

ANALYSIS OF MICROPLASTIC ABUNDANCE, POLYMER COMPOSITION, AND THE EFFECT OF NATURAL FILTRATION ON TRADITIONALLY PRODUCED COOKING SALT FROM WATU ASA VILLAGE

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Abstract

Traditional sea salt production is highly vulnerable to marine debris; however, comprehensive data on microplastic contamination and quality improvement through filtration technologies in boiling-based systems in emerging coastal regions, such as Central Sumba, remain severely limited. This study aimed to determine the physicochemical quality, normalized abundance, morphological characteristics, and specific polymer compositions of microplastics in sea salt and brine from the coastal area near the estuary of Watu Asa Village. The study applied a completely randomized design with three replicates to evaluate physical filtration treatments utilizing charcoal, sand, and palm fiber media, alongside a control. Samples were analyzed for moisture and NaCl levels, followed by wet digestion using 30% H₂O₂, quantification under a stereomicroscope, and chemical identification via Fourier-transform infrared spectroscopy. The results showed that the filtration treatments significantly affected moisture and NaCl levels ($p < 0.05$), where charcoal filtration yielded the highest NaCl content of $95.60 \pm 0.53\%$ and lowered moisture to $5.20 \pm 0.12\%$. Furthermore, an independent sample t-test showed a significant difference in microplastic abundance between brine and final salt crystals ($p < 0.05$). Microplastic contamination showed 100% prevalence, surging from 285 particles/L in brine to $35,000 \pm 2,500$ particles/kg in salt crystals. Fibers and fragments predominated with sizes under 250 μm , while FTIR spectroscopy identified various synthetic polymers, including poly(vinyl alcohol) (PVA), polyethylene (PE), polyacrylonitrile (PAN), and polyurethane (PU). This study concludes that while coconut shell charcoal filtration successfully upgrades the physicochemical quality of traditional salt to meet

national standards, the pervasive accumulation of micro-sized fragments presents a critical food safety warning that demands urgent and advanced intervention.

Keywords: boiling method, contaminant accumulation, food safety, polymer identification, physicochemical properties

Analisis Kelimpahan Mikroplastik, Komposisi Polimer, dan Pengaruh Filtrasi Alami Terhadap Garam Masak Tradisional Dari Desa Watu Asa

Abstrak

Produksi garam laut tradisional sangat rentan terhadap sampah laut, namun data komprehensif mengenai kontaminasi mikroplastik dan peningkatan kualitas melalui teknologi filtrasi pada sistem berbasis perebusan di wilayah pesisir berkembang seperti Sumba Tengah masih sangat terbatas. Penelitian ini bertujuan untuk menentukan kualitas fisik-kimia, kelimpahan ternormalisasi, karakteristik morfologi, dan komposisi polimer spesifik dari mikroplastik pada garam laut dan air tua (brine) dari wilayah pesisir dekat estuari Desa Watu Asa. Penelitian ini menggunakan rancangan acak lengkap dengan tiga ulangan untuk mengevaluasi perlakuan filtrasi fisik menggunakan media arang, pasir, dan ijuk, beserta kontrol. Sampel dianalisis untuk kadar air dan kadar NaCl, yang dilanjutkan dengan destruksi basah menggunakan H_2O_2 30%, kuantifikasi di bawah stereomikroskop, dan identifikasi kimia melalui spektroskopi fourier transform infrared. Hasil penelitian menunjukkan bahwa perlakuan filtrasi berpengaruh nyata terhadap kadar air dan NaCl ($p < 0,05$), di mana filtrasi arang menghasilkan kadar NaCl tertinggi sebesar $95,60 \pm 0,53\%$ dan menurunkan kadar air menjadi $5,20 \pm 0,12\%$. Lebih lanjut, uji t sampel independen menunjukkan perbedaan yang signifikan pada kelimpahan mikroplastik antara air tua dan kristal garam akhir ($p < 0,05$). Kontaminasi mikroplastik menunjukkan prevalensi 100%, melonjak dari 285 partikel/L pada air tua menjadi 35.000 ± 2.500 partikel/kg pada kristal garam. Serat dan fragmen mendominasi dengan ukuran di bawah $250 \mu\text{m}$, sementara spektroskopi FTIR mengidentifikasi berbagai polimer sintesis termasuk *polyvinyl alcohol* (PVA), polietilena (PE), poliakrilonitril (PAN), dan poliuretan (PU). Penelitian ini menyimpulkan bahwa meskipun filtrasi arang cangkang kelapa berhasil meningkatkan kualitas fisik-kimia garam tradisional hingga memenuhi standar nasional, akumulasi fragmen berukuran mikro yang masif menyajikan peringatan keamanan pangan krusial yang menuntut intervensi mendesak dan tingkat lanjut.

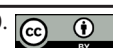
Kata kunci: akumulasi kontaminan, identifikasi polimer, keamanan pangan, metode perebusan, sifat fisikokimia

INTRODUCTION

Salt is a strategic commodity that contains sodium chloride (NaCl) and essential minerals, including magnesium, calcium, and sulfate. The fishery product processing industry depends on salt because it functions as a preservative that reduces water activity to stop microbial growth (Nurjanah *et al.*, 2021). The salt produced must meet national regulations for purity and food safety because salt is an essential ingredient in all food products (BSN, 2016; BSN, 2017). Traditional methods of salt production in East Nusa Tenggara (NTT) Province rely on solar

evaporation and brine boiling, which depend on coastal environmental conditions and their limited technological capabilities (Horwitz, 2006; Maulana *et al.*, 2017; Dawa *et al.*, 2020).

