

Unlocking the Pharmaceutical Potential of Assam Tea-Processing Waste: Sustainable Bioactive Recovery and Advanced Drug-Delivery Systems

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ABSTRACT

The sustainable utilisation of agro-industrial waste has gained increasing attention as researchers explore opportunities to recover valuable bioactive compounds from underutilised resources. Tea-processing waste represents a potential source of bioactive constituents that may have applications in pharmaceutical research and advanced drug-delivery systems. However, the effective utilisation of these materials requires a clearer understanding of the existing research landscape, recovery technologies, sustainability considerations, and challenges associated with pharmaceutical applications. This study maps the broader tea-related research landscape through bibliometric analysis using Biblioshiny and critically examines its relevance to the sustainable valorisation of tea-processing waste, bioactive compound recovery, and advanced drug-delivery systems, with particular reference to Assam tea. The bibliometric analysis examines publication patterns, influential sources, contributing countries, research collaboration, and prominent thematic areas. The bibliometric findings and critical review are synthesised to identify research opportunities linking tea-processing-waste utilisation, sustainable bioactive recovery, and pharmaceutical formulation development. Particular attention is given to extraction efficiency, compound characterisation, formulation development, safety assessment, and the need for experimental validation. The study proposes a sustainability-oriented research direction for converting tea-processing residues into potentially valuable resources while identifying the scientific and technological barriers that must be addressed before pharmaceutical applications can be established.

Keywords: Assam tea, Tea-processing waste, Bioactive compounds, Pharmaceutical applications, Nanocarriers, Nanoencapsulation, Controlled drug delivery, Sustainable valorization.

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1. Introduction

The growing emphasis on sustainability has encouraged researchers and industries to explore ways of converting agricultural and agro-industrial waste into valuable resources. Conventional waste-management practices often focus on disposal, despite the possibility that residual biomass may contain compounds with potential economic and functional value. The recovery and reuse of suitable agro-industrial residues may improve resource efficiency and reduce waste generation. However, the sustainability of individual valorisation pathways depends on their material requirements, energy and solvent consumption, processing costs, and environmental impacts. In this context, the recovery of bioactive compounds from agricultural residues has attracted interest because it connects waste valorisation with opportunities for food, biotechnology, cosmetics, and pharmaceutical research [1].

Tea (*Camellia sinensis*) is an economically important crop cultivated and processed across several regions, including Assam, India. Tea processing generates different types of residual materials, depending on the production stage and processing method. These may include discarded leaves, coarse leaf fractions, stalks, and other plant-derived residues. Although the composition and potential uses of these materials vary, some tea-derived residues may contain polyphenols, catechins, caffeine, and other compounds of scientific interest. Their recovery could provide opportunities to improve the utilisation of tea-processing resources while reducing the amount of potentially valuable biomass directed towards disposal. Nevertheless, the composition of the residues must be established through appropriate chemical characterisation rather than assumed from the composition of commercially consumed tea.

The potential value of tea-processing waste extends beyond conventional waste management. Sustainable extraction and purification techniques may enable the recovery of selected compounds for further investigation in pharmaceutical and related applications. Conventional and emerging techniques have been investigated for extracting, purifying, and identifying tea polyphenols [2]. However, the presence of bioactive constituents does not automatically establish their therapeutic effectiveness or suitability for pharmaceutical use. Recovery efficiency, chemical stability, purity, biological activity, toxicity, and reproducibility are important considerations when evaluating the potential of extracted compounds. Furthermore, the use of advanced drug-delivery systems may offer approaches for addressing challenges associated with the solubility, stability, controlled release, and delivery of selected compounds, and recurring research themes. The bibliometrix package provides a systematic approach to bibliometric analysis and science mapping, while Biblioshiny provides a user interface for conducting these analyses

Bibliometric analysis can help examine the development and structure of a research field by identifying publication patterns, influential sources, contributing authors and countries, and collaboration networks. The bibliometrix package provides a systematic approach to bibliometric analysis and science mapping, while Biblioshiny provides a user interface for conducting these analyses [3]. In the present study, Biblioshiny is used to analyse the available tea-related bibliometric dataset, while a critical review connects the resulting research landscape with sustainable waste valorisation, bioactive recovery, and advanced drug-delivery applications. This combined approach provides a basis for identifying established research directions as well as areas requiring further investigation. However, the broader tea-research dataset must be distinguished from the narrower body of evidence specifically addressing Assam tea-processing waste and pharmaceutical formulation. Accordingly, this study aims to examine the research landscape surrounding tea-processing research and assess its relevance to the sustainable utilisation of Assam tea-processing waste. The study also seeks to identify opportunities and limitations associated with bioactive recovery and advanced drug-delivery systems, with particular attention to sustainability, material characterisation, extraction, formulation, and safety. By connecting bibliometric mapping with a critical assessment of the literature, the study seeks to develop a research direction for the responsible valorisation of tea-processing residues and the future investigation of their potential pharmaceutical applications.

1.1. Research objectives

The study has five objectives:

1. To map publication patterns, influential sources, contributing authors and countries, and major research themes in the available tea-related bibliometric dataset.
2. To examine the potential of tea-processing waste as a source of bioactive compounds for sustainable resource utilisation.
3. To critically assess extraction, purification, and characterisation approaches relevant to bioactive recovery.
4. To evaluate the opportunities and limitations associated with advanced drug-delivery systems for tea-derived compounds.
5. To identify research gaps and propose a sustainability-oriented framework for future research on Assam tea-processing waste.

Research questions

- RQ1: What are the major publication patterns and research themes in the available tea-related bibliometric dataset?
- RQ2: What opportunities exist for the sustainable recovery of bioactive compounds from tea-processing waste?
- RQ3: What technical and safety challenges affect the potential pharmaceutical application of recovered compounds?
- RQ4: How can advanced drug-delivery approaches contribute to the future development of tea-waste-derived pharmaceutical ingredients?
- RQ5: What research gaps should be addressed to support sustainable tea-waste valorisation?

2. Sustainable Valorisation of Tea-Processing Waste

Tea-processing waste represents a potential resource for sustainable production when residual plant materials can be converted into useful products rather than treated solely as waste. The concept of waste valorisation involves recovering material, chemical, or functional value from residues through suitable processing and utilisation pathways. In the tea sector, this approach can connect agricultural resource efficiency with waste reduction and the development of value-added applications. However, the feasibility of each pathway depends on the type of residue generated, its chemical composition, the quantity available, and the technical and economic requirements of recovery [4].

