

Microplastic contamination in traditional herbal beverages: sources, transfer pathways, and mitigation across the field-to-consumption continuum

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Abstract

Traditional herbal beverages, including jamu, wedang pakak, herbal infusions, and liquid herbal medicines, may be exposed to microplastic contamination throughout production and consumption. This structured critical review synthesizes peer-reviewed Scopus-indexed studies published mainly from 2019 to August 2026 to identify contamination sources, transfer pathways, and mitigation strategies across the field-to-consumption continuum. Direct evidence from herbal teas and liquid herbal medicines was distinguished from transferable findings involving agricultural systems, tea processing, spices, commercial beverages, and food contact materials. Evidence identifies agricultural soils, irrigation water, atmospheric deposition, plant surfaces, potential plant uptake, processing equipment, filtration, hot extraction, and packaging as contamination sources or pathways. Tea-based analogue studies suggest that manufacturing may contribute more substantially to microplastic abundance than cultivation or brewing, while heating plastic-packaged liquid herbal medicines can markedly increase particle release. However, differences in particle-size thresholds, sample preparation, contamination controls, and polymer identification limit cross-study comparisons and quantitative exposure assessment. Consequently, existing exposure estimates should be interpreted as preliminary screening indicators rather than definitive health-risk thresholds. This review proposes a field-to-consumption management framework integrating cleaner raw materials and water, reduced high-temperature plastic contact, low-shedding processing equipment, validated packaging, and microplastic-specific quality assurance. Future studies should employ standardized analytical protocols and paired sampling across traditional herbal beverage production chains, particularly in tropical regions, to identify critical contamination stages, quantify transfer, and validate mitigation effectiveness.

KEYWORDS

emerging contaminants; herbal beverages; medicinal plants; microplastics

1. INTRODUCTION

Traditional herbal beverages occupy an unusual position at the intersection of food, medicine, culture, and small-scale agroindustry. In Indonesia, jamu and related beverages are prepared from roots, rhizomes, bark, leaves, flowers, seeds, and spices and are consumed both as household preparations and as commercial products. Contemporary forms range from freshly boiled drinks to powders, tea bags, syrups, bottled beverages, and flexible pouch products. Wedang pokok, for example, is commonly associated with aromatic ingredients such as ginger, clove, cinnamon, nutmeg, and other locally available spices, whereas other Indonesian drinks use turmeric, tamarind, kencur, sappanwood, and related botanicals. This diversity means that a single beverage can connect agricultural soil, irrigation water, atmospheric deposition, postharvest handling, grinding, boiling, filtration, packaging, and consumer reheating within one production chain (Estiasih et al., 2025; Setyowati et al., 2023). Modernisation improves convenience and market access, but it also increases contact with synthetic materials through mulches, irrigation components, sacks, grinders, hoses, filters, storage vessels, seals, bottles, and multilayer pouches. These interfaces are rarely considered when the safety of traditional herbal beverages is discussed.

Microplastics are persistent polymer-containing particles generally considered to be smaller than 5 mm, while nanoplastics occupy the submicrometer size range; operational definitions vary among analytical methods. Their occurrence in agricultural soils and food systems has shifted the problem from a marine litter issue to a soil-plant-water and food processing concern. Agricultural sources include fragmentation of mulch films and irrigation components, contaminated compost or biosolids, wastewater irrigation, runoff, atmospheric deposition, and degradation of packaging or farm plastics. Once present in soil, particles can be redistributed vertically and horizontally, interact with other contaminants, adhere to plant surfaces,

and under some conditions enter plant tissues (Jin et al., 2022; Lwanga et al., 2022; Singh et al., 2023). Recent experimental evidence has strengthened the biological plausibility of crop contamination. Foliar exposure can contribute to particle accumulation in plants, and deep root wounds can provide an entry route to the vascular system for micrometer-scale particles (Li et al., 2025; Yin et al., 2026). These findings are particularly relevant to medicinal plants because leaves, rhizomes, roots, bark, flowers, and fruits may all serve as raw materials and because many traditional production systems rely on open drying, manual handling, and repeated washing or grinding.

Previous reviews have addressed important but largely separate components of microplastic contamination relevant to herbal beverages. These include micro and nanoplastics in tea and tea-based drinks, microplastic behavior within the soil-plant system, and contamination associated with drinking water and food packaging (Fard et al., 2025; Muhib et al., 2023; Singh et al., 2023). More recent original studies have extended this evidence to packaged herbal teas, heated liquid herbal medicines, tea-processing chains, and dried spices (Gökkaya & Güzel İzmirli, 2025; Jahedi et al., 2026; Mondal et al., 2025; Xing et al., 2024; Yang et al., 2025). However, these lines of evidence remain fragmented across agricultural, processing, packaging, and beverage studies, while traditional herbal beverages such as jamu and comparable Southeast Asian products remain poorly represented.

Taken together, the existing literature remains compartmentalized by matrix or individual process stage. A field-to-consumption framework that connects agricultural inputs and plant exposure with botanical raw-material handling, processing operations, thermal extraction, filtration, packaging, and consumer practices within traditional herbal beverage systems remains lacking. The conceptual novelty of this review lies in integrating these stages into a single contamination continuum while distinguishing direct evidence from herbal products

from transferable evidence derived from analogous food and beverage systems. This approach allows potential entry, transfer, and amplification points to be evaluated within the same production chain rather than as isolated sources of contamination.

Accordingly, this review critically synthesizes evidence on the sources and transfer pathways of microplastic contamination across the field-to-consumption continuum of traditional herbal beverages and identifies practical mitigation options at critical stages. By linking environmental inputs with processing and consumer-level practices, this framework provides a basis for microplastic-aware production and quality-management strategies and helps prioritize future research where contamination can be most effectively identified and reduced.

2. MATERIALS AND METHODS

2.1 Review design and scope

This study was designed as a structured critical review with narrative synthesis. This approach was selected because the available evidence spans heterogeneous matrices, analytical methods, and study designs that are not suitable for quantitative pooling. The review focused on peer-reviewed, Scopus-indexed literature available through August 2026, with emphasis on studies published from 2019 onward to capture recent developments in microplastic detection, plant uptake, food processing, and food contact materials. Earlier studies and reviews were retained when they provided essential methodological or conceptual context. The review covered six interconnected domains: (1) agricultural sources and transport within the soil-plant-water continuum; (2) contamination of medicinal plants, tea leaves, spices, and other botanical materials; (3) processing water; (4) manufacturing equipment and unit operations; (5) thermal contact, packaging, storage, and reheating; and (6) analytical quality assurance and exposure interpretation. Because substantial differences exist in particle definitions, detection limits, reporting units, extraction recoveries, and polymer identification criteria, the evidence was

synthesized narratively rather than quantitatively pooled.