The combination of open production systems and seawater as a raw material results in community-produced salt that is highly susceptible to multiple environmental pollutants. Marine plastic pollution, which degrades into microplastics smaller than 5 mm, is a serious global threat to food safety (Auta *et al.*, 2017; Peixoto *et al.*, 2019). These particles function as persistent materials that scientists have discovered in sea salt products



worldwide (Iñiguez *et al.*, 2017; Barboza *et al.*, 2020). According to Nugroho *et al.* (2018), Kurniawan *et al.* (2021), and Puspita *et al.* (2022), microplastic contamination exists throughout coastal waters and salt products in several Indonesian regions. The research findings from Recent studies conducted in NTT have demonstrated that microplastics exist in both pond water and krosok salt because of human industrial activities (Hidayat *et al.*, 2022; Gadi *et al.*, 2024).

Research on microplastics in solar evaporation systems is currently expanding, but scientists have not yet determined how boiling systems affect microplastic contamination. The brine-processing method used in Watu Asa Village of Central Sumba Regency requires the application of intense heat for a brief duration. The unique production method provides strong evidence that it affects the quantity, physical characteristics, and material composition of microplastics in the final product. The identification process requires Fourier transform infrared (FTIR) spectroscopy, which establishes polymer identification, including polyethylene (PE) and polypropylene (PP), to assess their consequences for food safety (Veerasingam *et al.*, 2021; Salsabila *et al.*, 2023).

To date, a comprehensive evaluation of microplastics in boiling-based salt production systems in Central Sumba has been lacking in the scientific literature. Although recent studies have examined broader profiles of traditional salt across NTT, including areas where microplastics were undetected (Dawa *et al.*, 2026) alongside sites confirming contamination (Gadi *et al.*, 2024), mitigating these quality gaps remains a priority. Various innovations continue to be developed to improve the quality of traditional salt so that it meets national standards and aligns with the demands of healthier functional foods. Excessive sodium consumption from conventional dietary salt has long been identified as a primary risk factor for degenerative diseases, particularly hypertension and cardiovascular disorders, prompting the World Health Organization

(WHO) to recommend strict limits on daily sodium intake.

In response to both contaminant and health challenges, the development of alternative functional salts derived from marine bioresources, such as seaweed, has emerged as a promising strategic solution. Seulalae *et al.* (2023) reported that seaweed salt not only complies with dietary salt standards through lower NaCl levels but also exhibits a sodium-to-potassium (Na/K) ratio close to the WHO recommendations, alongside being rich in essential minerals, dietary fiber, and phenolic antioxidants. Despite its health benefits, the use of seaweed salt requires a comprehensive evaluation of its physicochemical and sensory profiles. Seulalae *et al.* (2023) noted that seaweed salt exhibits lower relative saltiness than standard NaCl and introduces distinct sensory attributes, such as a savory taste, bitterness, and faint sulfur notes, driven by natural minerals and volatile compounds from seaweeds.

Therefore, beyond direct table consumption, assessing the application of aspartame in processed food products is crucial. Ummah *et al.* (2023) demonstrated that incorporating low-sodium seaweed salt derived from *Sargassum* sp. into diversified fishery products (such as surimi-based products or kamaboko) successfully increases ash, crude fiber, and potassium levels while yielding food products with a safe Na:K ratio of <1 for health-conscious consumers. This study aimed to determine the physicochemical quality, normalized abundance, morphological characteristics, and specific polymer compositions of microplastics in sea salt and brine from the coastal area near the estuary of Watu Asa Village. By comparing these findings with regional baseline data and existing impurity levels in traditional salt from other areas, such as Jeneponto (914.67 particles/kg) (Amqam *et al.*, 2022), this study provides essential insights into artisanal salt contamination profiles, serving as foundational data to enhance the quality and safety of community-produced salt in alignment with sustainable fishery product standards.

MATERIALS AND METHODS

Sampling Procedure

Following the methodological frameworks established by Dawa *et al.* (2021) and Dawa *et al.* (2024), this study was conducted from February to March 2026 at a traditional boiling-based salt production site in Watu Asa Village, Mamboro District, Central Sumba Regency, East Nusa Tenggara. In this area, salt production utilizes traditional leaching and boiling approaches. The process begins by gathering salt-enriched soil sediment, which is placed in a filtration container. Following the leaching process with seawater, concentrated brine (*air tua*) is produced. The brine is then boiled until salt crystals are formed. Finally, the crystals are collected, filtered, and sun-dried to produce the final traditional cooking salt product.

Sampling was conducted using purposive sampling to ensure the representativeness of the materials. To account for spatial variability, triplicate brine (*air tua*) samples (200 mL per sample, totaling 600 mL per sampling location) were collected from the storage containers immediately before boiling. For the salt crystal samples, 100 g was collected following the filtration and sun-drying stages. To ensure that the samples were homogeneous and representative of the production conditions, a composite sampling strategy was applied by gathering salt crystals from multiple points across the production batch. This procedure is based on the production scale of a single unit in the study area, which typically processes approximately 100 kg of soil sediment placed on a filtration medium leached with 200 L of seawater to yield 150–180 L of brine per cycle, ultimately producing approximately 100 kg of salt crystals. Consequently, the sampling volume applied was deemed sufficient to provide a representative reflection of the actual production conditions.

Salt Quality Analysis

To provide context on the quality of the salt produced, basic physical and chemical parameters, including moisture content and NaCl levels, were determined in accordance with the Indonesian National Standard

3556:2016 (BSN, 2016). Moisture content was measured gravimetrically, and the NaCl levels were determined by titration. All measurements were performed in triplicate ($n=3$).