2.1 Tea-Processing Waste and Its Characteristics

Tea-processing residues may arise at different stages of leaf handling, sorting, processing, grading, and manufacturing. Depending on the production system, these materials may include rejected leaves,

coarse leaf fractions, stalks, dust, and other plant-derived residues [5]. These categories should not be treated as chemically identical because processing conditions, leaf maturity, storage, and exposure to heat or moisture can influence their composition [6]. In Assam, where tea production is an important agricultural activity, the systematic characterisation and utilisation of suitable processing residues could provide opportunities for improving resource efficiency. Nevertheless, the quantity and composition of waste generated at specific Assam tea-processing facilities must be established through empirical evidence.

2.2 Bioactive Compounds and Recovery Potential

Tea plants contain several classes of chemical constituents that have attracted scientific interest, including polyphenols, catechins, caffeine, and other plant-derived compounds [7]. Some of these constituents may remain in residual materials after processing, although their concentrations and recoverability can vary considerably. Therefore, the pharmaceutical potential of tea-processing waste should be evaluated through chemical characterisation rather than inferred from findings on fresh leaves or commercial tea extracts [8].

Bioactive recovery generally involves selecting an appropriate extraction procedure, separating the desired constituents, and assessing the purity and stability of the recovered material. Conventional solvent extraction and emerging techniques may be investigated according to the properties of the target compounds and the characteristics of the feedstock. The selection of a method should consider not only extraction yield but also solvent consumption, energy requirements, environmental impacts, process reproducibility, and the feasibility of scaling up operations. A sustainable recovery process should balance the quality of the recovered compounds with the resources required to obtain them.

2.3 Sustainability and Circular Resource Utilisation

The valorisation of tea-processing residues can be considered within a circular-economy perspective, in which materials are retained in productive use for as long as practicable [9]. Recovering valuable compounds from suitable residues may reduce the need to discard potentially useful biomass and may create additional value from existing production systems [10]. Other residual fractions may also be assessed for appropriate non-pharmaceutical uses, depending on their composition and safety characteristics.

However, sustainability should not be assumed solely because a process uses agricultural waste as its raw material. Solvent selection, water and energy consumption, waste generation, chemical recovery, transportation, and processing costs can affect the overall environmental performance of a recovery pathway. Consequently, future investigations should evaluate environmental and economic performance

alongside technical efficiency. Life-cycle assessment and techno-economic analysis may provide useful approaches for comparing alternative processing routes when sufficient process data are available.

2.4 Relevance to Advanced Drug-Delivery Systems

Advanced drug-delivery systems may provide opportunities to formulate selected tea-derived compounds where limitations such as poor aqueous solubility, chemical instability, or inadequate release characteristics have been demonstrated [11]. Depending on the compound and intended application, research may investigate polymeric nanoparticles, lipid-based carriers, nanoemulsions, or other suitable formulation platforms [12]. These systems should be selected according to the properties of the recovered compound and the requirements of the intended delivery route.

The development of a delivery system requires more than the preparation of a formulation. Relevant evaluation criteria may include particle size and distribution, encapsulation efficiency, loading capacity, stability, release behaviour, compatibility, and safety. The biological performance of the formulation must also be established using appropriate experimental models. Furthermore, a successful formulation containing a tea-derived compound does not, by itself, establish that the compound can be recovered efficiently or sustainably from industrial tea-processing waste. The connection between the original residue, the recovered compound, and the final formulation must therefore be documented.

2.5 Research Challenges and Future Direction

Several challenges need to be addressed before tea-processing waste can be established as a reliable source of pharmaceutical ingredients. These include variability in feedstock composition, the identification and purification of target compounds, the selection of environmentally responsible extraction methods, and the assessment of contaminants and potential toxicological risks. Additional challenges include batch-to-batch consistency, formulation stability, manufacturing scalability, regulatory requirements, and the economic feasibility of commercial production.

A systematic research approach should consequently connect residue characterisation, extraction and purification, compound identification, formulation development, biological evaluation, and sustainability assessment. Bibliometric analysis can help identify the broader research themes and potential areas of limited scholarly attention, while a critical review can evaluate whether existing studies provide sufficient evidence to support the proposed applications. This distinction is particularly important when interpreting general tea research in relation to the more specific objective of developing

sustainable pharmaceutical applications from Assam tea-processing waste.

3. Literature Survey

Following the layout of your reference paper, this section will review previous studies, compare their research approaches and findings, and identify the gaps that justify the study. The literature survey should connect four areas: tea bioactive compounds, tea-processing-waste utilisation, sustainable extraction technologies, and advanced drug-delivery systems. A key requirement is to distinguish studies using actual tea-processing residues from those examining fresh tea leaves, conventional tea extracts, or isolated compounds.

3.1 Review of Previous Studies

Research on tea waste has increasingly examined its chemical composition, bioactive constituents, extraction technologies, and potential value-added applications. [5] Reviewed the composition, bioactivity, extraction methods, and utilisation of tea waste. Their review identified compounds such as polyphenols, caffeine, proteins, and fibre, while highlighting the need for further research on bioactive recovery and utilisation.

[4] examined recent advances in tea-waste processing and high-value applications, including thermal conversion, bioconversion, packaging materials, nanocomposites, and biochar. This work broadens the understanding of tea waste beyond conventional disposal and demonstrates the diversity of potential valorisation pathways.

Research on extraction technologies has also considered approaches such as ultrasound-assisted extraction, microwave-assisted extraction, pressurised liquid extraction, pulsed electric fields, and supercritical-fluid extraction. These techniques offer different possibilities for improving compound recovery, although their performance depends on the material, target compound, and operating conditions. Results obtained from tea leaves or conventional extracts must therefore be distinguished from those obtained specifically from industrial processing residues.

More recently, reviews of tea-waste management have examined resource recovery within a circular-bioeconomy perspective, including energy production, environmental remediation, material development, and bioactive extraction. These studies support the broader sustainability rationale for tea-waste utilisation, while also identifying challenges relating to feedstock variability, economic feasibility, scalability, and environmental assessment.

3.2 Comparative Analysis of Previous Studies

The previous studies were compared based on their research objectives, methodological approaches, principal findings, and limitations to identify research gaps concerning the pharmaceutical valorisation of Assam tea-processing waste and its potential application in advanced drug-delivery

systems. The key studies identified to date are summarized in the Table 1 below.