2.2 Literature identification and eligibility

Literature identification was guided by combinations of the terms microplastic, nanoplastic, herbal beverage, herbal tea, herbal medicine, jamu, medicinal plant, spice, tea, agricultural soil, irrigation, plant uptake, processing water, food processing, filtration, hot water, food contact material, packaging, bottle, pouch, and beverage. Scopus was used as the primary bibliographic database for identifying peer-reviewed studies relevant to this review. Publisher records and backward reference tracking were subsequently used to verify article metadata and identify additional relevant Scopus-indexed studies. Retrieved studies were screened for relevance to the field-to-consumption pathway and retained when they examined an identifiable food, beverage, plant, water, processing, or packaging matrix and described a particle identification approach. Original studies were prioritized for quantitative findings, whereas reviews were used primarily to interpret contamination pathways, methodological limitations, and broader environmental context. Retracted articles were excluded. Evidence was classified as direct when the investigated matrix involved herbal tea, liquid herbal medicine, medicinal botanical ingredients, or traditional herbal beverages, and as transferable when it addressed an analogous pathway, including tea manufacturing, spices, commercial beverages, drinking water, hot food contact materials, or crop uptake.

2.3 Evidence synthesis and interpretation

The narrative synthesis was conducted by organizing eligible studies according to sequential production stages: agricultural environment, raw botanical material, water, preparation and size reduction, extraction or brewing, filtration, filling, packaging, storage, reheating, and consumption. Within each stage, findings were compared in terms of contamination source, particle generation or transfer mechanism, analytical approach, strength

and directness of evidence, and potential control measures. Direct evidence from herbal products was interpreted separately from transferable evidence obtained from analogous food and beverage systems. To avoid assigning equal interpretive weight to evidence from different systems, studies were further considered according to a three-level hierarchy of relevance to traditional herbal beverages. Level 1 comprised direct evidence from herbal teas, liquid herbal medicines, medicinal botanical ingredients, or traditional herbal beverages. Level 2 included closely transferable evidence from analogous plant-derived beverage and processing systems that shared relevant unit operations or food contact conditions, such as tea manufacturing, commercial beverages, filtration, and packaging. Level 3 comprised mechanistic or contextual evidence from agricultural soils, irrigation systems, crop-uptake studies, and general hot-contact experiments that supported pathway plausibility but did not directly demonstrate contamination in herbal beverages. These levels reflect proximity to the target production system rather than formal study quality scores. Reported particle abundances were retained in their original units and were not normalized or pooled because analytical size thresholds, sample preparation, polymer identification methods, and reporting practices differed substantially among studies. Study specific exposure or health risk indices were

therefore interpreted as contextual screening outputs rather than universal safety thresholds.

3. TRADITIONAL HERBAL BEVERAGES AS A FIELD-TO-CONSUMPTION CONTAMINATION CONTINUUM

The central finding of the evidence synthesis is that microplastic contamination in herbal beverages is best understood as a cumulative chain rather than a single event. A traditional herbal beverage may begin with plants exposed to plastic-derived inputs through soil, irrigation water, compost, or atmospheric deposition. Additional contamination can occur during harvesting, washing, and drying through contact materials, water, and airborne fibers. Milling, grinding, boiling, and extraction may introduce or mobilize particles through mechanical abrasion and hot contact with polymeric components. Filtration can remove some particles while also releasing fibers from synthetic filter media, whereas packaging may contribute additional particles during filling, storage, opening, or reheating. Because the final beverage is a liquid matrix, particles introduced at earlier stages can remain suspended, settle, or become associated with plant colloids and other solids. The absence of visible plastic debris is therefore not evidence of absence. The major field-to-consumption contamination pathways discussed in this review are summarized schematically in [Figure 1](#).

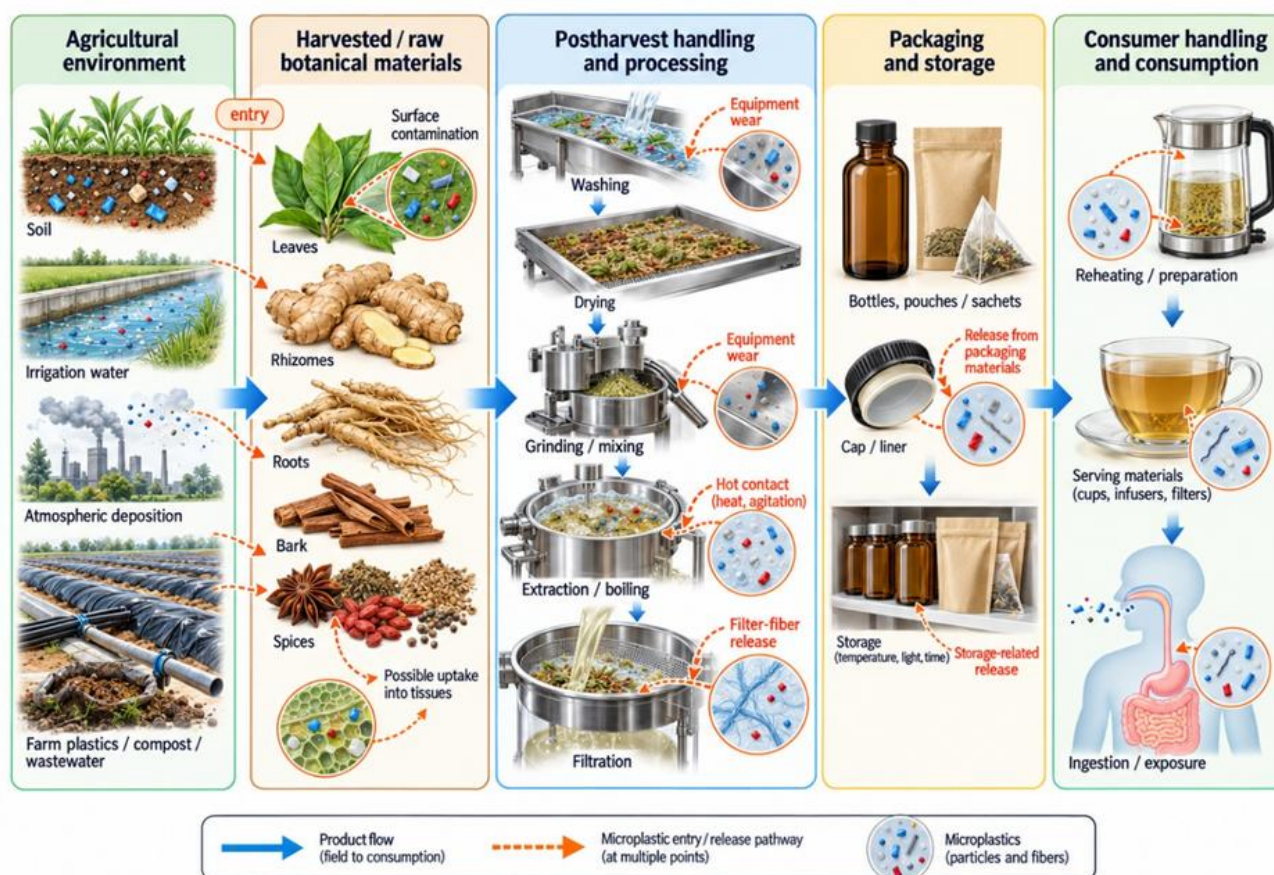


Figure 1. Schematic overview of the field-to-consumption microplastic contamination pathway in traditional herbal beverages.