Microplastic Isolation and Preparation

Microplastic isolation was conducted using filtration and organic matter oxidation methods modified from Nugroho *et al.* (2018). Brine samples (200 mL) were filtered using Whatman filter paper No. 42. For the salt crystal samples, 2 g of the sample was dissolved in 200 mL of deionized water until completely dissolved, and then filtered using the same method.

The residue on the filter paper was transferred into a beaker, and a 30% H_2O_2 solution was added for the oxidation process. Oxidation was performed at 60°C for 24 h using a hot plate stirrer. After oxidation was complete, the residue was dried in an oven at 60°C for 24 h for further observation.

Microplastic Analysis

Visual identification and abundance

Morphological observations (fiber, fragment, film, granule, and foam) and color identification were performed using a stereo microscope at 40x magnification. All visual identification procedures were conducted in triplicate ($n=3$) for each sample to ensure reproducibility and minimize observer bias. Each particle identified as a microplastic was recorded individually based on its morphological characteristics and color (Amqam *et al.*, 2022). The abundance of microplastics in brine and salt crystals was calculated using Equations (1) and (2), respectively:

$$K_{\text{brine}} = \frac{N}{V} \quad (1)$$

$$K_{\text{salt}} = \frac{N}{M} \times 1,000 \quad (2)$$

Where:

K_{brine} = microplastic abundance in brine (particles/L)

K_{salt} = microplastic abundance in salt crystals (particles/kg)



- N = total number of identified microplastic particles (particles)
V = sample volume of brine (L)
M = sample mass of salt crystals (g)

Polymer type identification with FTIR methods

To identify the polymer types, representative particles were selected based on their prevalence and morphological diversity observed during the visual identification stage. By selecting particles that reflect the dominant morphological categories (the most frequent fiber or fragment types) found across all triplicates, we ensured that the FTIR analysis was representative of the total microplastic population in the samples. These particles were analyzed using FTIR within the wavenumber range of 4,000–400 cm^{-1} via a QATR accessory, and the spectra were compared against a polymer reference library (N=15, HQI>800) to determine the polymer types based on characteristic functional group absorption peaks. Salt crystals exhibited more pronounced peaks than brine owing to their higher concentration during crystallization. Non-polymeric signals, such as inorganic silica/silicate mineral residue at 1088.75 cm^{-1} , originating from coastal sediments (Nugroho *et al.*, 2018) and guanidino-sulfate, were excluded. The confirmed synthetic polymers included polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyacrylonitrile (PAN). Characteristic peaks included C–H stretching (2850–2950 cm^{-1}) for polyolefins and carbonyl C=O stretching (1700–1750 cm^{-1}) for PET and weathered plastics (Yang *et al.*, 2015). Morphologically, PAN primarily appeared as fibers, whereas PE, PP, and PET appeared as fragments and films, aligning with findings for other traditional salt products (Sait *et al.*, 2021; Amqam *et al.*, 2024; Ula *et al.*, 2025). Finally, polymer signatures persisted from the source water into the final salt matrix (Peixoto *et al.*, 2019), although coconut shell charcoal filtration noticeably reduced polymer-related absorption peaks, indicating effective contaminant removal via adsorption (Nilawati *et al.*, 2024).

Data Analysis

This study employed a descriptive quantitative design. To ensure data reliability and minimize measurement bias, all laboratory procedures, including microplastic isolation, morphological identification, abundance calculations for each microplastic type, and determination of salt quality parameters (moisture and NaCl content), were performed in triplicate ($n=3$). Microplastic abundance was defined as the number of particles per unit volume (particles/L) for brine and per unit mass (particles/kg) for salt crystals. Visual identification, abundance assessments, and salt quality measurements were performed in triplicate for each sample. Spectroscopic analysis via Fourier-transform infrared (FTIR) spectroscopy was performed once on representative particles to confirm the polymer types. All collected data were processed using the Statistical Package for the Social Sciences (SPSS) software version 29 (IBM Corp., 2022) to calculate the mean values and standard deviation. The results are presented in tables and graphs to illustrate the microplastic characteristics and physicochemical quality of the salt at the research location. To evaluate significant differences among treatments, a one-way analysis of variance (ANOVA) followed by Duncan's multiple range test (DMRT) was performed for salt quality parameters (moisture and NaCl content) across the filtration treatments using palm fiber, sand, and coconut shell charcoal. Additionally, a t-test was used to analyze the differences in microplastic abundance, morphological characteristics, and size distribution.

RESULTS AND DISCUSSION

Salt Quality Characteristics

The physical and chemical qualities of the traditional boiling-based salt produced in Watu Asa Village were evaluated based on the Indonesian National Standard (SNI 3556:2016) for food-grade salt (BSN, 2016). This evaluation measures key parameters, including moisture and sodium chloride (NaCl) content, to determine the purity and market standard suitability of the final product.

Furthermore, implementing appropriate filtration techniques prior to boiling serves as a crucial intervention to minimize impurities and elevate the chemical grade of traditional salt crystals. The moisture and NaCl content of the salt crystals are presented in Table 1.

