

Review Article

## Valorization of Tea Waste Biomass for Biofuel Production

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### Abstract

Tea waste biomass (TWB), a byproduct of global tea processing industries, represents a largely untapped lignocellulosic resource with promising applications in sustainable energy. This literature review critically examines the potential of TWB as a renewable feedstock for second-generation (2G) biofuels such as bioethanol and bio-oil. It analyzes the compositional characteristics of TWB and relevant conversion technologies (pretreatment, fermentation, pyrolysis) within the framework of integrated biorefineries. The study positions TWB valorization as a strategic approach within the circular bioeconomy, supporting the integration of biorefinery processes with conventional petroleum refining to reduce CO<sub>2</sub> emissions and advance the energy transition. The studies review compiles and analyze data on agricultural lignocellulosic biomass and (especially the TWB) compositional characteristics (e.g., cellulose, hemicellulose, lignin, bioactive and non-bioactive compound), and relevant technologies including pretreatment, fermentation and pyrolysis processes etc. for biofuel production.

**Keywords** Tea waste . Lignocellulosic biomass . Biofuel, Biorefinery . Petroleum refinery . Bioenergy

### Introduction

The rising global energy demand, coupled with mounting concerns about climate change and energy security, has intensified the search for sustainable and renewable alternatives to fossil fuels. In this context, second-generation (2G) biofuels derived from non-edible lignocellulosic biomass (LCB) have emerged as a promising pathway to reduce greenhouse gas emissions and support decarbonization. This transition aligns with policy-driven shifts toward low-carbon energy systems and circular bioeconomy models, wherein agricultural and industrial waste streams—such as tea waste biomass (TWB)—are valorized into renewable fuels. Integrating biorefinery concepts with conventional petroleum refining offers a hybrid strategy to gradually replace fossil-based

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feedstocks with biomass-derived inputs, thereby advancing both energy security and climate objectives. Millions of tons of TWB are generated annually, creating a pressing need for high-value valorization pathways in which comprising tea pruning, discarded leaves as tea waste biomass (TWB) and spent tea leaf (STL) caused from domestic popular consumption of made tea (MD) as a relaxing drink. This issue creates a pressing need to find high-value valorization pathways for this inexpensive and tea abundant material. However, the optimal commercial routes for this specific biomass into valuable biofuels and the scalability of these technologies still face significant challenges for LCB's feedstock. Preliminary and scattered studies have confirmed the significant potential of tea waste for producing various biofuels, including bioethanol (via hydrolysis and fermentation), biodiesel (via oil extraction and transesterification from tea seeds), biogas (via anaerobic digestion), and biochar (from pyrolysis). As this hybrid strategy by blending of non-renewable & renewable fuels or gradually replacing fossil-based feedstocks with biomass-derived inputs, it becomes possible to replace renewable fuels such as bio-gasoline, bio-jet fuel, biodiesel as sustainable version of fuel with conventional fuel of petroleum refinery.

The research review is providing a background to do an experimental work in laboratory to produce biofuel from TWB in the supply chain of tea waste generation. This research review focuses on the following key question: What and which conversion pathways (biochemical or thermochemical such as: pretreatment, fermentation and pyrolysis) are suitable to transform TWB as a type of LCB into valuable biofuel in the laboratory or pilot scale?

## Materials and Methods

This review article is conducted by a structured literature search and screening protocol aligned with the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA 2020) guidelines. A search studies Identification, Screening and included was performed for 90 topics of reports and studies by using PRISMA via databases and registers including databases such as: Scopus, ScienceDirect, Google Scholar and registers such as: Zenodo, Figshare, Re3data and other methods such as: websites, organizations, citation searching. Search terms included combinations of: "tea waste biomass", "Camellia sinensis waste", "lignocellulosic biomass", "bioethanol", "bio-oil", "biofuel" "pyrolysis", "fermentation", "biorefinery" and "petroleum refinery". Inclusion criteria comprised: (i) studies focused on tea waste biomass (TWB) as the primary feedstock, (ii) original experimental, pilot-scale, or review studies related to biofuel production, (iii) articles published in English between 2000–2025 and are totally 79 in review. Exclusion criteria included: (i) studies unrelated to biofuel conversion, (ii) non-peer-reviewed sources, and (iii) studies focusing solely on tea chemistry without discussion of valorization pathways, (iv) non-open access and are 11 topics. (A PRISMA flow diagram summarizing the identification, screening, eligibility, and inclusion stages is provided in Figure 1a, Appendix A).