This chain perspective also changes how contamination should be managed. End product testing alone can establish occurrence but provides weak source attribution. A low final count may reflect genuinely clean production, efficient removal during filtration, or simply a high analytical size cutoff. Conversely, a high count does not identify whether the dominant source was field exposure, processing equipment, water, or packaging. Studies that sample sequential stages are therefore more informative for management. Xing et al. (2024) followed tea from planting to the final product and found that processing contributed more

strongly than cultivation or brewing, while Mondal et al. (2025) linked stage-specific contamination to particular manufacturing equipment. Representative evidence from related studies relevant to potential microplastic contamination pathways across traditional herbal beverage production chains is summarized in [Table 1](#). These studies are not measurements of jamu, but they provide the strongest available design model for future traditional herbal beverage research: paired sampling before and after each unit operation with polymer fingerprints used to connect particles to candidate sources.

Table 1. Representative Scopus-indexed evidence relevant to microplastic contamination in herbal beverage production chains.

Study and matrix	Production stage	Key finding	Main polymer/morphology information	Evidence level and relevance
Xing et al. (2024), loose tea	Cultivation processing brewing	70-3472 particles kg ⁻¹ were reported across stages; the highest abundance occurred during processing, especially rolling (2266 ± 1206 particles kg ⁻¹).	Fibers were prominent; surface wear and degradation were observed.	Level 2 – Closely transferable process analogue
Gökkaya and Güzel İzmirli (2025), packaged herbal teas	Packaged product brewing	Microplastics were detected in green, sage, linden, and chamomile tea samples; particle size was approximately 35.7–604.9 µm.	Fibers dominated; EVA, PET, and PAN were identified.	Level 1 – Direct
Yang et al. (2025), liquid herbal medicine in flexible sachets	Packaging reheating	Estimated daily intake increased from 0.042 particles kg ⁻¹ bw day ⁻¹ unheated to 0.148 after hot-water-bath heating; sachet surfaces showed greater degradation after heating.	PE, PP, PS, and PET; mainly 20-500 µm.	Level 1 – Direct
Mondal et al. (2025), CTC tea	Industrial processing	Stage abundance ranged from about 0.4-1.1 particles g ⁻¹ ; plastic-containing equipment was implicated as a source.	PE, polyacrylates, PVC, and nylon; fibers and fragments.	Level 2 – Closely transferable process analogue
Jahedi et al. (2026), turmeric, red pepper, black pepper	Raw dried botanicals market handling	Microplastics occurred in all tested spice samples; bulk products generally had greater loads than packaged products.	Fibers and fragments; common packaging- and processing-associated polymers were recovered.	Level 1 – Direct botanical evidence
Li et al. (2025), crop leaves	Preharvest atmospheric exposure	Foliar absorption contributed to microplastic accumulation in plants under controlled and environmental observations.	Polymer-specific quantification included PET and PS.	Level 3 – Mechanistic/contextual evidence
Yin et al. (2026), crop roots	Preharvest soil root interface	Deep root wounds enabled uptake and vascular transport of 1-5 µm particles in crop	PS plus tests with PLA, PMMA, PVC, and PE.	Level 3 – Mechanistic/contextual evidence

		plants; intact/shallowly wounded roots were more resistant.		
Socas-Hernández et al. (2024), 73 commercial beverages	Processing packaging final product	Anthropogenic particles occurred across beverage categories; package-derived phenoxy resin was detected in metal-container products.	Cellulosic particles common; polyester among plastic polymers.	Level 2 – Transferable beverage evidence
Li et al. (2023), food grade PP nonwoven bags	Hot filtration/cooling	One boiling event released 0.12-0.33 million MPs (>1 µm) and 17.6-30.6 billion NPs (<1 µm) under the study conditions.	PP fibers and fragments.	Level 2 – Transferable filtration evidence
Ranjan et al. (2021), plastic-lined paper cups	Hot contact serving	Hot water (85-90 °C) degraded cup liners and released micron and submicron sized particles.	Most tested liners were HDPE.	Level 2 – Transferable hot-contact evidence
Hussain et al. (2023), plastic containers and reusable food pouches	Heating storage	Microwave heating produced the greatest release among tested usage scenarios, with both micro and nanoplastics detected.	Food-grade polymer containers/pouches.	Level 2 – Transferable packaging evidence
Hernandez et al. (2019), plastic tea bags	Hot brewing	Very high micro and nanoparticle release was reported at 95 °C; later reviews emphasize that counts are strongly method dependent.	Nylon and PET.	Level 2 – Transferable hot-brewing evidence

Note: Numerical values are retained in the reporting units used by the original studies and should not be compared as prevalence estimates because analytical size cutoffs and identification methods differ.

3.1 Agro environmental entry routes: soil, irrigation water, and atmospheric deposition

Agricultural production creates the first potential entry points. Microplastics reach cropland from intentional plastic use and from diffuse environmental inputs. Plastic mulches, greenhouse films, irrigation tubing, coated fertilizers, packaging waste, contaminated compost or biosolids, and wastewater irrigation can contribute particles that persist and fragment in soil (Jin et al., 2022; Khan et al., 2023; Lwanga et al., 2022; Singh et al., 2023). In tropical production systems, ultraviolet radiation, high surface temperatures, intense rainfall, and repeated wetting drying can accelerate the physical

weathering of exposed plastics, although the rate and particle-size distribution remain highly material-specific. For medicinal-plant production, this matters because many useful plant parts develop at or below the soil surface. Rhizomes such as ginger and turmeric are harvested through direct contact with soil, and root crops can retain soil particles in crevices even after preliminary cleaning. A microplastic source in soil therefore creates at least two pathways: external contamination of harvested surfaces and, under certain conditions, biological uptake.