Table 1. Comparative analysis of previous studies.

S	Auth	Rese	Revie	Princip	Limita
	or(s)	arch	w or	al	tions
N	and	objec	analy	finding	and
o	publi	tive	tical	s	relevan
.	catio	and	appr		ce to
	n	scope	oach		the
	year				present
					review
1	[5]	Comp osition and valorisation of tea waste	Litera ture review	Examin ed bioacti ve constitu ents, extracti on	Further evidenc e is needed on efficien t recover y and specific pharma ceutical applica tions of Assam process ing residue s.
2	[4]	High- value tea- waste applic ations	Revie w of proce ssing and utilisa tion techn	Examin ed thermal and biologi cal convers ion, biochar ,	The relation ship betwe n sustain able waste convers ion,

Literature Review						Research Methodology			
Study ID	Author(s)	Title	Year	Journal	Findings	Methodology	Data Collection	Analysis	Conclusion
1	Smith et al.	Effect of Temperature on the Growth of Bacteria	2018	Journal of Microbiology	Bacterial growth is significantly higher at 37°C compared to 25°C.	Lab experiment	Incubation at different temperatures	Quantitative analysis of growth curves	Optimal growth temperature is 37°C.
2	Johnson et al.	Impact of pH on Enzyme Activity	2019	Enzymes International	Enzyme activity is highest at pH 7.0 and decreases as pH deviates from neutrality.	In vitro assay	Measurement of reaction rate at various pH levels	Statistical analysis of reaction rates	Enzyme is most active at neutral pH.
3	[13]	Extra-Cellular Matrix (ECM) and its Role in Cell Differentiation	2020	Developmental Biology	ECM components play a crucial role in regulating cell fate and differentiation.	Review of literature	Analysis of various ECM components and their effects	Comparative analysis of different ECM models	ECM is essential for proper cell differentiation.
4	[14]	Bioremediation of Heavy Metals Using Microorganisms	2021	Environmental Science	Microorganisms can effectively degrade and immobilize heavy metals in contaminated soil.	Field study	Monitoring of metal concentrations over time	Chemical analysis of soil samples	Bioremediation is a promising method for heavy metal cleanup.
5	[15]	Sustainable Waste Management Practices for the Future	2022	Environmental Management	Implementing sustainable waste management practices can reduce environmental pollution and conserve resources.	Case study	Analysis of various waste management strategies	Economic and environmental impact assessment	Sustainable waste management is crucial for a better future.

	cycle	warrant
	assess	specific
	ment.	examin
		ation.

Source: Authors

3.3 Research Gap

The reviewed literature provides a foundation for understanding tea-waste composition, extraction technologies, and sustainable resource utilisation. However, the relevance of these findings to pharmaceutical development depends on whether the studies investigate actual tea-processing residues, conventional tea extracts, or purified compounds. These material differences must be considered when assessing the contribution of previous research to the proposed application. However, three issues are particularly relevant to the present study.

First, tea-waste research encompasses multiple materials, including spent tea leaves, manufacturing residues, discarded plant parts, and conventional tea extracts. These materials differ in origin and composition, making it necessary to identify precisely which residue types are relevant to Assam tea processing.

Second, sustainable bioactive recovery and pharmaceutical application involve distinct stages. Identifying potentially valuable compounds does not establish that they can be recovered economically, formulated effectively, or used safely. The relationship between extraction performance, formulation characteristics, biological activity, and environmental performance therefore requires careful evaluation.

Third, the broader research landscape identified through Biblioshiny needs to be connected explicitly with the narrower focus of this paper. The bibliometric analysis can reveal prominent themes, publication patterns, and research relationships, while the critical review can assess the extent to which those themes support the proposed pathway from tea-processing waste to pharmaceutical applications.

Accordingly, this study seeks to connect bibliometric mapping of tea-related research with a critical assessment of sustainable bioactive recovery and advanced drug-delivery opportunities, with particular attention to Assam tea-processing waste. Its contribution lies in bringing these themes together in a sustainability-oriented research framework rather than assuming that the existing literature has already established the pharmaceutical effectiveness of the waste material.

4. Research Methodology

This study employed a combined bibliometric analysis and critical literature review to examine the broader tea-related research landscape and assess its

relevance to the sustainable valorisation of tea-processing waste and potential pharmaceutical applications. Bibliographic records were retrieved from Scopus and analysed using Biblioshiny, the web-based interface of the Bibliometrix package in R. The analysis examined publication patterns, publication sources, author and institutional contributions, country-level research output, and keyword patterns. The results were interpreted alongside relevant literature on tea-waste characterisation, bioactive recovery, extraction and purification, nanocarrier formulation, safety, and sustainability.

5. Bibliometric Analysis and Research Framework

The bibliometric analysis examines the development of research on tea and its potential for sustainable resource utilisation. Using Biblioshiny, the study analyses publication trends, leading journals, influential authors, institutional contributions, country-wise research output, and keyword co-occurrence. These indicators help identify major research themes and emerging areas in tea research. Particular attention is given to the sustainable utilisation of tea-processing waste, bioactive compound recovery, and potential pharmaceutical applications. The findings provide a basis for identifying research gaps and developing a framework that connects waste valorisation, bioactive extraction, sustainability, and drug-delivery applications.

5.1 Publication Trends and Growth

The Scopus dataset comprises 219 documents distributed across 144 sources during the reported period of 2020–2027. The publications cover several areas, including tea chemistry, food science, biomass utilisation, environmental assessment, and tea processing. These research areas provide a broader context for investigating the sustainable valorisation of tea-processing waste and its potential pharmaceutical applications.

Table 2. Overview of the bibliometric dataset

Description	Results
MAIN INFORMATION ABOUT DATA	
	2020:202
Timespan	7
Sources (Journals, Books, etc)	144
Documents	219
Annual Growth Rate %	-31.41
Document Average Age	2.24
Average citations per doc	12.94
References	13994
DOCUMENT CONTENTS	

Keywords Plus (ID) 2912

Author's Keywords (DE) 826

AUTHORS

Authors 1037

Authors of single-authored docs 3

AUTHORS COLLABORATION

Single-authored docs 3

Co-Authors per Doc 6.47

International co-authorships % 16.44

DOCUMENT TYPES

Article 166

Book 2

book chapter 9

conference paper 10

Erratum 1

Review 31

Source: Scopus data analysed using Biblioshiny.