### *Tea Waste*

This section discusses the importance of agricultural and food products, highlighting the mass generation of agricultural waste, particularly in the tea industry. It cites data revealing considerable economic losses from food waste and emphasizes the potential for valorizing tea waste into biofuel and bioactive and non-bioactive products. Studies show global tea production involves the processing of approximately 33 million tons of fresh tea leaves in plantation area annually in the different areas of geographical worldwide, and yielding around 6.6 million tons of dry made tea (MT) per year. This transformation process results in a substantial volume of by-products and

waste. Most notably, globally an estimated 5.94 million tons of spent tea leaf (STL) are generated each year as about 90% of MT after its domestic drink. In addition to STL, about 2 to 4 percent (or 3-5 % as a rule of thumb or more in sometimes) is the waste of tea processing factories (Aaqil et al. 2023) and contributes around 0.2 to 0.33 million tons of tea waste biomass (TWB) as mainly stems and sweepings. Finally, FTL has the potential to generate the global total tea waste to approximately 6.14 to 6.27 million tons annually. These estimates are supported by global and regional data from sources such as FAOSTAT, IISD, and peer-reviewed studies (Bermúdez et al. 2024). The global TWB tonnage was derived using a mass-balance approach based on FAOSTAT and IISD tea production statistics. Regarding research review studies fresh tea leaf (FTL) to made tea (MT) conversion was assumed at a ratio of 4.5:1 (FTL:MT), consistent with industrial norms. Spent tea leaves (STLs) were estimated as 90% of MT mass, while factory waste (stems, sweepings) was estimated as 3–5% of total FTL processed (Nsanabera et al. 2024). (A spreadsheet containing calculations, assumptions, and data sources is provided in supplementary materials section after reference section.)

The six leading tea-producing nations (China, India, Kenya, Sri Lanka, Vietnam, and Turkey) collectively account for approximately 86.5% of global made tea output FAOSTAT (2023), ITC (2024). Using the mass-balance assumptions (90% of made tea converts to spent leaves, plus 3–5% factory waste from fresh leaf processing), this translates to an estimated 5.3 – 5.4 million metric tons of annual TWB generation potential within these countries alone. This significant concentration indicates that the valorization of TWB is not merely a diffuse global opportunity but a targeted regional imperative. The majority of the world's readily available TWB feedstock is located in specific agro-industrial zones in Asia and East Africa. Consequently, strategies for TWB collection, pre-processing, and conversion into biofuels are likely to be most economically and logistically viable in these high-density regions. Developing integrated biorefinery models in these key producing countries could simultaneously address local waste management challenges and contribute substantially to regional bioenergy targets and circular bioeconomy goals.

### *Agricultural Waste Biomass Characteristics and Energy Supply*

The characteristics of few sustainable agricultural waste and its lignocellulosic materials (C: Cellulose, HC: Hemicellulose, L: Lignin) are explained in some references as: Sugarcane Bagasse (C: 40-45, HC: 25-30, L: 20-25), Corn Stover (C: 38-42, HC: 20-25, L: 15-20), Rice Straw (C: 46, HC: 26, L: 17) and Wheat Straw (C: 41, HC: 25, L: 12.6), (Blasi et al. 2023) (Rahman et al. 2022). Sustainable agricultural waste biomass (AWB) includes great amount lignocellulosic contents and other organic & non-organic compounds in which offer a renewable feedstock for energy production and other bio-based raw material (Barbieri et al. 2013) (Duque-Acevedo et al. 2022). Sustainable AWB have potential to supply energy through direct combustion (heat/power), or thermochemical processes (e.g., pyrolysis for bio-oil), biochemical processes (e.g., fermentation for bioethanol) in biorefineries (Clauser et al. 2021). Under this scenario, modern renewable would reach just under 32 percent of TFE (total final energy consumption) in 2030 as following figure (Reyes 2022). Typically agricultural waste biomass (AWB) comprises cellulose (30-50%), hemicellulose (20-35%), and lignin (15-25%) (Blasi et al. 2023).