Plant uptake should nevertheless be described carefully. Earlier reviews emphasized that particle

entry and translocation are strongly controlled by size, surface chemistry, plant species, growth medium, and exposure conditions, with nanoplastics generally more mobile than larger particles (Azeem et al., 2021; Singh et al., 2023). Recent work has added important mechanistic detail. Li et al. (2025) demonstrated that leaves can absorb microplastics and contribute to accumulation in plants, strengthening the relevance of atmospheric deposition for leafy medicinal materials. Yin et al. (2026) showed that deep root wounds exposing vascular tissues can facilitate the uptake and upward transport of micrometer-scale particles, while intact and shallowly wounded roots provided greater resistance. These studies argue against two simplistic interpretations: that crop uptake never occurs, or that all soil microplastics readily enter edible tissues. For herbal beverage risk management, the practical implication is to reduce environmental loading and surface contamination regardless of uncertainty about internal uptake, while designing analytical studies that distinguish particles attached to the plant surface from particles actually present in tissue.

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Irrigation water connects aquatic contamination with crop production. Treated wastewater and contaminated surface water can contain micro and nanoplastics as well as other pollutants, creating opportunities for deposition on soil and plants and for co-exposure with metals or organic contaminants (Naziri et al., 2023). Even where medicinal plants are irrigated with groundwater or municipal water rather than wastewater, water remains relevant during

postharvest washing and beverage preparation. The same water source can therefore act twice in the chain: first as an agricultural input and later as a processing ingredient. Source attribution requires these functions to be sampled separately. A manufacturer that tests only the finished beverage cannot distinguish a particle carried in by ginger from one introduced by the water used to wash or boil it.

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3.2 Raw medicinal plants, herbs, and spices as carriers of microplastics

The raw material stage is particularly important for traditional herbal drinks because ingredients are often minimally refined. Leaves may be dried whole, rhizomes may be sliced or ground, and bark or spices may be stored for long periods before extraction. Each practice changes the probability that environmental particles remain attached. Open-air drying can collect atmospheric fibers; woven plastic sacks can abrade during transport; plastic trays and tarpaulins can weather under sunlight; and repeated grinding can transfer particles from contact surfaces. Direct evidence from spices supports the need to treat dry botanicals as a possible contamination matrix. Jahedi et al. (2026) detected microplastics in turmeric, red pepper, and black pepper, with fibers and fragments prominent and bulk products generally showing higher loads than packaged products. Because turmeric and related spices are also used in traditional beverages, this evidence is more transferable than observations from unrelated foods.

Tea studies provide a second line of evidence. Xing et al. (2024) found particles in plantation soil and leaves before following the material through processing and brewing. The value of this work lies

less in its numerical concentration than in its source tracing design. Morphology and surface features changed across stages, suggesting that particles can be inherited from the field and added or modified during manufacturing. For jamu and pokak, an analogous design should analyze washed and unwashed ingredients, exterior wash water, peeled versus unpeeled rhizomes, and pre versus post grinding material. Such paired measurements would determine whether washing actually reduces microplastic burden, merely redistributes particles to wastewater, or introduces new particles from water and cleaning equipment.

Raw material control should therefore extend beyond botanical identity, pesticide residues,

moisture, and microbial quality. A microplastic-aware purchasing specification could document cultivation practices, mulch use, irrigation source, drying surface, storage container, and transport packaging. This does not require rejecting all plastic use, which may be impractical for small producers. Instead, the purpose is to identify high contact and high wear points where substitution or better maintenance is feasible. Botanicals that undergo direct soil contact, extended open drying, or repeated transfer through plastic sacks should be prioritized for monitoring. These agro-environmental entry routes and their connections to medicinal plant contamination are summarized schematically in [Figure 2](#).

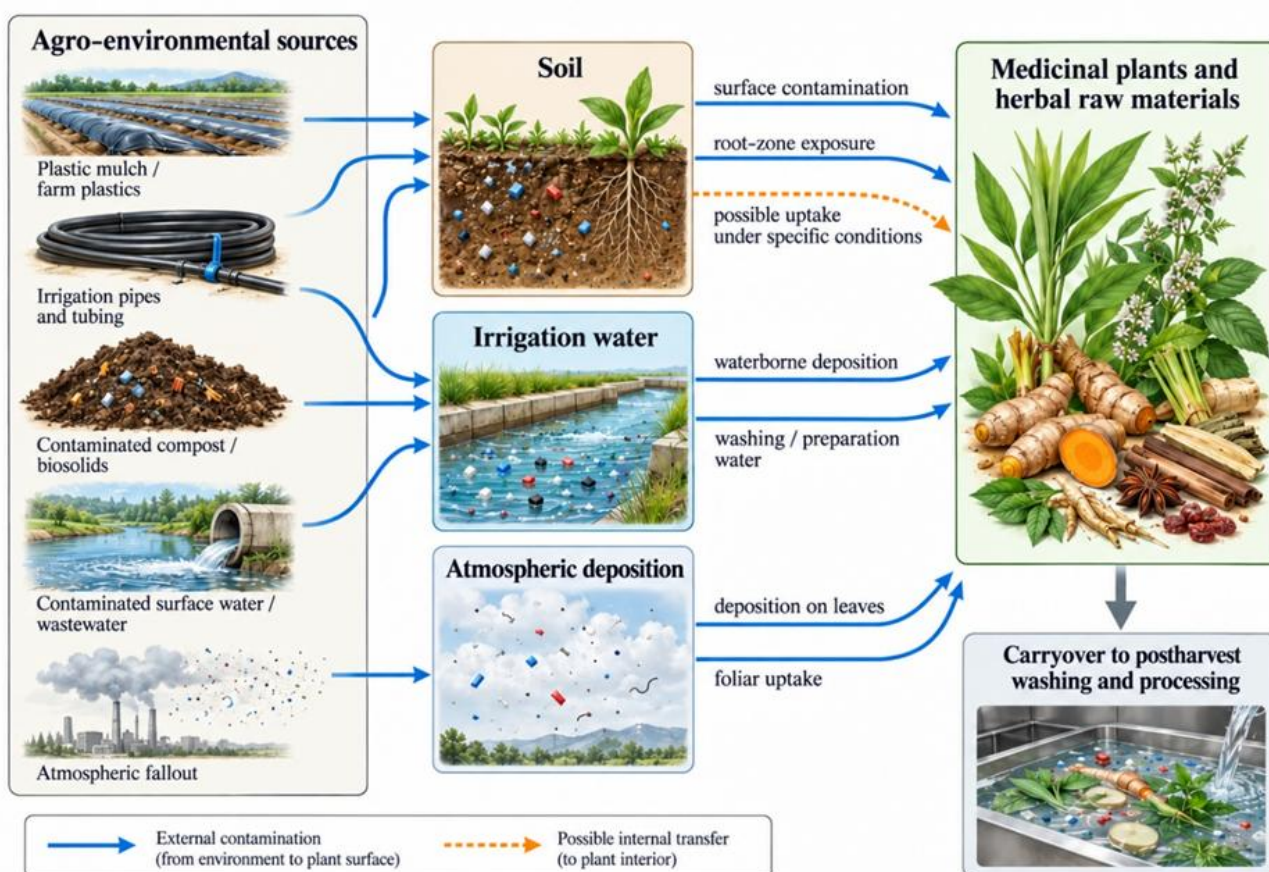


Figure 2. Schematic diagram of agro-environmental microplastic entry routes into medicinal plants and herbal raw materials.