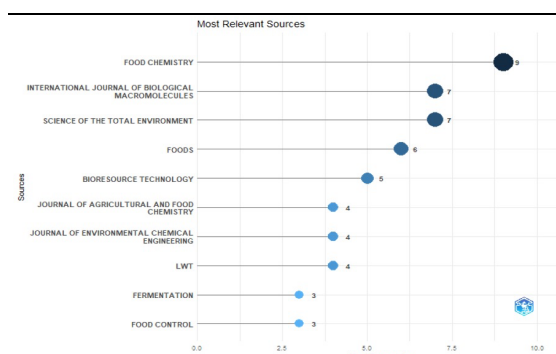
5.2 Leading Journals and Publication Sources

The source analysis identifies journals represented in the tea-related dataset, spanning food chemistry, environmental science, agricultural chemistry, and biomass utilisation. To establish their relative contribution, the sources should be compared using verified publication counts and, where appropriate, citation-based indicators. As presented in Table 3, these sources cover food chemistry, biological macromolecules, environmental science, agricultural chemistry, and biomass utilisation. Their presence highlights the multidisciplinary nature of the field and provides potential publication outlets for research on sustainable tea-waste valorisation.

Table 3. Prominent publication sources in the analysed dataset

S. No.	Journal name	Major research area
1	Food Chemistry	Food composition and chemical analysis
2	International Journal of Biological and Macromolecules	Biomolecules and bioactive materials

3	Science of the Total Environment	Environmental science and sustainability
4	Foods	Food science and technology
5	Bioresource Technology	Biomass and resource recovery
6	Journal of Agricultural and Food Chemistry	Agricultural and food chemistry
7	Journal of Environmental Chemical Engineering	Environmental and chemical processes
8	LWT	Food science and processing
9	Fermentation	Fermentation and bioprocessing
10	Food Control	Food safety and quality
11	Food Research International	Food science and applied research



Source: Scopus data analysed using Biblioshiny.

Source: Scopus data analysed using Biblioshiny.

5.3 Leading Authors and Institutional Contributions

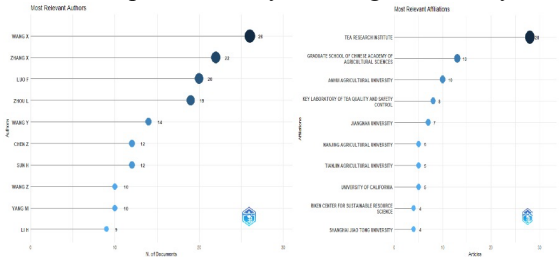
The Biblioshiny analysis identifies several active contributors and research institutions in the tea-related literature. As shown in Table 4, Wang X, Zhang X, Luo F, Zhou L, Wang Y, and Chen Z are among the visible authors. The institutional results include the Tea Research Institute, Anhui Agricultural University, Jiangnan University, and Nanjing Agricultural University. These

contributions indicate the involvement of agricultural and scientific institutions in tea research, including its chemical composition, quality, processing, and potential resource applications.

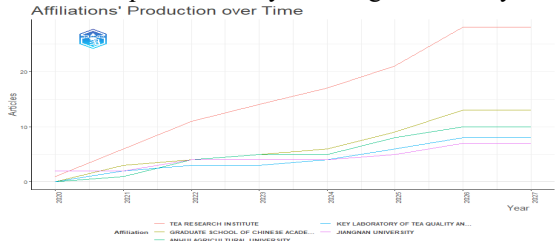
Table 4. Prominent authors and research institutions

Category	Names identified in the Biblioshiny output	
Leading authors	Wang X, Zhang X, Luo F, Zhou L, Wang Y, Chen Z	
Additional authors	Sun H, Wang Z, Yang M, Li H, Guo M	
Research institutions	Tea Research Institute; Anhui Agricultural University	
Additional institutions	Jiangnan University; Nanjing Agricultural University	
Other affiliations	Graduate School of Chinese Academy of Agricultural Sciences; Sichuan University	

Source: Scopus data analysed using Biblioshiny.



Source: Scopus data analysed using Biblioshiny.



Source: Scopus data analysed using Biblioshiny.

5.4 Country-Wise Research Contributions

The Biblioshiny analysis indicates contributions from several countries, with China and India among the visible contributors to tea-related research. Other countries represented include the United States, Japan, Indonesia, Thailand, Spain, Egypt, Turkey,

and Brazil. This geographical distribution reflects the international scope of research on tea chemistry, processing, quality assessment, and resource utilisation.

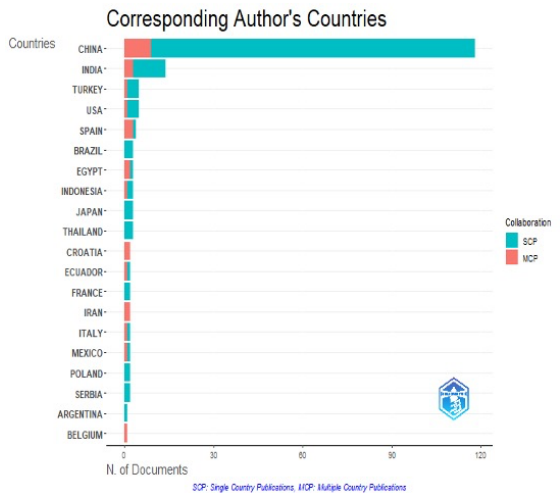


Table 5. Countries represented in the tea-related research dataset

S. No.	Country
1	China
2	India
3	United States
4	Japan
5	Indonesia
6	Thailand
7	Spain
8	Egypt
9	Turkey
10	Brazil

Source: Scopus data analysed using Biblioshiny.

5.5 Keyword Analysis and Major Research Themes

The Biblioshiny keyword analysis identifies recurring terms such as tea, chemistry, pesticide residues, Camellia sinensis, biomass, risk assessment, liquid chromatography, mass spectrometry, and tea processing. The identified keywords indicate that the dataset encompasses tea composition, analytical characterisation, food safety, and biomass utilisation. These patterns describe the broader tea-research landscape but do not, on their own, establish the prominence of pharmaceutical bioactive recovery or advanced drug-delivery systems.