### *Tea Production & Tea Characteristics*

Tea leaves (*Camellia sinensis*) contain a diverse array of chemical and bioactive compounds that contribute to their nutritional, medicinal, and industrial value. Key constituents include

polyphenols, amino acids, enzymes, carbohydrates (cellulose, hemicellulose), lignin, alkaloids (e.g., caffeine), flavonoids, organic acids, minerals, and volatile aromatics (Nsanjabera et al. 2024). These compounds undergo transformation and changing in composition weight percent during tea processing to produce finished tea products and solid tea waste biomass (TWB). Some of typical important composition (%) of constituents of tea leaves based on dry weight in fresh green tea leaves are following as: Polysaccharides (structural carbohydrates; cellulose/hemicellulose, fiber) 20–30%, Lignin 6–7 %, Polyphenols 25–35% etc., (Wang et al. 2022). Six main types of made tea (MT) are white, yellow, green, oolong, black and post-fermented (or dark). Each type of MT products and TWB may have a unique composition (%) of constituents.

### *Biofuels: Environmental and Economic Assessment Evidence*

Biofuels, spanning from first-generation (1G) to fourth-generation (4G), play an increasingly vital role in combating climate change by providing renewable alternatives to fossil fuels to reducing GHG emissions. First-generation biofuels, derived from food crops like corn and sugarcane, offer immediate but limited benefits due to land-use and food security concerns. Second-generation biofuels utilize non-food biomass such as agricultural wastes (such as TWB) and wood, reducing competition with food supply and improving sustainability. Third-generation biofuels harness algae, which have high yield potential and minimal land requirements. Fourth-generation biofuels incorporate advanced technologies, including carbon capture and genetically modified organisms, to create carbon-negative fuels.

Life cycle assessment (LCA) and techno-economic analysis (TEA) studies of lignocellulosic feedstocks reveal substantial environmental and economic potential for biofuel production. Existing LCA data indicate that lignocellulosic bioethanol can achieve 55–85% greenhouse gas (GHG) reductions compared to fossil gasoline, depending on process configurations and energy inputs (Jeswani et al., 2020). For instance, biorefineries using sugarcane bagasse have demonstrated over 50% energy savings relative to petroleum refining, alongside significant GHG mitigation (Clauser et al., 2021). While TWB-specific LCA/TEA studies are still limited, preliminary assessments based on analogous agricultural residues suggest that tea waste biomass could offer competitive environmental performance and economic viability within integrated biorefinery systems. Biofuels support net-zero goals by enabling carbon-neutral cycles, as CO<sub>2</sub> released during combustion is offset by biomass growth. They also promote a circular bioeconomy by valorizing wastes (Clauser et al. 2021). The energy transition requires biofuels to replace 29% of transport fuels by 2060 (Nogueira et al. 2020).

### *Lignocellulosic Compounds & Biorefineries*

Agricultural biomass is composed of the lignocellulosic compounds detailed in sub-section—cellulose, hemicellulose, and lignin—each offering distinct pathways for the production of biofuels and biochemicals and across reviewed studies, cellulose content in TWB ranged between 15–20%, hemicellulose 60–70%, and lignin 16–20%. Their individual properties and roles in energy production processes are thoroughly analyzed and linked to their application in biorefineries. The structural polysaccharides (cellulose and hemicellulose) can be hydrolyzed into fermentable sugars for producing bioethanol while lignin can be processed into bio-oil. For example, bioethanol yields varied between 18–25 g/L for enzymatic hydrolysis–fermentation pathways, while pyrolysis bio-oil yields from TWB lignin averaged 35–45% (Chai et al. 2022).

Unlike petroleum refineries that process crude oil into fossil-based fuels, biorefineries utilize renewable lignocellulosic biomass to produce biofuels, biochemicals, and biomaterials. This shift can significantly reduce energy demands and greenhouse gas emissions compared to conventional refining; for example, using sugarcane bagasse for bioethanol has shown over 50% energy savings (Clauser et al., 2021). A comparative overview is presented in Table 1. A comparison summary of biorefinery & petroleum refinery products and feedstocks is presented in Table 1.

**Table 1.** Biorefinery vs. Petroleum Refinery Comparison

Aspect	Biorefinery	Petroleum Refinery
Feedstock	Renewable LCB	Hydrocarbon Crude Oil
Products	Biofuels (Renewable Fuels)	Gasoline, Diesel, Jet Fuel (Non-Renewable Fuels)
GHG Impact	Low	High

### *Production of Bioethanol & Renewable Bio-Oil Methods from Tea Waste Biomass*

The biofuel production processes involved in converting lignocellulosic TWB into bioethanol & renewable bio-oil is possible through the steps of pretreatment, fermentation, and pyrolysis routes known as: biochemical (fermentation) and thermochemical (pyrolysis) processes to valorize TWB. The conversion of TWB to bioethanol typically involves three main stages: (i) pretreatment to disrupt lignocellulosic structure, (ii) enzymatic hydrolysis to release fermentable sugars, and (iii) fermentation of cellulose compounds using *Saccharomyces cerevisiae* or engineered microbial strains. Acid pretreatment (1–3% dilute sulfuric acid) operates at 120–160°C, while alkaline pretreatment (1–4% NaOH) is effective in lignin removal. These ranges were validated by recent studies on lignocellulosic residues similar to tea waste (Lin & Lu 2021; Liu et al. 2023).