3.3 Processing water as an ingredient, carrier, and analytical confounder

Water is often the largest mass component of a herbal beverage and can be used at several steps: washing, soaking, extraction, dilution, equipment cleaning, and final formulation. Reviews of tap and bottled water consistently show that microplastic occurrence depends on source, treatment, distribution, packaging, and analytical method (Muhib et al., 2023). Commercial beverage surveys similarly demonstrate that anthropogenic particles can be present even when the beverage contains no obvious particulate ingredient (Socas-Hernández et al., 2024). For traditional herbal beverage producers, this means that 'clean water' in a microbiological sense is not automatically a particle free process blank.

A practical monitoring program should test source water before it contacts herbs and again after key treatment steps. If a producer uses cartridge filtration, reverse osmosis, storage tanks, flexible hoses, or polymeric membranes, the system can both remove and potentially contribute particles depending on maintenance and material condition. Water sampling also has a methodological function: it allows the background contribution of the liquid phase to be separated from particles released by ingredients or equipment. Without a water blank, a final concentration expressed as particles per liter can incorrectly be attributed to herbal materials. This is especially important when the expected contamination level is low, because laboratory and process blanks may represent a meaningful fraction of the observed count.

Management priorities include protecting source water, using well-maintained treatment systems, minimizing aged or visibly degraded flexible plastic lines in hot water service, and storing treated water in materials appropriate for the intended temperature. Where feasible, stainless steel or glass contact surfaces provide an important comparison for source investigation trials. Nevertheless, replacement decisions should be evidence-based because new materials can

introduce other environmental burdens or chemical migration concerns. Microplastic mitigation should therefore be integrated with existing drinking water, food contact, and sustainability requirements rather than pursued as a stand-alone objective.

3.4 Grinding, conveying, mixing, and filtration as secondary contamination points

Mechanical processing can transform plastic from an environmental contaminant into a process-generated contaminant. Tea manufacturing offers direct evidence that particle abundance can increase during unit operations. Xing et al. (2024) reported the highest tea-associated abundance during processing, particularly rolling. Mondal et al. (2025) found stage dependent contamination in crush, tear, and curl tea and identified equipment such as withering troughs, conveyor belts, and fiber extractors as plausible sources. The relevance to herbal beverages is straightforward: many jamu and instant-herbal operations use grinders, blenders, conveyors, sieves, hoses, buckets, gaskets, and filters with polymer components. Mechanical abrasion, vibration, blade contact, repeated flexing, and cleaning can generate particles even when the equipment is certified for food contact because food-contact approval does not necessarily mean zero particulate shedding under all service conditions.

The relevance to herbal beverages is straightforward: many jamu and instant-herbal operations use grinders, blenders, conveyors, sieves, hoses, buckets, gaskets, and filters with polymer components.

Grinding deserves special attention. Dry spices and fibrous plant materials are abrasive, and high-speed size reduction creates friction and local heating. If the grinder chamber, lid, scraper, gasket, feeding funnel, or collection container contains plastic, wear particles may be incorporated into a powder that is later difficult to separate. A field to cup study should therefore sample immediately before and after grinding and compare polymer

spectra with equipment components. Similar source fingerprinting can be used for tubing, seals, and conveyor belts. If a particle recovered from product matches a worn polymer contact surface in chemistry and morphology, the evidence for source attribution is much stronger than a count alone.

Filtration creates a more complex trade-off. Filtering a decoction can remove coarse botanical debris and some larger microplastics, but polymeric filter bags, nonwoven materials, and synthetic cloth can themselves release fibers. Li et al. (2023) demonstrated substantial micro and nanoplastic release from polypropylene nonwoven food bags after boiling. Wang et al. (2023) also showed that

hot water passing through polymer-containing drip coffee bags can release microplastics. These experiments used conditions that do not replicate every herbal beverage process, but they establish a mechanism that should be tested wherever hot decoctions contact disposable synthetic filters. Stainless steel screens, appropriately selected cellulose-based filters without synthetic binders, or other low-shedding alternatives may reduce this pathway, but each substitute should be verified rather than assumed to be plastic-free. The major secondary contamination points associated with grinding, conveying, mixing, and filtration are summarized schematically in [Figure 3](#).



Figure 3. Schematic diagram of secondary microplastic contamination during grinding, conveying, mixing, and filtration.

3.5 Thermal extraction and hot-contact materials

Boiling and hot extraction are defining steps for many traditional herbal drinks. Heat improves extraction of soluble constituents and provides microbial control, but it also increases the importance of material selection. Temperature can soften polymers, accelerate oxidation, promote surface cracking, and amplify mechanical release during stirring, squeezing, pouring, or repeated use. Hot-contact studies across food systems consistently show that particle release can rise under elevated temperature and energetic handling. Ranjan et al. (2021), for example, observed degradation of polyethylene lined paper cups exposed to 85-90 °C water and reported release of micron and submicron sized material. Hussain et al. (2023) found that microwave heating of plastic containers and reusable pouches generated greater micro and nanoplastic release than several other tested storage or use conditions.

The most directly relevant evidence comes from liquid herbal medicine. Yang et al. (2025) evaluated products in flexible sachets under unheated, microwave, and hot water bath conditions. Heating increased microplastic release, with the hot water bath condition producing the highest estimated daily intake and clear surface deterioration of the sachets. The study identified polyethylene, polypropylene, polystyrene, and polyethylene terephthalate among recovered polymers. For traditional herbal beverages sold in pouches, this shifts attention from the beverage formulation to consumer preparation instructions. A product that is microbiologically stable at room temperature may acquire additional particles if consumers are instructed to heat the sealed pouch directly in hot water or a microwave.

