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Research article

First-ever study uncovers microplastic contamination in Nepalese table salt

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ABSTRACT

Despite numerous studies on microplastic contamination in table salt worldwide, research focusing on Nepalese table salts is remarkably lacking. This study aims to address this gap by investigating microplastic contamination in salt samples collected from all seven provincial zones of Nepal. Our objective is to comprehensively assess the presence and characteristics of microplastics in salt sold within local markets across the country. Five salt packaging companies utilized by Nepalese consumers were identified. The collected salt samples were digested with Fenton's reagent to extract microplastics, which were then observed under a digital microscope. Using an OMAX stereomicroscope at 30× magnification and an OMAX A3503S digital camera, each microplastic was carefully identified and quantified. FTIR analysis was conducted to identify the polymer types. All tested salt samples (100 %) from both Nepalese and Indian packaging companies contained microplastics. Microplastic abundance exhibits variability among the samples, ranging from 80 to 1040 microplastics per kilogram of salt. The average value stands at 381 ± 219 microplastics per kilogram of salt sample. The distribution of microplastic concentrations within the salt samples reveals that the majority fall within the 301–400 microplastics per kilogram salt range, constituting 33 % of the total samples. Color analysis showed diverse contamination sources, while microplastic shapes included fibers (56 %), films (17 %), fragments (16 %) and pellets (11 %). Polymer type analysis confirmed the presence of polyethylene and polypropylene in tested microplastics. The study estimated that Nepalese individuals ingest an average of 1853 microplastics annually, indicating significant exposure from salt consumption. Surprisingly, factors such as storage conditions, date of salt packaging and thickness of packaging material did not significantly affect microplastic presence in the samples, suspecting manufacturing processes as the primary contributors to contamination. Therefore, the raw materials and purification practices for salt need improvement, as existing methods are insufficient to eliminate microplastics. These findings emphasize the need for further research and mitigation efforts to address microplastic contamination in Nepalese salt and its potential health impacts.

1. Introduction

Since the onset of mass plastic production in the 1950s, the global output of plastic has been steadily increasing. In 2020, nearly 367

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million tons of plastics were produced worldwide [1]. This exponential growth is driven by the widespread use of plastic in various industries, including packaging, construction, automotive, and consumer goods. The durability, versatility, and cost-effectiveness of plastic materials have led to their ubiquitous presence in daily life, contributing to this substantial rise in production [2]. This massive increase includes the production of hundreds of synthetic polymers, such as polyethylene, polypropylene, polyvinyl chloride, polyethylene terephthalate, polystyrene, polyurethanes, and polyamides [3]. The rapid growth in plastic production has led to a corresponding increase in plastic pollution, resulting in widespread environmental contamination [4,5]. These synthetic polymers are now found throughout the environment, including in the air, water bodies, soil, and various organisms [6]. Plastic pollution is a persistent environmental concern with far-reaching consequences [7]. Every year, millions of tons of plastic waste enter marine ecosystems, originating from various sources such as improper disposal, littering, and industrial activities [8].

The production of microplastics in the environment occurs through several processes aggravated by human activities. Microplastics (MPs) are classified into primary and secondary types. Primary microplastics are manufactured plastics for industrial or domestic use including virgin plastic pellets. They are used in various industries, such as cosmetics, textiles and medical applications [9,10]. Moreover, car tire abrasion during driving and laundering synthetic textiles are major sources of primary microplastics [11]. Plastic waste in land and oceans breaks down into smaller, more hazardous secondary microplastics through various degradation processes. These microplastics come from sources like fishing nets, industrial pellets, and household items. Various environmental and mechanical factors control the rates at which plastics fragment. Fragmentation is driven by biodegradation, photodegradation/UV-radiation, thermo-oxidative degradation, thermal degradation, and hydrolysis [12]. Furthermore, construction materials, household items, packaging materials, food and drink packaging waste, and waste from shipbuilding are significant sources of larger plastic debris on land [13,14]. Other prominent contributors to microplastic pollution in aquatic environments include sewage sludge [15,16] and medical waste including medical masks [17].

Microplastics, ranging from 1 to 5000 μm in size, are emerging pollutants that have infiltrated every environmental component. These tiny particles are found in physical components like outdoor and indoor air [18,19], lakes [20], rivers [21], snow [22] and soil [23]. They have also been detected in biological components, including various organisms such as fish and earthworms. Furthermore, they have made their way into various human foods, including sugar [24], milk [25], mineral water and soft drinks [26], honey [27], tea [28], bottled water [29,30], and even table salt [31–33]. Microplastics have been discovered in diverse locations, from the summit of Mount Everest [34] to the depths of the Sea floor [35].