Renewable bio-oil production from TWB-derived lignin follows fast pyrolysis at 450–550°C with heating rates >300°C/s, producing condensable vapors subsequently upgraded through hydrotreatment. Upgrading of produced bio-oil to other valuable biofuels such as bio-gasoline, biojet and biodiesel requires 30–80 bar H<sub>2</sub> and catalysts such as NiMo/Al<sub>2</sub>O<sub>3</sub>, similar to conventional petroleum refinery hydrotreaters (Saber et al. 2016). By the way, in a non-renewable crude oil refinery also the petroleum and heavy hydrocarbon oil is further processed through distillation and deep conversion units such as atmospheric distillation unit (ADU), hydro-cracking (HC), fluid catalytic cracking (FCC) units and etc. to produce non-renewable oil products (gasoline, jet fuel, diesel) (Saber et al. 2016). Now, it is possible to blend renewable & non-renewable fuels such as E5 (including: 5% bioethanol of a biorefinery plus 95% fossil gasoline of a petroleum refinery), B5 (including: 5% biodiesel of a biorefinery plus 95% fossil diesel of a petroleum refinery), SAF5 (including: 5% bio-jet of a biorefinery + 95% fossil air fuel jet of a petroleum refinery).

### *Summary of Experimental and Field Studies on TWB*

Table 2 titled “Summary of Experimental Studies on Conversion of TWB to Biofuels” provides a structured synthesis of key laboratory and bench-scale investigations focused on the valorization of tea-waste biomass. By presenting essential parameters—such as process type, operational scale, feedstock preparation, conversion conditions, product yields, and associated energy inputs—the table enables a clear comparison of the technological pathways explored in the literature. The

compiled studies encompass a range of biochemical, thermochemical, and solvent-based approaches, including enzymatic hydrolysis–fermentation, organosolv fractionation, (NADES), fast pyrolysis, and green-solvent extraction. Collectively, these data illustrate the diverse mechanisms through which TWB can be transformed into bioethanol, bio-oil, purified cellulose, lignin, and polyphenolic compounds. The concise evidence framework offered by the table supports a comprehensive understanding of TWB’s conversion performance and highlights its potential as a viable feedstock within integrated biorefinery systems.

**Table 2.** Summary of experimental studies on conversion of TWB to biofuels

Reference	Process	Scale	Feedstock	Conversion Conditions	Yields / Outputs	Energy Inputs
Rahman et al. (2017)	Enzymatic hydrolysis + fermentation	Lab-scale	TLWF pretreated	2–4% H <sub>2</sub> SO <sub>4</sub> , cellulase 30 FPU	18–22 g/L ethanol	Heating + enzyme load
Wang et al. (2020)	Organosolv fractionation	Bench-scale	Tea leaf waste	140–180°C, ethanol/water	Cellulose (high purity), lignin	Thermal + solvent recovery
Echresh Zadeh (2020)	Fast pyrolysis	Lab reactor	Lignin from TWB	500 °C	38–42% bio-oil	Electrical heating
Liu et al. (2023)	Polyphenol extraction	Lab-scale	Spent tea leaves	NADES solvents	15–20% phenolics	Stirring + solvent

### *Extraction and applications of Cellulose, Hemicellulose, and Lignin*

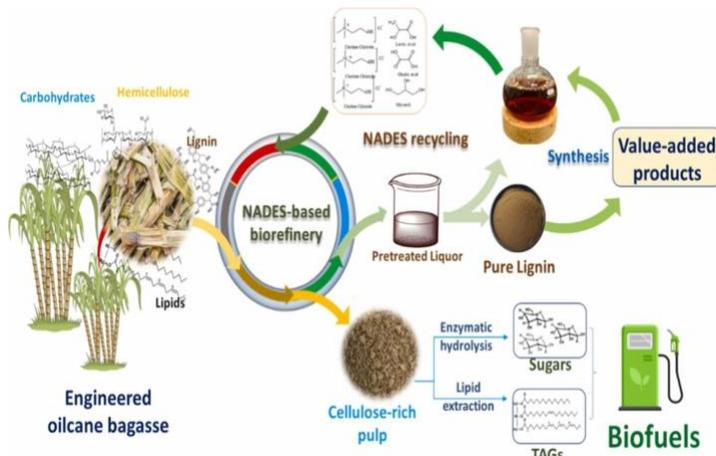
Cellulose, hemicellulose and lignin of agricultural LCB are usually extracted via pretreatment (e.g., acid/alkali as harsh chemicals or natural solvents) and then cellulose fermented to bioethanol and lignin is used via pyrolysis for bio-oil production (Blasi et al. 2023). It is shown in Table 3.