Temperature control should therefore be applied at two stages. During production, hot decoctions should preferentially contact durable, low-shedding vessels and pipes designed for repeated thermal service. During filling, producers should validate whether hot fill temperature,

residence time, and packaging polymer increase particle release. At the consumer stage, reheating instructions should avoid unnecessary direct heating of plastic packages when the product can instead be transferred to an appropriate container. These measures are feasible even before regulatory microplastic limits are established because they target a preventable source mechanism.

3.6 Packaging, storage, serving, and consumer handling

Packaging is often treated as the final barrier protecting a beverage from contamination, yet it can also be a source. Bottles, caps, liners, multilayer pouches, seals, dispensing components, and coated paper products can shed particles through manufacturing residues, friction, opening and closing, thermal stress, ultraviolet exposure, and aging. Jadhav et al. (2021) and Muhib et al. (2023) summarized microplastic occurrence associated with food packaging and bottled water, while Socas-Hernández et al. (2024) detected particles in a range of commercial beverages and reported evidence of coating-derived material in metal containers. The important point for herbal beverages is that switching from one package type to another does not automatically eliminate particulate contamination; the specific material, process temperature, filling method, storage duration, and opening mechanism must be considered together.

Tea bags provide an instructive example of why analytical caution is necessary. Hernandez et al. (2019) reported billions of micro and nanoparticles released from nylon and polyethylene terephthalate tea bags during steeping at 95 °C. This landmark result established that hot beverage preparation can fragment polymeric packaging, but later evaluations have shown that reported particle numbers from tea bags vary enormously because studies use different size cutoffs, sample preparation procedures, and detection technologies (Canga et al., 2024; Fard et al., 2025). It would therefore be inappropriate to cite the Hernandez value as the expected exposure from jamu sachets or herbal tea bags. Its value is mechanistic: high-temperature contact can generate

particles, and nanoscale-sensitive methods detect a population that routine optical methods miss.

Tea bags provide an instructive example of why analytical caution is necessary.

Serving materials can extend exposure beyond the factory. Plastic-lined paper cups may appear to be a nonplastic alternative but can contain polyethylene films, while reusable bottles and cups may develop surface wear over time. Traditional vendors frequently serve hot drinks in disposable cups or transfer products with plastic ladles, funnels, and bags. A realistic risk management plan must therefore include point-of-sale practices and consumer preparation, not only industrial packaging. For small and medium enterprises, a simple material inventory that records which surfaces contact hot product, how often they are replaced, and whether visible wear is present can identify priority substitutions without requiring immediate replacement of every plastic item.

3.7 Why published microplastic concentrations are difficult to compare

The analytical literature is sufficiently heterogeneous that numerical comparison can be misleading. A study detecting particles down to 1 μm will almost inevitably report a higher count than a study limited to particles larger than 100 μm , even if the samples are identical. Sample digestion can destroy organic matter but may also alter susceptible polymers; density separation selects particles according to the density of the solution; membrane pore size controls what is retained; visual microscopy can misclassify cellulose or natural fibers; and spectroscopy may analyze all particles or only a subset. Kadac-Czapska et al. (2023) emphasized the need to align definitions, sample preparation, and characterization methods in food studies, while Canga et al. (2024) demonstrated how methodological choices contribute to inconsistent food and beverage measurements.

For herbal matrices, the challenge is amplified by pigments, essential oils, polysaccharides, plant

fibers, starch, proteins, and suspended colloids. Aggressive oxidation may be needed to expose particles, but the digestion method must be validated for the polymers of interest. A visually identified fiber should not be classified as a microplastic without chemical confirmation because natural cellulose and semisynthetic fibers can resemble synthetic polymers. Micro Fourier transform infrared spectroscopy and Raman microscopy are therefore important for particle level polymer confirmation, with each having strengths and limitations related to fluorescence, particle size, throughput, and spectral libraries. Thermal methods such as pyrolysis gas chromatography mass spectrometry can provide polymer mass but do not retain particle number, shape, or size information. Surface-enhanced Raman spectroscopy combined with chemometrics has also been explored for identifying polymer types in liquid herbal medicine matrices, showing promise for rapid qualitative screening but not replacing validated quantitative occurrence methods (Joshi et al., 2025).

Contamination control is equally important. Airborne fibers, synthetic laboratory coats, plastic pipette tips, tubing, caps, and unfiltered reagents can all create false positive results. At minimum, future herbal beverage studies should use glass or metal laboratory ware where feasible, cover samples, filter reagents, include field and procedural blanks, report blank subtraction rules, document recovery with representative polymers and sizes, and identify a defined proportion of suspected particles spectroscopically. Reporting should include both count and size distribution, polymer type, morphology, minimum detectable size, sample mass or volume, and whether values were blank corrected. The minimum analytical information recommended to improve methodological transparency, reproducibility, and comparability across studies of microplastics in herbal beverages is summarized in [Table 2](#). Without these details, apparent differences among brands or production stages may reflect laboratory method rather than true contamination.

Table 2. Minimum analytical information recommended for microplastic studies of herbal beverages.

Analytical element	Minimum reporting expectation	Reason for importance
Sampling	Matrix mass/volume; container material; sampling location; stage of production; field blanks when applicable.	Allows source attribution and detects contamination introduced during sampling.
Contamination control	Covered samples; filtered reagents; glass/metal ware where feasible; cotton laboratory clothing; procedural and airborne blanks.	Airborne fibers and laboratory plastics can materially bias low-concentration food samples.
Matrix preparation	Digestion chemistry, temperature, duration, density solution, filtration material, and pore size.	These choices determine polymer recovery and the minimum particle population retained.
Recovery validation	Spiking with representative polymer types, shapes, and sizes; report recovery percentage.	Demonstrates whether botanical matrices or digestion procedures cause particle loss.
Identification	Polymer confirmation by μ -FTIR, Raman, or validated thermal/spectrometric approach; report spectral match criterion.	Visual identification alone cannot reliably distinguish synthetic from natural particles.
Particle reporting	Abundance, size distribution, morphology, color if used, polymer composition, lower size cutoff, blank correction.	Enables meaningful interpretation and comparison across stages.
Nanoplastic claims	Use a method with demonstrated submicrometer capability; avoid extrapolating nanoplastic numbers from optical microscopy.	Nanoplastics are below the reliable range of many routine particle-counting approaches.
Source tracing	Compare recovered polymer spectra with packaging, filters, hoses, seals, and other contact materials.	Moves the study from occurrence reporting toward actionable process management.

Abbreviations: μ -FTIR, micro-Fourier-transform infrared spectroscopy.