Table 6. Major research themes identified through keyword analysis

Keywords	Identified theme	research
Tea; Camellia sinensis	Tea cultivation and general tea research	
Chemistry; amino acids	Chemical composition and constituent analysis	
Pesticide residues; crop residues	Food safety and residue assessment	
Liquid chromatography; mass spectrometry	Analytical characterisation	
Biomass; tea processing; food processing	Processing residues and resource utilisation	
Risk assessment; pesticides	Safety and contamination assessment	
Fermentation	Processing and potential transformation of tea materials	

Source: Scopus data analysed using Biblioshiny.



Source: Scopus data analysed using Biblioshiny.

5.6 Research Gaps and Proposed Research Framework

The bibliometric findings reveal a multidisciplinary body of tea-related research covering chemical characterisation, processing, biomass utilisation, and safety assessment. However, further investigation is needed to connect these areas with the pharmaceutical valorisation of tea-processing waste. Table 7 presents the major research gaps and corresponding research opportunities.

Table 7. Research gaps and future research opportunities

Identified research gap	Proposed research direction
Limited distinction between tea extracts and processing waste	Classify residues by source, processing stage, and composition

Variability in bioactive compounds	Develop standardised extraction and characterisation protocols
Potential contamination and impurities	Conduct systematic safety and quality assessments
Limited integration of recovery and formulation research	Investigate the suitability of recovered compounds for drug-delivery systems
Uncertain environmental and economic feasibility	Evaluate resource efficiency, life-cycle impacts, and processing costs

Based on these gaps, this study proposes a framework linking tea-processing waste identification, bioactive compound extraction, chemical characterisation, safety assessment, formulation development, and sustainability evaluation. The framework provides a structured pathway for investigating Assam tea-processing residues as potential sources of value-added pharmaceutical ingredients.



Figure 1. Proposed framework for sustainable valorisation of Assam tea-processing waste.

4. Tea-Processing Waste as a Source of Pharmaceutical Bioactives

Tea-processing residues may contain recoverable bioactive compounds, although their composition and concentrations depend on the residue type, processing conditions, and storage history. Their suitability for pharmaceutical research therefore requires material-specific chemical characterisation and evidence of consistent recovery [16]. Tea residues contain varying quantities of polyphenols, catechins, caffeine, and other chemical constituents, depending on the raw material, processing conditions, and storage practices [17]. The recovery of these compounds offers opportunities for sustainable waste utilisation and value-added product development. However, their

pharmaceutical suitability depends on chemical composition, purity, safety, and consistency across batches.

4.1 Types of Tea-Processing Residues

Tea-processing residues are generated during harvesting, manufacturing, packaging, and consumption. These materials differ in their chemical characteristics and potential applications [18]. Table 7 presents the major categories of tea-derived residues and their relevance to bioactive compound recovery.

Table 7. Types of tea-processing residues and their potential research applications

Tea-processing residue	Potential research application	Major limitation
Rejected or damaged tea leaves	Recovery of polyphenols and other bioactive compounds	Variation in chemical composition
Tea dust and processing fragments	Extraction of soluble bioactive constituents	Particle-size variation and contamination
Spent tea leaves	Recovery of remaining bioactive compounds	Depletion of soluble compounds
Pruned tea leaves and stems	Alternative biomass utilisation	Differences in chemical composition
Mixed factory residues	Integrated waste valorisation	Difficulties in standardisation

Source: Conceptual synthesis of tea-waste utilisation literature. The applications listed require experimental validation.

For Assam's tea industry, rejected leaves, tea dust, and factory residues may provide opportunities for sustainable bioactive recovery. However, appropriate feedstock selection requires consideration of material availability, chemical consistency, storage conditions, contamination risks, and extraction costs [18].

4.2 Major Bioactive Compounds in Tea-Processing Waste

Tea contains several biologically relevant constituents, particularly polyphenols, catechins, caffeine, and other phenolic compounds. Among these, epigallocatechin gallate (EGCG), epigallocatechin, epicatechin gallate, and epicatechin have attracted research attention because of their chemical properties and potential biological activities [19]. These compounds are also investigated in pharmaceutical formulation and drug-delivery research. Nevertheless, their concentrations in processing residues may differ considerably from those in fresh tea leaves, making chemical analysis essential before further utilisation.

4.3 Chemical Characterisation and Standardisation

Chemical characterisation is essential for evaluating the pharmaceutical potential of tea-processing waste. Techniques such as high-performance liquid chromatography (HPLC) and liquid chromatography–mass spectrometry (LC–MS) can be used to identify and quantify selected bioactive compounds. Additional assessments should examine moisture content, chemical stability, pesticide residues, heavy metals, and microbial contamination. Standardisation across different processing batches is particularly important to ensure reproducibility, extract quality, and suitability for subsequent pharmaceutical formulation studies [20].

The recovery of bioactive compounds from Assam tea-processing residues could contribute to circular bioeconomy initiatives by converting industrial by-products into potentially valuable materials. However, pharmaceutical applications require systematic evaluation of extraction efficiency, compound stability, safety, and regulatory requirements.

5. Extraction and Purification of Tea-Derived Compounds

The extraction and purification of bioactive compounds are essential steps in converting tea-processing waste into potentially useful pharmaceutical ingredients. The effectiveness of these processes depends on the type of residue, target compounds, solvent selection, and operating conditions [21,22]. Sustainable extraction methods should aim to improve compound recovery while minimizing energy consumption, solvent use, and chemical degradation.

5.1 Conventional Extraction Methods

Solvent extraction is commonly used to recover polyphenols and other soluble constituents from tea materials [23]. Water, ethanol, and water–ethanol mixtures may be selected according to the chemical properties of the target compounds and the intended application [24]. Extraction efficiency is influenced by temperature, extraction time, particle size, solvent composition, pH, and the solid-to-liquid

ratio. However, maximizing the total extract yield does not necessarily produce the highest-quality extract, as unwanted substances may also be recovered. Therefore, extraction conditions should be optimized to achieve both effective recovery and suitable chemical composition.

5.2 Emerging Extraction Technologies

Emerging techniques, including ultrasound-assisted extraction, microwave-assisted extraction, pressurized extraction, and supercritical-fluid-based extraction, offer alternative approaches to recovering bioactive compounds [25]. Depending on the material and process conditions, these techniques may improve extraction efficiency, reduce processing time, or limit solvent consumption. Their suitability should be assessed based on target-compound recovery, selectivity, chemical stability, energy requirements, environmental impact, and reproducibility. Further evaluation is necessary before assuming that laboratory-scale advantages will translate into cost-effective industrial applications.