**Table 3.** Extraction Processes of lignocellulosic components

Component	Pretreatment	Process	Product
Cellulose	Acid hydrolysis	Fermentation	Bioethanol
Hemicellulose	Alkali treatment	Fermentation	Bioethanol
Lignin	Thermal separation	Pyrolysis	Bio-Oil

De-Polyphenolization & delignification of TWB by the enzymatic and harsh chemical solvent or natural deep eutectic solvents (NADES) could be considered to extract polyphenol and then chemical extraction and separation of lignocellulosic polymers (cellulose/hemicelluloses and lignin) from other soluble and non-soluble biochemical compounds of tea waste biomass (TWB) in a processing step in a biorefinery (Liu et al. 2023) (Oriez et al. 2020) (Raj and Singh 2025). Lignocellulosic compound is a type of biochemistry material that is also existed in TWB. Cellulose is used in bioethanol, paper, and textiles production; hemicellulose in biofuels and biochemicals production; and lignin in adhesives, biochar, and chemicals and biofuel compatibility production (Lin and Lu 2021). In the extraction pathway analysis, it is important firstly to extract of polyphenols for use as antioxidants or nutraceuticals from TWB before extractions of lignocellulosic contents (Tanis et al. 2025), then extractions of cellulose & lignin & hemicellulose

from agricultural waste biomass(AWB)could be done by different types of solvents such as: harsh chemical(alkaline,...) solvents or green solvents (NADES, Organosolv) (Abdul Rahman et al. 2017) (Oriez et al. 2020) (Raj and Singh 2025) (Wang et al. 2020).There are applications from extraction of LCB components using chemical or natural solvents in which are shown in Table 4. Figure 1 also shows Natural deep eutectic solvents (NADES) extraction of LCB (cellulose & lignin), (Raj and Singh 2025).



**Figure 1.** Natural deep eutectic solvents (NADES) extraction of lignin and cellulose (Raj & Singh 2025).

**Table 4.** Some of applications of lignocellulosic components extracted from LCB

Main Components	Primary Applications
Cellulose	<ul style="list-style-type: none"> <li>- Paper and pulp production</li> <li>- Textiles (cotton, rayon)</li> <li>- Biofuels (bioethanol)</li> <li>- Bioplastics and composites</li> <li>- Food additives (thickener, fiber)</li> <li>- Pharmaceuticals (excipients, drug delivery)</li> </ul>
Hemicellulose	<ul style="list-style-type: none"> <li>- Biofuels (fermentation to bioethanol)</li> <li>- Biochemicals (xylitol, furfural)</li> <li>- Food industry (fiber, stabilizer)</li> <li>- Biodegradable films and packaging</li> <li>- Animal feed</li> </ul>
Lignin	<ul style="list-style-type: none"> <li>- Bioenergy (solid fuel, bio-oil)</li> <li>- Chemicals (adhesives, dispersants)</li> <li>- Carbon fibers and bioplastics</li> <li>- Soil amendments</li> <li>- Pharmaceuticals and cosmetics (antioxidants, UV protection)</li> </ul>

## Results and Discussion

The manuscript emphasizes the benefits of utilizing TWB for producing renewable sustainable biofuels. Although TWB-specific LCA/TEA data remain limited, this gap finding underscores the need for dedicated TWB-focused LCA/TEA research to fully quantify its sustainability and scalability potential and also this review aims to inform through future experimental and modeling work.

As a result, the researcher of this research review has planned to continue subsequently his research studies in further laboratory work in the form of his PhD program (bioenergy) by the supporting of FCT (faculdade de ciências e tecnologia) of NOVA University (Portugal) on the production of TWB-derived biofuels with the help of natural (NADES) and also doing its life cycle analysis (LCA) analysis by OpenLCA software (as an academic relevant tool) and finally its TEA (if possible, for a commercialized scale).