3.8 Dietary exposure and health-risk interpretation

Dietary exposure is a legitimate concern because ingestion is a continuous route for particles present in food and beverages, but current evidence does not support a single quantitative 'safe'

microplastic concentration for herbal drinks. Several studies calculate estimated daily intake from measured particle abundance and consumption assumptions. Xing et al. (2024) estimated low dietary exposure from brewed tea under their analytical conditions, Mondal et al. (2025) reported

low screening level noncancer and cancer indices for the polymers assessed in crush tear curl tea, and Yang et al. (2025) showed that heating conditions materially changed estimated intake from liquid herbal medicine. These calculations are useful for comparing scenarios within a study, but they are not directly interchangeable because the detected particle size ranges and risk equations differ.

Dietary exposure is a legitimate concern because ingestion is a continuous route for particles present in food and beverages, but current evidence does not support a single quantitative 'safe' microplastic concentration for herbal drinks

Two limitations are particularly important. First, number based exposure can be dominated by the smallest detectable particles. A method that includes submicrometer material may produce orders of magnitude more particles than a method that begins at tens of micrometers, without necessarily implying a proportional increase in polymer mass. Second, polymer hazard indices often use hazard scores for bulk chemicals or monomers and do not fully represent particle toxicokinetics, additives, sorbed contaminants, biological coronas, or nanoscale behavior. Consequently, a statement that a calculated index is 'within safety limits' should be interpreted as a result of a specific model rather than proof that the detected particles are harmless.

A method that includes submicrometer material may produce orders of magnitude

more particles than a method that begins at tens of micrometers, without necessarily implying a proportional increase in polymer mass

For a review focused on environmental and agricultural management, the most defensible approach is prevention under uncertainty. Producers do not need a finalized toxicological threshold to justify reducing avoidable plastic fragmentation in hot processes, maintaining equipment, improving water quality, or preventing environmental plastic loading in medicinal plant production. At the same time, risk communication should avoid implying that occasional consumption of a herbal beverage is proven to cause disease. The evidence supports exposure potential and a need for better measurement; causal human health conclusions remain much less certain than evidence for environmental occurrence and process release. The main elements involved in dietary exposure estimation and health-risk interpretation are summarized schematically in [Figure 4](#).

Producers do not need a finalized toxicological threshold to justify reducing avoidable plastic fragmentation in hot processes, maintaining equipment, improving water quality, or preventing environmental plastic loading in medicinal plant production.

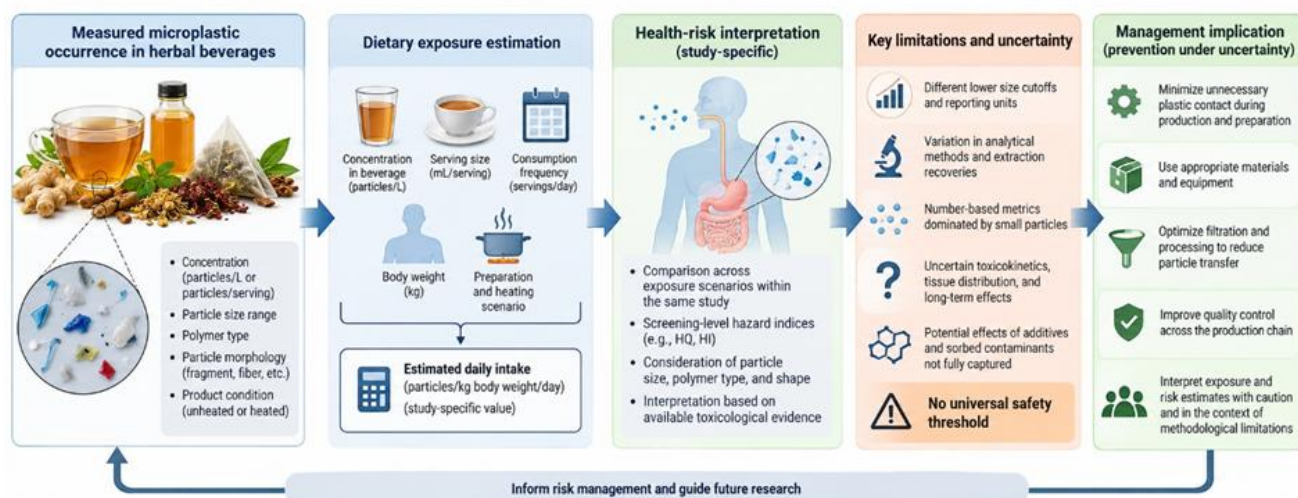


Figure 4. Conceptual framework for dietary exposure and health-risk interpretation of microplastics in traditional herbal beverages.

3.9 A microplastic-aware control framework for jamu and other herbal beverage producers

Microplastic control can be integrated into existing good manufacturing practice rather than established as a separate quality system. The most useful concept is a hazard analysis compatible framework that identifies stages where plastic particles may enter or be generated, establishes preventive measures, and verifies whether interventions reduce particles. Formal critical limits cannot yet be proposed because standardized regulatory thresholds are lacking. However, producers can define internal performance criteria such as absence of visibly degraded contact materials, use of qualified water, documented filter specifications, replacement schedules for high wear components, and no direct reheating of finished products in unvalidated plastic packaging.

The most useful concept is a hazard analysis compatible framework that identifies stages where plastic particles may enter or be generated, establishes preventive measures, and verifies whether interventions reduce particles.

At the farm and supplier stage, prevention should target unnecessary plastic residues, contaminated compost inputs, and irrigation water quality while encouraging covered drying and clean storage. During ingredient preparation, producers can separate soil rich washing steps from final rinse water, avoid damaged plastic baskets or sacks where direct abrasion occurs, and inspect grinders and seals. During extraction and filtration, the highest priority should be hot contact: stainless steel or other validated low shedding surfaces are preferable for repeated boiling, and disposable polymeric filter bags should not be assumed inert. During filling and packaging, the package should be tested under actual hot fill, storage, transport, and reheating conditions rather than only at room temperature. Consumer instructions should recommend transfer to a suitable vessel before heating when direct pouch heating is unnecessary.

This framework also has an environmental dimension. Simply replacing conventional plastics with a material labeled biodegradable is not sufficient because composite and biodegradable tea bag materials can still release micro and nanoplastic like particles depending on composition and use conditions (Fard et al., 2025). A sustainable intervention should therefore consider shedding,

chemical safety, recyclability, durability, cost, and waste generation together. For small scale jamu producers, durable reusable equipment may be more realistic than complex packaging redesign. For larger manufacturers, supplier qualification and standardized migration or shedding tests can be incorporated into packaging procurement. The

proposed field-to-consumption control framework, integrating preventive measures, monitoring priorities, and verification strategies across the herbal beverage production chain, is summarized in [Table 3](#). The principle is to remove high-risk plastic contact where feasible and to validate any material that remains in the process.

