant, anti-microbial and anti-inflammatory properties, so these can be utilised in pharmaceuticals, nutraceuticals cosmetics and functional fruit. Polysaccharides found in leaves and buds of the tea plant can act as bioactive compound, contributing to the health promoting properties (antitumor, anti-fatigue, anti-obesity, antidiabetic and anti-ageing).

Synthesis of metal-based nanoparticles from tea waste

Green bio-based synthesis of nanoparticles becomes a major focus in the research field. Tea waste biomass is found to be very efficient for the synthesis of metal-based nanoparticles. The polyphenols like catechins present in tea leaves act as reducing and capping agents for the production of metal nanoparticles and stabilize them. Tea waste was utilized for the synthesis of silver nanoparticles using $AgNO_3$ solution, nanoparticles with size in the range of 2–34 nm and circular shape were obtained. The study concluded that the polyphenolic compounds of tea waste such as epigallocatechin acted as capping agents and reduced $AgNO_3$ into Ag Nano Particles (AgNPs), also stabilized them. The formed AgNPs were found to be effective for removing methylene blue, crystal violet, brilliant green and congo red from textile industry wastewater.

Synthesis of valuable cellulosic derivatives from tea waste

Microcrystalline cellulose (MCC) and nanocrystalline cellulose (NCC) are the most well-known and widely used crystalline derivatives of cellulose which has tremendous potential for application in the environmental field, biomedical and pharmaceutical sector. The MCC isolated from tea waste was also found to possess good thermal stability. the tea waste NCC exhibited better thermal stability as compared to the NCCs prepared from wood and commercial MCC. Thus, tea waste can be utilized as a potential source for the production of valuable crystalline cellulosic derivatives for application in different emerging fields.

Chinese Pinyin of tea and wood (CHAMU) and the establishment of the Tea Waste Recycling System is meant for mitigating the problem of tea waste disposal in the tea production process. CHAMU refers to the tea stem and tea residue produced in the process of tea production and processing, which can then be used as a product after mechanical Tea stems forming a good mechanical strength after hot pressing and having a Modulus of rupture of 13.2Mpa is suitable for processing artificial board. The formed tea stem artificial board meets the national standard (China) in various mechanical strengths.

Polymer Industry

Natural fibers, when used as reinforcing agents in polymer matrices, create green, biodegradable composites with improved performance and reduced environmental impact. While natural fibers are abundant and cost-effective, they lack mechanical strength compared to synthetic fibers. Combining both in a hybrid composite merge their strengths.

A hybrid polymer composite using tea waste, sisal, and glass fibers in an epoxy resin matrix. Alkali treatment (5% NaOH) improved the bonding of tea waste and sisal fibers by removing lignin and hemicellulose. The composite with 10% tea waste and 20% sisal exhibited the best tensile (75.6 MPa) and flexural strength (218 MPa), while 15% tea waste and 15% sisal provided the highest impact strength (96.2 kJ/m^2). A composition of 20% tea waste and 5% sisal demonstrated excellent sound absorption (0.9). Compared to pure glass fiber composites, the hybrid improved tensile, flexural, impact strength, and sound absorption by 6.3%, 22.4%, 42.0%, and 35%, respectively.

Another hybrid using tea waste, banana, and flax fibers also showed superior mechanical properties with 5% tea waste and 25% banana fiber. These composites are suitable for automotive, aircraft, and furniture applications, showcasing sustainable and eco-friendly advancements in polymer composite materials.

Conclusion

The significant potential of tea waste as a versatile resource for numerous emerging applications. The increasing global consumption of tea generates vast quantities of waste, posing environmental challenges if not properly managed. Tea waste, rich in cellulose, lignin, polyphenols, and proteins, can be effectively utilized to produce value-added products with pharmaceutical, environmental, and industrial benefits. These include health-promoting compounds, materials for environmental remediation, bioenergy,

polymer composites, and advanced energy storage devices.

While the research demonstrates the diverse applicability of tea waste, large-scale industrial utilization remains underdeveloped. Addressing these challenges through innovative scientific approaches and modern technologies could enable sustainable extraction processes and expand the commercial use of tea waste. This would not only reduce environmental impact but also foster circular economy practices and sustainable development. The insights provided in this review aim to inspire further research and practical applications, contributing to a greener and more resource-efficient future.

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