5.3 Purification and Preparation of Standardized Extracts

Following extraction, purification may be required to remove unwanted constituents and improve the consistency of the recovered material. Filtration, membrane separation, adsorption, and chromatographic techniques can be selected according to the extract's composition and the required purity [26]. A standardized botanical extract should be distinguished from an isolated chemical compound because each requires different quality specifications. For Assam tea-processing waste, batch identification, chemical profiling, and reproducible processing procedures would help ensure that variations in the starting material do not compromise subsequent formulation development. Overall, sustainable extraction and purification provide the foundation for investigating tea-derived bioactives in pharmaceutical applications. The selection of an appropriate method should balance recovery efficiency, chemical quality, environmental performance, and economic feasibility.

6. Nanocarrier Technologies for Tea-Derived Bioactives

Nanocarrier technologies are being investigated to improve the stability, dispersion, and delivery of selected bioactive compounds. Tea-derived polyphenols, including catechins, may be explored using different carrier platforms depending on their chemical properties and the intended application [27]. However, the suitability of these systems for extracts obtained from Assam tea-processing waste requires experimental validation.

6.1 Polymeric Nanoparticles

Polymeric nanoparticles can encapsulate or associate with selected bioactive compounds. Materials such as chitosan, alginate, and other suitable polymers may be investigated to achieve

desirable particle characteristics and release profiles [28]. Their performance depends on polymer composition, formulation conditions, and interactions between the carrier and the extracted compounds. Crude tea-waste extracts may behave differently from purified catechins because they contain multiple constituents that can influence particle formation and stability.

6.2 Lipid-Based Nanocarriers

Lipid-based systems, including liposomes and solid lipid nanoparticles, offer alternative approaches for incorporating selected bioactive compounds [29]. Liposomes contain lipid bilayers surrounding an aqueous compartment, whereas solid lipid nanoparticles use a solid lipid matrix. Their suitability depends on the characteristics of the target compound and the intended formulation. Important evaluation parameters include particle size, encapsulation efficiency, storage stability, compound leakage, and chemical degradation.

6.3 Nanoemulsions and Related Systems

Nanoemulsions may improve the dispersion of suitable compounds in liquid formulations. Their properties depend on the oil phase, surfactant composition, droplet size, and compatibility of the ingredients. Unlike polymeric nanoparticles and liposomes, nanoemulsions have distinct structural characteristics and should be evaluated using appropriate methods. Improved dispersion alone does not demonstrate enhanced bioavailability, therapeutic effectiveness, or safety [30].

6.4 Comparison of Potential Carrier Platforms

Table 8. Potential nanocarrier platforms for tea-derived bioactives

Carrier platform	Potential advantage	Key evaluation parameter
Polymeric nanoparticles [31]	Adjustable composition and release properties	Particle stability and polymer compatibility
Liposomes [32]	Incorporation of compounds in aqueous or lipid compartments	Encapsulation efficiency and leakage

Solid lipid nanoparticles [33]	Lipid-based incorporation of selected compounds	Loading capacity and storage stability
Nanoemulsions [34]	Improved dispersion of suitable compounds	Droplet size and physical stability
Biopolymer-based carriers [34]	Potential use of biodegradable materials	Biocompatibility and reproducibility

Source: Conceptual comparison of potential formulation platforms.

The choice of carrier should be guided by the target compound, intended route of administration, formulation objectives, safety requirements, and manufacturing feasibility. Future research should directly compare selected platforms using chemically characterised tea-waste extracts rather than assuming that results obtained with purified compounds will apply equally to complex extracts.

7. Encapsulation Efficiency, Stability, and Controlled Release

The performance of nanocarrier-based formulations depends on their ability to incorporate bioactive compounds, maintain stability, and release the encapsulated material under defined conditions. For tea-derived compounds, these properties require careful evaluation because extract composition and interactions between bioactives and carrier materials may influence formulation performance.

7.1 Encapsulation Efficiency and Loading Capacity

Encapsulation efficiency represents the proportion of the initial target compound successfully incorporated into or associated with a carrier, whereas loading capacity indicates the amount of compound present relative to the mass of the formulation or carrier, depending on the calculation used [35]. Both parameters are important for comparing formulations. For tea-waste extracts, analytical methods should distinguish selected compounds, such as catechins, from other extract constituents to ensure reliable measurements.

7.2 Physicochemical Stability

Tea polyphenols may undergo chemical changes when exposed to unfavourable temperature, light, oxygen, or pH conditions. Nanocarriers may help protect selected compounds, but the degree of protection must be demonstrated experimentally [36]. Stability studies should assess particle size,

size distribution, surface charge where relevant, changes in compound concentration, precipitation, and potential degradation during storage. Testing extracts from different batches may also reveal whether compositional variability affects formulation stability.

7.3 Controlled-Release Mechanisms

Controlled release involves regulating the rate or pattern at which an encapsulated compound becomes available [37]. Depending on the formulation, release may occur through diffusion, matrix swelling, carrier erosion, dissolution, or combinations of these processes. Release studies should clearly report the experimental medium, temperature, sampling intervals, and analytical methods. Mathematical models such as zero-order, first-order, Higuchi, and Korsmeyer–Peppas may be used to examine release patterns. However, a good statistical fit alone does not establish the underlying release mechanism; interpretation must also consider the carrier's physical properties and the assumptions of each model.

7.4 Bioavailability and Biological Relevance

Improved encapsulation or slower release does not necessarily indicate enhanced bioavailability or therapeutic effectiveness. These outcomes depend on additional factors, including compound stability, dissolution, absorption, metabolism, and the intended route of administration [37]. Preliminary in-vitro studies can support formulation comparisons, while further biological or clinical evaluation requires appropriate study design, controls, and ethical oversight where applicable.

For Assam tea-processing waste, the distinction between crude extracts and purified compounds is particularly important. Their chemical complexity may influence formulation behaviour and biological responses. Therefore, pharmaceutical potential should be established through systematic chemical, physicochemical, biological, and safety evaluations rather than inferred from encapsulation efficiency alone.

8. Pharmaceutical Applications and Strength of Evidence

Tea-derived bioactive compounds have attracted research interest because of their potential biological properties and suitability for formulation research. However, the pharmaceutical relevance of tea-processing waste must be assessed according to the type and strength of available evidence. Findings from purified tea compounds cannot automatically be generalised to extracts obtained from Assam tea-processing residues.