The moisture content of the produced salt ranged from 5.20% to 5.25% (Table 1). Statistical analysis using One-way ANOVA ($p=0.965$) confirmed that variations in the filtration media did not significantly affect the moisture levels. This stability suggests that the evaporation process, controlled by macroenvironmental parameters such as solar radiation, humidity, and wind speed, remained uniform across all treatment sites (Batafor, 2020). Although charcoal treatment yielded the lowest moisture value (5.20%), the lack of significant variance indicates that traditional salt drying is primarily governed by environmental conditions rather than brine filtration. All samples successfully met the SNI 3556:2016 standard, which sets a maximum threshold of 7.0% for food-grade salt (BSN, 2016).

In contrast to moisture, the NaCl content showed a highly significant increase across the treatments ($p=0.000$). The Control sample (84.89%) failed to meet the minimum standard for food-grade salt. However, filtration significantly improved the purity. The use of sugar palm fiber (91.27%) acted as a mechanical strainer, effectively retaining Total Suspended Solids (TSS) (Teke *et al.*, 2021). The Sand filter (93.47%) improved this process through deep-bed filtration, trapping finer colloidal particles (Prassetio *et al.*, 2024).

The Charcoal filter achieved the highest purity (95.60%), consistent with the findings of Cescon and Jiang (2020), which highlights the dual-action mechanism of activated carbon: mechanical filtration and chemical adsorption of impurities. By adsorbing hydrophilic impurities such as Mg^{2+} and Ca^{2+} , which typically inhibit NaCl crystal growth, the charcoal filter allows for the formation of cleaner, more optimal cubic NaCl lattices (Gemati *et al.*, 2013; Redjeki *et al.*, 2023).

When evaluated against SNI 4435:2017 for industrial raw salt, the charcoal treatment is the only one that achieved “Quality 1” (Q1) status ($\geq 94.7\%$), while sand and sugar palm fiber reached “Quality 2” (Q2). The control sample fell below the minimum Q3 standard (85.0%), mirroring the structural weaknesses often observed in traditional salt production (BSN, 2017; Batafor, 2020; Dawa *et al.*, 2024). This study confirms that the implementation of simple, low-cost filtration technology, specifically using coconut shell charcoal, can bridge the gap between traditional salt production and national industrial standards. This is a critical step toward reducing Indonesia’s dependence on imported salt and supporting the national targets for salt self-sufficiency (Mangeswuri & Ramadhan, 2024).

Microplastic Abundance

Microplastic abundance data show all identified particles within brine samples, which were measured at the boiling point, and throughout salt crystal samples, which had weight measurements of particles per kilogram. Data were calculated from three

Table 1 Moisture and NaCl content of salt crystals

Treatment	Moisture (%)	NaCl (%)
Control	5.25±0.06 ^a	84.89±0.40 ^a
Sugar palm fiber	5.23±0.15 ^a	91.27±0.15 ^b
Sand	5.22±0.14 ^a	93.47±0.15 ^c
Charcoal	5.20±0.12 ^a	95.60±0.53 ^d

Note: values are presented as mean ± standard error (n=3). Different superscript letters within the same column indicate statistically significant differences based on one-way ANOVA followed by Duncan’s Multiple Range Test ($p<0.05$).



replicates and are presented as mean $\pm$ standard deviation. The results of the microplastic abundance observations are shown in Table 2.

Table 2 shows the abundance of microplastics in *air tua* (brine) and salt crystals. Based on the independent samples *t*-test analysis ($p < 0.05$), the microplastic abundance in salt crystals differed significantly from that in *air tua* for all shapes. The total microplastic abundance in *air tua* was 285 particles/L, consisting of fibers (155.00 $\pm$ 8.66 particles/L), fragments (110.00 $\pm$ 5.00 particles/L), and films (20.00 $\pm$ 5.00 particles/L). The total abundance of salt crystals increased significantly to 35,000 particles/kg, comprising fibers (17,500 $\pm$ 1,000 particles/kg), fragments (13,666.67 $\pm$ 763.76 particles/kg), and films (3,833.33 $\pm$ 763.76 particles/kg). Different superscript letters (a and b) in each column indicate significant differences between the two sample types.

Furthermore, the distribution and types of microplastics identified in both the brine and final salt crystals were analyzed to assess the contamination transition during boiling. As shown in Figure 1, there is a notable variation in the abundance of the fiber, fragment, and film types between the concentrated brine and the resulting salt crystals.

The results of the observation showed that all samples were contaminated with microplastic particles, as shown in Figure 1. The brine sample contained 285 particles/L, indicating that the Central Sumba coastal areas experience severe human-induced contamination of their water sources. This site functions as an estuarine and coastal region that collects all pollutants that enter from land-based runoff, domestic activities, and fishery waste (Auta *et al.*, 2017). Salsabila

et al. (2023) found that human activities and current movements determine microplastic pollution levels in salt production areas used by local communities. The river mouth area receives more plastic waste, which breaks down into tiny plastic particles that remain suspended in water at sizes smaller than 5 mm (Auta *et al.*, 2017; Li *et al.*, 2020).

The liquid matrix (brine) showed a major increase in microplastic concentrations compared to the solid matrix (salt crystals), as shown in Figure 1. The crystallization process shows a concentration effect, which leads to an abrupt increase in the number of sodium chloride crystals. The traditional heating process leads to water evaporation, which causes a major reduction in water volume, while microplastic particles that do not dissolve remain in the sodium chloride crystal matrix (Peixoto *et al.*, 2019). The accumulation phenomenon is reinforced by the high thermal stability of polymers, including polyethylene (PE) and polypropylene (PP), because these materials have melting points that exceed standard boiling temperatures, ensuring particle integrity during production (Auta *et al.*, 2017; Kim *et al.*, 2018).