### Declarations

There is no conflict of interest (COI) in this manuscript. This manuscript also benefited from AI-based tools for language refinement, grammar correction, and structuring. But all scientific content, interpretations, and conclusions were developed solely by the authors.

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### Appendix A. PRISMA flow diagram

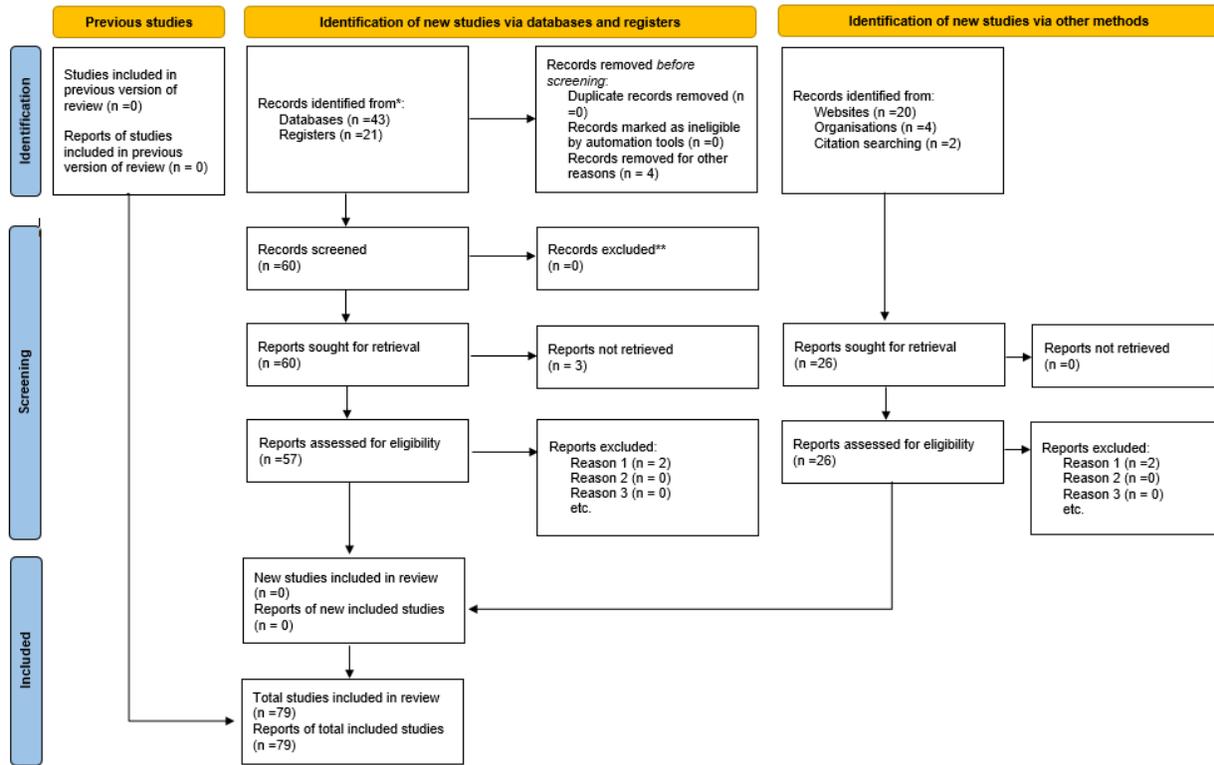


Figure 1a. PRISMA 2020 flow diagram for updated systematic reviews which included searches of databases, registers and other sources

### Appendix B. Total TWB tonnage calculations

Table 1a. Total TWB tonnage calculations (Supplementary spreadsheet)

	A	B	C
1	Parameter	Value	Source
2	Fresh Tea Leaves processed (FTL)	33.0 million tons/y	Manuscript Table 1
3	Made Tea Production (MT)	6.604 million tons/y	Manuscript Table 1
4	Spent Tea Leaf (STL) fraction	90% of MT	Manuscript Table 1
5	Spent Tea Leaf (STL) mass	5.94 million tons/y	6.604 × 0.90
6	Factory tea waste share(FTWS)	3–5% of FTL	Manuscript Table 1
7	Factory waste mass, Limit	0.99–1.65 million tons/y	33 × (0.03–0.05)
8	<b>Total Tea Waste (TWB)=STL+FTWS</b>	6.93–7.59 million tons/y	STLs + factory tea processing waste
9			