8.1 Antioxidant and Other Biological Properties

Tea polyphenols are widely investigated for antioxidant activity and other biological effects. Nevertheless, results from chemical antioxidant assays do not directly establish clinical benefits because laboratory measurements may not reflect absorption, metabolism, or biological activity in the

human body. Pharmaceutical development should therefore begin with a clearly defined intended application and appropriate experimental evaluation [38].

8.2 Drug-Delivery Applications

Tea-derived materials may be investigated in three distinct ways: as bioactive compounds encapsulated within a carrier, as components contributing to a delivery system, or as materials incorporated into a carrier used to deliver another pharmaceutical ingredient [39]. Each approach requires separate evaluation of chemical composition, compatibility, release behaviour, and safety. These applications remain research possibilities for Assam tea-processing waste until supported by relevant experimental evidence.

9. Safety, Quality Control, and Regulatory Considerations

The development of pharmaceutical products from tea-processing waste requires careful assessment of raw-material safety, formulation quality, manufacturing consistency, and regulatory compliance [40]. Although tea is widely consumed, concentrated extracts and nanocarrier-based formulations may have different safety profiles from conventional tea products. Therefore, the potential pharmaceutical use of Assam tea-processing residues must be supported by systematic quality and safety evaluation.

9.1 Raw-Material Safety

Tea-processing residues may contain contaminants originating from cultivation, manufacturing, storage, or handling. Depending on the source material and intended application, evaluation should include pesticide residues, heavy metals, microbial contamination, foreign matter, and relevant degradation products [41]. Residues collected from different factories should be assessed separately where necessary, as their composition and contamination profiles may vary. Traceable collection, appropriate storage, and documented pretreatment procedures are essential for maintaining material quality.

9.2 Nanocarrier Safety

The safety of nanocarrier formulations depends on carrier composition, particle characteristics, exposure level, and the intended route of administration [36]. The use of natural or biodegradable materials does not automatically establish biocompatibility. Assessment should consider the carrier, encapsulated compounds, residual processing chemicals, and final formulation. Depending on the intended application, relevant testing may include cytotoxicity, irritation, systemic toxicity, and other appropriate safety endpoints.

9.3 Standardisation and Manufacturing

Standardisation should be maintained throughout the development process, from raw-material selection and extraction to the final formulation.

Quality-control measures may include target-compound content, impurity limits, residual solvents, microbial quality, particle characteristics, and stability [42]. Manufacturing scale-up also requires attention because changes in equipment and processing conditions can affect extraction yield, particle properties, and release behaviour. Reproducibility studies are therefore necessary before considering larger-scale production.

9.4 Regulatory Considerations

Regulatory requirements depend on the product's intended use, composition, claims, administration route, and target jurisdiction. A pharmaceutical product may face different requirements from a food ingredient or nutraceutical. Accordingly, therapeutic claims should not be made without appropriate supporting evidence. Early consultation with regulatory specialists can help identify the quality, safety, and preclinical requirements relevant to the proposed product category [43].

Overall, a reliable pathway for the pharmaceutical valorisation of Assam tea-processing waste must integrate traceable sourcing, chemical standardisation, formulation quality, safety assessment, and regulatory planning. These requirements are essential for determining whether waste-derived materials can be developed into consistent and suitable pharmaceutical products.

10. Research Gaps and Future Directions

Although tea-waste valorisation and tea-derived bioactive delivery systems are important research areas, further investigation is needed to establish the pharmaceutical potential of Assam tea-processing waste. The following research priorities emerge from the bibliometric findings and critical review.

10.1 Assam-Specific Material Characterisation

Future studies should examine tea-processing residues collected from different sources in Assam to identify their chemical composition, bioactive content, and contamination profiles. Comparing production batches and processing histories would help determine whether selected residues provide a consistent source of target compounds.

10.2 Standardised Extraction and Recovery

Comparative studies should evaluate conventional and emerging extraction techniques using measures such as target-compound recovery, selectivity, chemical stability, solvent consumption, energy requirements, and reproducibility. The objective should be to identify methods that produce consistent extracts while supporting sustainable processing.

10.3 Formulation Using Waste-Derived Extracts

Research should directly investigate nanocarriers prepared using chemically characterised tea-waste extracts. Comparing these formulations with those containing purified tea compounds would help establish how the extract matrix influences particle formation, encapsulation efficiency, stability, and release behaviour.

10.4 Comparative Evaluation of Nanocarriers

Selected carrier platforms should be compared under consistent experimental conditions. Relevant parameters include particle size, loading capacity, encapsulation efficiency, storage stability, release kinetics, and material compatibility. Such comparisons would provide a stronger basis for selecting suitable delivery systems.

10.5 Safety and Biological Evaluation

Future research should progress from chemical characterisation and physicochemical testing to appropriate biological and toxicological evaluation. The selection of tests should depend on the intended application and preliminary findings. Claims of improved therapeutic efficacy must be supported by relevant comparative evidence rather than inferred from encapsulation or release results alone.

10.6 Sustainability and Economic Feasibility

The environmental and economic viability of the proposed pathway should be assessed alongside technical performance. Important considerations include residue collection, extraction yield, solvent recovery, energy consumption, purification costs, waste generation, and manufacturing scale-up. Waste-derived materials should not automatically be considered sustainable without evaluating the resources required for processing.

Overall, these research priorities highlight the need for an integrated approach connecting Assam-specific residue characterisation, bioactive recovery, formulation development, safety evaluation, and sustainability assessment. Addressing these gaps would help determine whether tea-processing waste can serve as a reliable and economically viable resource for pharmaceutical research.

11. Proposed Research Framework for Assam Tea-Processing Waste

Based on the bibliometric findings and critical review, a conceptual framework is proposed to evaluate the pharmaceutical potential of Assam tea-processing waste. The framework connects residue selection, chemical characterisation, bioactive recovery, nanocarrier formulation, performance evaluation, and sustainable scale-up. It provides a structured pathway for future research rather than a validated experimental model.

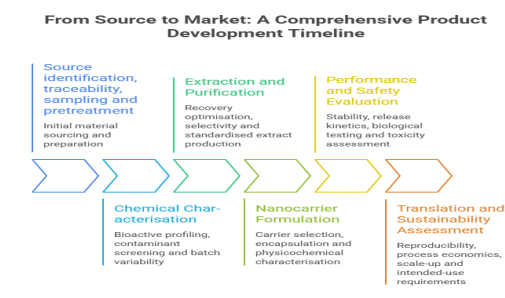


Figure 2. Proposed conceptual framework for evaluating the pharmaceutical potential of Assam tea-processing waste.