Table 3. Proposed field-to-consumption microplastic control framework for traditional herbal beverages.

Stage	Potential source or mechanism	Evidence status	Priority management action	Suggested verification
Cultivation	Mulch, irrigation components, compost/biosolids, atmospheric fallout, contaminated irrigation.	Strong agro environmental evidence; limited direct medicinal plant data.	Reduce residual farm plastics; document irrigation and amendment sources; protect drying areas.	Soil/water survey; paired plant surface and tissue analysis.
Harvest and drying	Plastic crates/sacks, tarpaulins, airborne fibers, soil adhesion.	Transferable; direct spice evidence supports handling contribution.	Use clean, intact containers; cover drying; minimize contact with weathered plastics.	Compare pre/post drying botanicals; airborne blank/deposition sampling.
Washing and water preparation	Contaminated source water, tanks, hoses, filters.	Strong water evidence.	Qualify water; maintain treatment systems and hot water lines.	Source water and post-treatment particle analysis.
Grinding and mixing	Abrasion of grinder parts, seals, lids, buckets, conveyors.	Strong tea processing analogue.	Inspect wear; prioritize metal contact surfaces in high-friction zones; replace damaged components.	Before/after unit operation sampling and polymer fingerprinting.
Extraction/boiling	Thermal degradation of plastic utensils, liners, tubes, gaskets.	Strong hot contact evidence.	Avoid unnecessary plastic contact with boiling product; use heat-rated durable surfaces.	Hot-water shedding test using actual equipment/material.

Filtration	Synthetic cloth/nonwoven bags can shed fibers while removing other particles.	Strong transferable experimental evidence.	Select low shedding filter media; avoid boiling disposable PP bags unless validated.	Blank filtration test at process temperature.
Filling/packaging	Hot fill stress, bottle/pouch/cap abrasion, multilayer packaging.	Direct liquid herbal medicine and beverage evidence.	Validate package under actual fill and storage conditions; control hot-fill residence time.	Pre/post packaging comparison; package only blank.
Consumer reheating/serving	Heating sealed pouches; plastic lined cups; repeated-use containers.	Strong direct/transferable evidence.	Provide heating instructions that minimize hot plastic contact; use suitable serving vessels.	Simulated use study following label instructions.
Quality assurance	Laboratory contamination and inconsistent size cutoffs.	Strong methodological evidence.	Adopt blanks, recovery controls, polymer confirmation, and defined size ranges.	Routine QA/QC acceptance criteria and interlaboratory comparison.

The framework is preventive and does not imply established regulatory critical limits for microplastics in herbal beverages.

3.10 Knowledge gaps and future research priorities

Direct field-to-consumption evidence for jamu, wedang pokak, and comparable tropical herbal beverages remains limited. Existing studies provide direct evidence for packaged herbal teas and liquid herbal medicines, whereas stage-specific source tracing has been demonstrated mainly in analogous systems such as tea production (Gökkaya & Güzel İzmirli, 2025; Mondal et al., 2025; Xing et al., 2024; Yang et al., 2025). Future studies should therefore follow the same production batch across irrigation or source water, harvested material, washing, drying, grinding, extraction, filtration, packaging, and consumer-style reheating, while simultaneously characterizing potential source materials.

A second gap concerns particle size and analytical comparability. Many food and beverage studies are biased toward micrometer-scale particles because smaller particles are more difficult to isolate and chemically confirm, while reported abundance can vary substantially with the minimum detectable size and analytical method (Canga et al., 2024; Fard et al., 2025; Kadac-Czapska et al., 2023). Future studies should clearly distinguish microplastic and nanoplastic detection capabilities and, where possible, combine particle-resolved spectroscopy with polymer-mass approaches.

The relative importance of internal plant uptake and surface deposition also remains uncertain for medicinal botanicals. Recent studies show that foliar absorption and root-mediated uptake can occur under specific conditions, but these pathways

depend strongly on particle size, exposure conditions, and plant characteristics (Li et al., 2025; Singh et al., 2023; Yin et al., 2026). Studies should therefore distinguish surface-associated particles from particles present within plant tissues and compare different harvested organs under realistic field conditions.

Intervention studies are also needed because much of the current literature documents occurrence or release without directly testing practical mitigation. Experimental evidence indicates that hot contact, polymeric filters, processing equipment, and packaging can contribute particles under specific conditions (Hussain et al., 2023; Li et al., 2023; Mondal et al., 2025; Yang et al., 2025). Future work should compare alternative contact materials, filtration systems, packaging types, hot-fill conditions, and reheating practices using consistent analytical protocols while considering product quality, cost, energy use, waste generation, and microbial safety.

Finally, greater consistency in exposure reporting is required. Minimum particle size, abundance metrics, polymer identity, morphology, blank correction, recovery, and consumption assumptions should be reported transparently to improve comparability across studies (Canga et al., 2024; Kadac-Czapska et al., 2023). Until analytical and toxicological uncertainties are reduced, research on traditional herbal beverages should prioritize identifying controllable contamination sources and demonstrating reproducible reductions rather than assigning definitive health-risk classifications to isolated particle counts.

4. CONCLUSION

Microplastic contamination is a credible emerging quality issue for traditional herbal beverages because the production chain links agricultural environments with multiple food contact operations. Current evidence does not justify claiming that jamu or wedang pokok universally contains a specific concentration of microplastics, but direct studies of herbal tea and liquid herbal

medicine, together with source tracing research in tea, spices, water, and packaging, show that the contamination pathways are plausible and measurable. The strongest evidence supports a multi source model: particles can originate from soil, irrigation and atmospheric deposition; remain on or enter botanical materials; be added through mechanical processing and water; and be generated during hot contact with filters, vessels, or packaging. Heating plastic packaged herbal medicine is particularly relevant because particle release increases under thermal stress. At the same time, numerical concentrations reported across studies should not be compared without considering analytical size limits, blanks, digestion, recovery, and polymer confirmation. For producers, the most appropriate response is preventive management rather than reliance on end product testing alone. Clean agricultural inputs, qualified water, covered drying, low wear processing surfaces, careful filtration, minimized hot plastic contact, validated packaging, and realistic consumer use testing can be incorporated into good manufacturing practice. Future research should prioritize paired, stage by stage studies of tropical herbal beverage systems and intervention trials that identify which control measures produce reproducible reductions without compromising product safety, affordability, or sustainability. Such work would connect emerging contaminant science with practical environmental management across the soil-plant-water production continuum.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Roy Hendroko Setyobudi: Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing, Supervision. Siti Alfiatul Amani: Writing – original draft, Writing – review & editing.

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The authors declares no conflicts of interest.

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Data available by request.

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