The matrices showed that fibers were the most prevalent morphological pattern. The dominance of fibers, shown in Table 2, establishes a connection to previous research from East Nusa Tenggara, which found that synthetic fibers from textile waste and fishing gear represent the primary sources of marine pollution in that area (Gadi *et al.*, 2024; Widiaratih *et al.*, 2024). The fibers maintain their suspended state because their long shape and light weight properties enable them to stick to salt crystals (Barboza *et al.*, 2020). The second most common type of waste material

Table 2 Abundance of microplastics in *air tua* (brine) and salt crystals

Sample type	Fiber	Fragment	Film	Total
Brine (particles/L)	155.00 $\pm$ 8.66 ^a	110.00 $\pm$ 5.00 ^a	20.00 $\pm$ 5.00 ^a	285
Salt (particles/kg)	17,500 $\pm$ 1,000 ^b	13,666.67 $\pm$ 763.76 ^b	3,833.33 $\pm$ 763.76 ^b	35,000

Note: Values are presented as mean $\pm$ standard error ($n = 3$). Different superscript letters with-in the same column indicate a statistically significant difference between brine and salt crystal samples based on an independent samples *t*-test ($p < 0.05$).

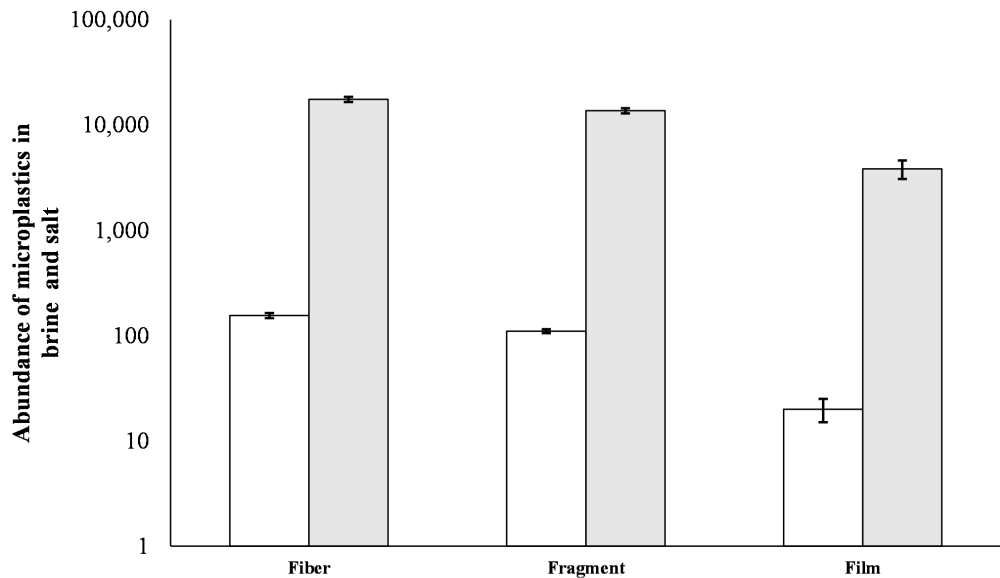


Figure 1 Comparison of microplastic abundance between brine (□) (particles/L) and salt crystals (■) (particles/kg)

originated from mechanical breakdown, which produced fragments of microplastics (Widiaratih *et al.*, 2024), while transparent films appeared in the lowest numbers because their clear appearance makes them difficult to see (Veerasingam *et al.*, 2021).

The finding of 35,000 particles/kg in consumable salt represents a serious warning regarding food safety. The salt production process substantially increases the synthetic particle concentrations, as shown in Figure 1 through its complete visual contrast. Contamination levels pose an ongoing threat to human exposure, potentially leading to oxidative stress and extended body function abnormalities (Ghosh, 2025).

Morphological Characteristics and Size Distribution of Microplastics

An analysis of the size limits was conducted to determine the full range

of microplastics in unfiltered brine and salt crystal samples. The data show which particle sizes can endure both the boiling and crystallization steps of the process. Table 3 shows the microplastic size measurements obtained from both testing matrices.

Table 3 presents the types and size ranges of microplastics found in *air tua* (brine) and salt crystals. Based on the independent samples t-test analysis ($p < 0.05$), the size dimensions of microplastics in salt crystals differed significantly from those in *air tua* for all morphological shapes. For the fiber type, the average size in *air tua* reached $237.50 \pm 19.36 \mu\text{m}$, which was significantly larger than the size found in salt crystals ($213.77 \pm 14.98 \mu\text{m}$). In contrast, the fragment size in *air tua* averaged $88.09 \pm 2.89 \mu\text{m}$, whereas salt crystals recorded a significantly smaller average of $32.14 \pm 1.05 \mu\text{m}$. A corresponding reduction was also observed in the film type, where

Table 3 Types and size ranges of microplastics (μm) in brine and salt crystals

Sample type	Fiber (Min–Max μm)	Fragment (Min–Max μm)	Film (Min–Max μm)
Brine	237.50±19.36 ^b	88.09±2.89 ^b	15.25±0.19 ^b
Salt	213.77±14.98 ^a	32.14±1.05 ^a	6.88±0.42 ^a

Note: Values are presented as mean $\pm$ standard error ($n = 3$). Different superscript letters within the same column indicate a statistically significant difference between brine and salt crystal samples based on an independent samples *t*-test ($p < 0.05$).