The framework emphasises that pharmaceutical development is a sequential process. Inconsistent raw materials or inadequate extract quality may compromise subsequent formulation performance. Similarly, promising encapsulation or release results are insufficient without appropriate safety evidence and reproducible manufacturing processes. For Assam tea-processing waste, the initial priority should be to identify suitable residues, characterise their chemical composition, and determine whether their bioactive compounds can be recovered consistently. Nanocarrier development should follow only after adequate characterisation and standardisation. Finally, technical performance should be assessed alongside safety, economic feasibility, and environmental sustainability.

12. Discussion

The bibliometric analysis provides an overview of the research landscape surrounding tea, its chemical composition, processing residues, biomass utilisation, analytical characterisation, and related environmental and food-safety concerns. The dataset comprises 219 documents from 144 sources, indicating a diverse body of literature distributed across several research disciplines. The presence of journals such as Food Chemistry, International Journal of Biological Macromolecules, Bioresource Technology, and Science of the Total Environment reflects the multidisciplinary nature of tea-related research. The keyword patterns indicate that existing research covers tea chemistry, pesticide residues, biomass, fermentation, crop residues, amino acids, and analytical techniques, including liquid chromatography and mass spectrometry. These themes provide a foundation for investigating the composition and potential utilisation of tea-processing residues. However, the bibliometric results should not be interpreted as direct evidence that pharmaceutical applications or advanced drug-delivery systems are established research priorities within the dataset. Rather, they identify related areas of knowledge that may support further investigation of these applications. A key implication of the review is the need to connect research on tea-derived bioactive compounds with the specific challenges of pharmaceutical development. Identifying potentially valuable compounds is only an initial step. Their recovery, purification, chemical stability, reproducibility, and suitability for formulation must also be evaluated. In particular, the composition of tea-processing waste may vary according to the residue type, processing conditions, storage practices, and source. Such variation highlights the importance of chemical characterisation and standardisation before developing pharmaceutical formulations. Nanocarrier technologies offer a potential route for improving the formulation characteristics of selected tea-derived compounds. Polymeric nanoparticles, liposomes, solid lipid nanoparticles, and nanoemulsions may be

investigated for their ability to improve compound protection, dispersion, stability, or release behaviour. Nevertheless, the suitability of these systems depends on the properties of the active compound, the intended delivery route, and the formulation requirements. Improved encapsulation efficiency or controlled release alone does not establish enhanced bioavailability, therapeutic efficacy, or safety. The proposed framework extends these insights to Assam tea-processing waste by establishing a systematic pathway from residue selection to sustainability assessment. It places raw-material characterisation and extraction standardisation before nanocarrier development, while incorporating performance evaluation and safety considerations into the later stages. This sequence is particularly relevant for determining whether waste-derived materials can be converted into consistent, reproducible, and economically feasible pharmaceutical ingredients. The study's contribution lies in bringing together bibliometric mapping and a critical, application-oriented review to identify potential research directions at the intersection of tea-waste valorisation, bioactive recovery, and advanced drug delivery. However, because the analysed dataset covers broader tea-related research, the findings do not independently establish the size of the pharmaceutical research gap. A more targeted bibliometric search focusing specifically on tea-processing waste, bioactive extraction, nanocarriers, and pharmaceutical applications would help verify the extent and development of this specialised research area.

Overall, the findings support further investigation of Assam tea-processing waste as a potential resource for high-value applications. Progress in this area will require interdisciplinary research integrating tea chemistry, extraction engineering, pharmaceutical formulation, toxicology, and sustainability assessment.

13. Conclusion and Future Research Directions

This study combines bibliometric analysis with a critical review to examine the potential of tea-processing waste as a source of bioactive compounds for pharmaceutical applications, with particular reference to Assam. The bibliometric findings reveal a multidisciplinary tea-research landscape encompassing chemical characterisation, biomass utilisation, food safety, fermentation, and environmental management. These areas provide a foundation for exploring higher-value applications of tea-processing residues, although the pharmaceutical potential of Assam-specific waste requires further targeted investigation.

The review identifies bioactive recovery, extraction and purification, nanocarrier formulation, stability, controlled release, and safety assessment as interconnected areas for future research. Technologies such as polymeric nanoparticles, liposomes, solid lipid nanoparticles, and

nanoemulsions may offer opportunities to investigate the delivery of selected tea-derived compounds. Previous reviews have discussed these carrier systems and their potential to improve the stability and bioavailability of tea polyphenols, while also identifying limitations that require further investigation [34,44]. However, their suitability must be established through systematic formulation studies, appropriate biological evaluation, and reproducible safety testing rather than inferred from their general advantages.

A key research priority is the systematic characterisation of tea-processing residues generated in Assam. Future studies should quantify relevant bioactive compounds, assess contaminants, examine batch-to-batch variability, and develop standardised extraction protocols. Subsequent investigations should compare suitable delivery systems using clearly defined measures of encapsulation efficiency, stability, release behaviour, biological activity, and toxicity. Economic feasibility, environmental impacts, and scalability should also be considered to determine whether waste valorisation can be translated into practical applications.

From a sustainability perspective, pharmaceutical valorisation may provide an additional pathway for utilising tea-processing residues and generating value from materials that might otherwise be underused. Nevertheless, such benefits will depend on the availability and consistency of suitable raw materials, the efficiency of recovery processes, manufacturing costs, and the safety and quality requirements associated with the intended application.

The principal contribution of this study is the proposed framework linking tea-waste characterisation and bioactive recovery with advanced drug-delivery development and sustainability assessment. The framework offers a basis for future experimental research and interdisciplinary collaboration. Since the bibliometric dataset covers broader tea-related research, future work should also undertake a focused bibliometric investigation of tea-processing waste, pharmaceutical bioactives, and nanocarrier-based delivery to establish the development and specific gaps of this emerging research area more precisely. Such a focused analysis would complement existing reviews of tea-polyphenol nanocarriers, which document progress in extraction, purification, formulation, and delivery while identifying unresolved technical challenges [45].

In conclusion, Assam tea-processing waste represents a promising research opportunity rather than an established pharmaceutical resource. Realising its potential will require rigorous chemical characterisation, standardised extraction, formulation optimisation, safety validation, and

evidence of practical feasibility. Addressing these requirements can help determine whether tea-processing residues can support sustainable, high-value pharmaceutical applications.

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