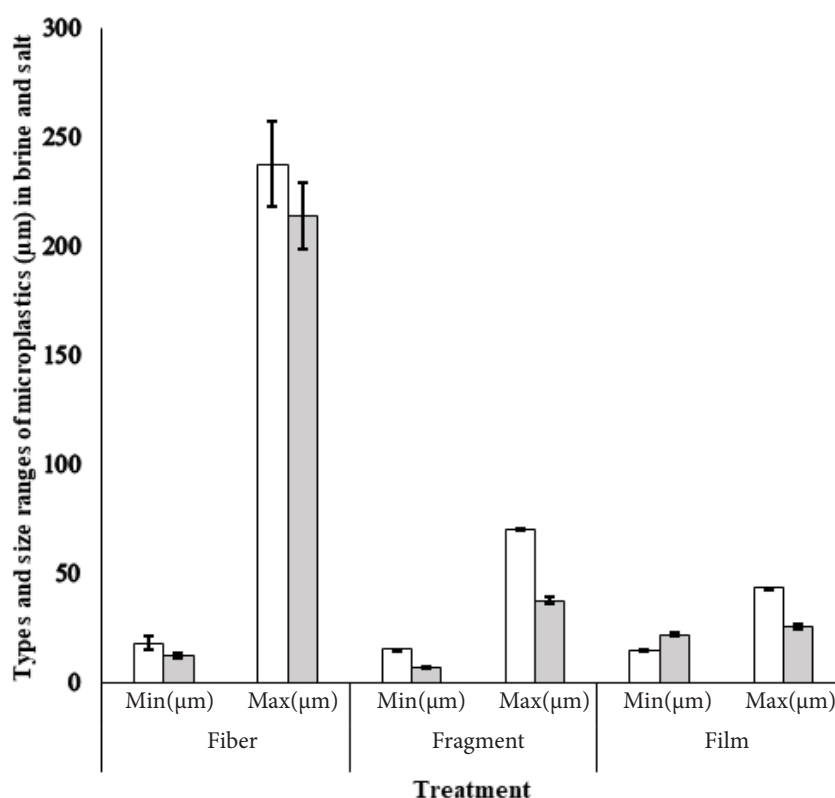


Figure 2 Comparison of size ranges across different microplastic morphologies in brine (□) and salt crystals (■)

the average size decreased significantly from $15.25 \pm 0.19 \mu\text{m}$ in *air tua* down to $6.88 \pm 0.42 \mu\text{m}$ in the resulting salt crystals. Different superscript letters (a and b) in each column indicate statistically significant differences between the two sample types.

The morphological characteristics of the microplastics were further evaluated by analyzing the size distribution of fibers, fragments, and films found in the brine and final salt product. As illustrated in Figure 2, the size ranges (minimum and maximum dimensions) exhibited distinct variations across different morphologies, providing insights into the physical transformation of microplastics during traditional boiling and filtration processes.

Photomicrographs in Figure 2 display the microplastic shape patterns found in Watu Asa Village. The particle size distribution patterns show considerable differences among the various shape categories according to the findings of the microscopic studies and

the data shown in Figure 2. The results show that fiber shapes dominate the analyzed samples because the maximum fiber size reaches $237.05 \mu\text{m}$ in brine and $213.77 \mu\text{m}$ in salt crystals. The thermal stress that occurs during standard crystallization procedures does not affect the physical structure of the fibers because they have a long and flexible design. The research results support Sait *et al.* (2021), who established that polymer textile fibers show extended durability because their degradation process occurs at slow rates when environmental temperatures change. The molecular structure density of polymer fibers renders them more resistant to fragmentation than other polymer forms (Li *et al.*, 2020). The distinct physical appearances of these fibers, along with the fragments and films identified in both matrices, are visually documented in Figure 3.

Microscopic observations revealed distinct distribution patterns across all morphological categories. Fibers remained

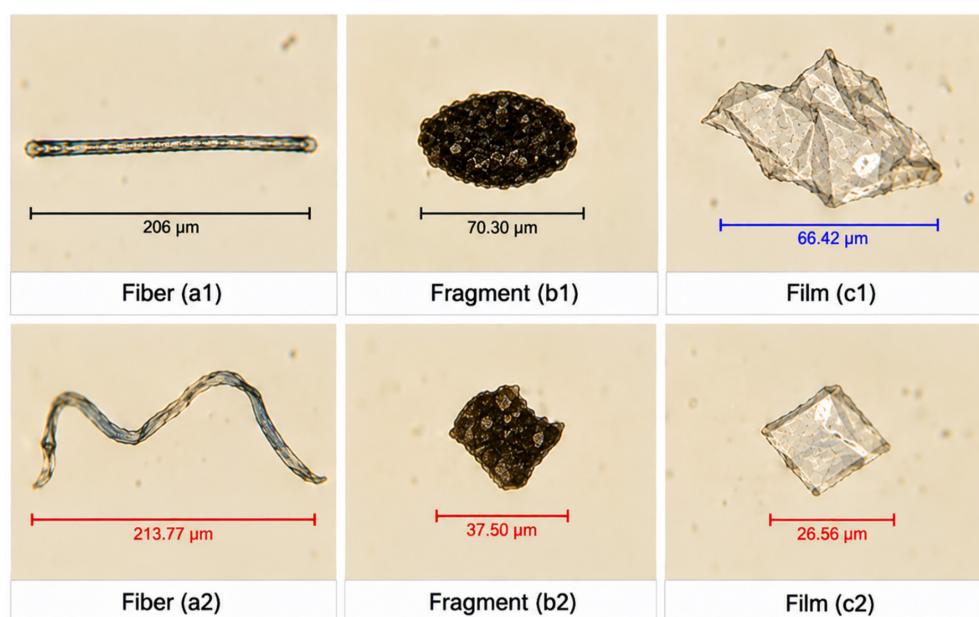


Figure 3 Morphological characteristics of microplastics: top row shows brine samples [(a1) fiber, (b1) fragment, (c1) film]; bottom row shows salt crystal samples [(a2) fiber, (b2) fragment, (c2) film]. Scale bar=100 μm .

the dominant shape in both matrices; their flexible structure provided high resistance to thermal degradation during crystallization, supporting the findings of Sait *et al.* (2021) and Li *et al.* (2020) regarding the durability of textile-derived polymers. In contrast, the fragments exhibited significant dimensional reduction. Fragments decreased from a mean size of $88.09 \pm 2.89 \mu\text{m}$ in *air tua* to $32.14 \pm 1.05 \mu\text{m}$ in salt crystals, while films reduced from $15.25 \pm 0.19 \mu\text{m}$ to $6.88 \pm 0.42 \mu\text{m}$ (Table 3). This breakdown is likely driven by mechanical abrasion and thermal stress during boiling, which compromises the integrity of rigid or thin-film plastic (Auta *et al.*, 2017; Veerasingam *et al.*, 2021). The presence of micro-sized fragments in the final salt product poses a particular concern for bioaccumulation once they are ingested by organisms (Salsabila *et al.*, 2023).

The prevalence of particles $<250 \mu\text{m}$ in the final product indicates that traditional crystallization and washing methods are insufficient for effective microplastic removal, posing a significant risk to food safety in the East Nusa Tenggara region (Widiarati *et al.*, 2024). Similar trends have been reported in global salt studies, where mechanical weathering accelerated by

coastal hydrodynamic forces systematically shifts particle distribution toward smaller cohorts (Sagawa *et al.*, 2018; Mao *et al.*, 2020). Furthermore, the high abundance of fibers is likely exacerbated by atmospheric deposition during open-air evaporation. Given that fibers and fragments frequently account for $>55\text{--}60\%$ of microplastics in sea salts, these results underscore the need for improved filtration to ensure quality control of local salt production.

Functional Group Analysis and Microplastic Polymer Identification (FTIR)

Fourier-transform infrared (FTIR) spectroscopy was employed to identify the synthetic polymers present and examine the chemical functional group transformations across different processing stages. Spectral comparisons between the control brine (Figure 4), control salt, and salt produced through coconut shell charcoal filtration (Figure 5) provide a comprehensive view of microplastic persistence and chemical weathering. By analyzing the vibration bands in the infrared spectra, this study evaluated the structural integrity of the polymers, indicating whether the traditional boiling process and charcoal filtration induced polymer degradation or

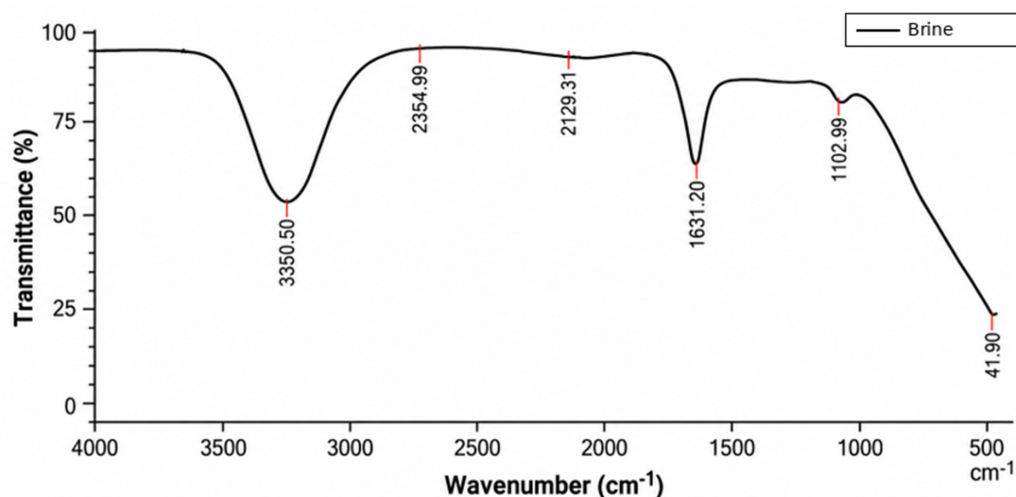


Figure 4 FTIR spectra of microplastics in brine samples

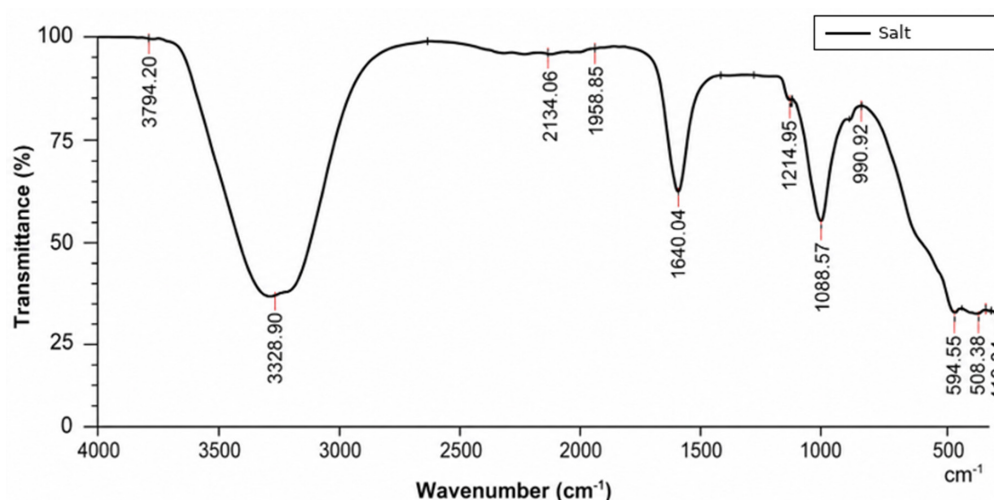


Figure 5 FTIR spectra of microplastics in salt samples

merely physical entrapment. Furthermore, the correlation between the absorption peaks in the brine and the final salt crystals illustrates how the processing conditions influence the specific chemical profile of the microplastic contaminants retained in the final food product.

FTIR characterization of both the control brine and control salt samples revealed distinct functional absorption peaks representative of organic functional groups embedded within an inorganic matrix. The spectroscopic profiles exhibited a prominent broad band at $3,350.50\text{ cm}^{-1}$ in raw brine and $3,328.90\text{ cm}^{-1}$ in control salt, corresponding to the hydroxyl (O-H) stretching vibrations (Veerasingham *et al.*, 2021; Cho *et al.*, 2023). Furthermore, strong absorption peaks

detected at $1,631.20\text{ cm}^{-1}$ (brine) and $1,640.04\text{ cm}^{-1}$ (salt) indicate C=O carbonyl stretching alongside C=C alkenyl structures and bound water bending modes, indicating the presence of weathered polymer fragments such as oxidized polyethylene terephthalate (PET) or poly(vinyl alcohol) (PVA) derivatives (Sait *et al.*, 2021; Vittal *et al.*, 2024). The additional peaks identified in the fingerprint region at $1,088.57\text{ cm}^{-1}$ and $1,102.99\text{ cm}^{-1}$ correspond to C-O alkoxy/ester stretching, which aligns with microplastic contamination profiles documented across Indonesian salt fields, validating that consumer packaging and anthropogenic runoff constitute key matrices embedding into traditional food salts (Vittal *et al.*, 2024; Ula *et al.*, 2025).

The dominant absorption bands at 1,631.20–1,640.04 cm^{-1} and 1,088.57 cm^{-1} strongly indicate environmental weathering and photo-oxidative degradation processes in the coastal environment. Tropical solar UV radiation and high ambient temperatures promote polymer chain scission, driving the formation of oxygenated functional groups (C=O and C-O) (Yang *et al.*, 2015; Sait *et al.*, 2021; Amqam *et al.*, 2024; Ula *et al.*, 2025). This degradation transforms larger macroplastic debris into brittle secondary microfragments before entering estuarine salt intake canals (Dewi *et al.*, 2015; Di & Wang, 2018; Ula *et al.*, 2025). The presence of these prominent oxygenated peaks in the control samples provides chemical verification that microplastics undergo structural alterations due to long-term environmental exposure before settling into salt pans (Sait *et al.*, 2021).

It is worth noting that these spectral classifications should be interpreted with caution, as functional group bands in complex environmental samples often overlap between natural organic matter and synthetic polymer classes (Wang *et al.*, 2021). Nevertheless, a comparative evaluation of the raw brine and final salt spectra demonstrated a distinct phase-trapping phenomenon. The primary absorption peaks (3,328–3,350 cm^{-1} , 1,631–1,640 cm^{-1} and 1,088–1,102 cm^{-1}) identified in raw control brine were consistently preserved in the final control salt, confirming that organic contaminants and microplastics were physically trapped in the sodium chloride (NaCl) crystal lattice during solar evaporation (Auta *et al.*, 2017; Peixoto *et al.*, 2019). As highlighted by Peixoto *et al.* (2019), this uninhibited transfer poses a major concern for food safety, as sea salt serves as a direct exposure pathway for synthetic contaminants in the human diet.

Chemical characterization via FTIR-QATR was utilized primarily for qualitative functional group identification rather than for the absolute quantitative determination of microplastic abundance, as peak heights in the ATR mode are strongly governed by the physical contact area, particle surface roughness, and sample geometry against the diamond crystal (Zhang *et al.*, 2017;

Jung *et al.*, 2018). The quantitative retention efficiencies across the treatments were determined via systematic particle counting using microscopy. A comparison of the FTIR spectra between the unfiltered control samples and charcoal-filtered treatments revealed that the primary organic absorption bands were markedly suppressed or eliminated. This spectral suppression confirms that physical entrapment and surface adsorption within the porous carbonaceous structure of coconut shell charcoal driven by hydrophobic interactions and surface complexation effectively removes organic micro-contaminants without altering the inorganic salt chemistry, offering a viable, low-cost intervention to enhance food safety in traditional salt production (Ojha, 2022; Amarh *et al.*, 2024; Nilawati *et al.*, 2024).

CONCLUSION

This study concludes that traditional sea salt from Watu Asa Village has low initial quality, where control samples fail to meet food grade standards. However, the implementation of a low-cost coconut shell charcoal filtration system successfully improved the salt quality to Quality 1 (Q1) status, with NaCl and moisture content meeting the national standard requirements for consumption salt. Despite this chemical improvement, the final product exhibits widespread microplastic contamination, primarily composed of fibers and secondary fragments made of synthetic polymers (PVA, PE, PAN, and PU), posing a critical food safety concern. Consequently, although charcoal filtration is effective for enhancing salt purity, advanced multistage filtration interventions are urgently needed to mitigate microplastic accumulation and ensure long-term food safety in traditional coastal salt production.

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