The relationship between microplastics and pollutants in the environment is intricate and interconnected. Microplastics can act as carriers or "sponges" for various pollutants in the environment. These pollutants can include persistent organic pollutants (POPs) like polychlorinated biphenyls (PCBs), heavy metals, pesticides, pharmaceuticals and other harmful chemicals [36]. Tetracycline (TTC), an antibiotic, can be absorbed by microplastics, posing harmful effects on human health [37]. Research has demonstrated the effectiveness of aquatic plants (algae) and certain fungi in the removal of microplastics. Zahmatkesh Anbarani et al. [38] found that *Saccharomyces cerevisiae* achieved 98.81 % polystyrene microplastic removal under optimized conditions, revealing its potential as a natural, eco-friendly biocoagulant. Similarly, Nasrabadi et al. [39] reported that a significant portion of studies (34.21 %) in their review has found polymer biodegradation over 21–30 days, with 44 % focusing on low-density polyethylene (LDPE) biodegradation by various Aspergillus species. Key strains, including *Aspergillus niger, Aspergillus flavus*, and *Aspergillus oryzae*, are remarkably effective in degrading microplastics. Furthermore, *Chlorella vulgaris* has been identified as an efficient, simple, and cost-effective biocoagulant capable of removing various pollutants via coagulation and flocculation, specifically targeting polyethylene microplastics [40]. Eydi Gabrabad et al. [41] found that *Spirulina. platensis* effectively removes polystyrene (81 %) from water, concluding that algae offer a convenient and eco-friendly alternative to chemical coagulants for removing microplastics. Collectively, these findings show the potential of both fungi and algae as sustainable solutions for mitigating microplastic pollution in aquatic environments.

Microplastics pose significant threats to organisms and ecosystems. They can be ingested by marine and terrestrial wildlife, causing harmful effects. Due to their smaller size, both microplastics and nano plastics are readily absorbed by a wide range of organisms [42]. In aquatic invertebrates, microplastics reduce feeding behavior and fertility and slow larval growth. In fish, microplastics can damage the intestine, liver, gills, and brain, affecting metabolic balance, behavior, and fertility. The severity of these effects depends on the particle sizes, doses, and exposure conditions [43]. Microplastics also play a role in affecting human health. Microplastics can lead to metabolic disorders, organ dysfunction, DNA damage, neurotoxicity, and reproductive and developmental toxicity [44]. Recent report has associated microplastic detection in human penis [45] with detrimental effects on male fertility and sperm quality, posing a potential threat to successful conception [46]. Microplastic exposure through ingestion, inhalation, and dermal contact reveals significant health risks. Ingestion is associated with gastrointestinal issues, endocrine disruption, and the potential transmission of pathogens. Inhalation of airborne microplastics poses concerns for respiratory and cardiovascular health [47].

Table salts contain traces of microplastics, potentially originating from various sources such as plastic waste in oceans and rivers [48]. These microplastics can enter the salt supply chain through environmental contamination during harvesting, processing, or packaging [49,50]. As a result, consuming table salt could accidently introduce microplastics into the human diet, raising concerns about potential health effects. Moreover, salts are predominantly sourced from the sea, saline lakes, rocks, and wells [50]. The production process typically involves crystallization in solar work ponds due to evaporation and sunlight [51]. However, saltworks in anthropogenically-impacted coastal areas are susceptible to contamination from various pollutant, including microplastics [49]. The circulation of sea and freshwater in solar saltwork ponds creates a gradient of environments with different salinity levels, potentially leading to the presence of microplastics in commercial sea salts [50].

Salt serves as an ideal medium for delivering iodine and other essential nutrients, as it is universally consumed at relatively uniform levels across society, irrespective of economic disparities [52]. The World Health Organization [53] provides guidelines recommending a daily salt intake of 5 g per person (adult). Salt intake among Nepalese individuals is notably high, averaging 13.3 g per person per day [54]. This figure exceeds the salt consumption levels observed in global average of 10.78 g [53]. Microplastic ingestion is likely to rise in Nepal due to the country's high salt intake. This is because higher salt intake increases the overall quantity of food consumed, potentially leading to greater exposure to microplastics present in salt and other food sources [55].

Despite numerous studies conducted on microplastic contamination in salt from various countries, there is a notable absence of research focusing on Nepalese salts. This study aims to fill this gap by investigating microplastic contamination in salt samples collected from all seven provincial zones of Nepal. The objective is to comprehensively assess the presence and characteristics of microplastics in salt sold within local markets across the country. Moreover, this research aims to assess the association between the abundance of microplastics in salt and key factors: the date of manufacture, storage conditions during sale, and the packaging practices of Nepalese and Indian salt companies. By conducting this study, researchers seek to contribute valuable insights into the extent of microplastic pollution in Nepalese salt and its annual ingestion by people living in Nepal.

2. Methodology

2.1. Sampling

In our comprehensive sampling effort spanning all 7 states of Nepal, from the Terai to the Himalayan region and from Eastern to Western Nepal, we identified a total of 5 salt packaging companies available in the market/district (Table 1) (Fig. 1) and utilized by Nepalese consumers. Out of the 24 salt samples collected, 15 were attributed to the popular brand "Aayo nun," packaged within Nepal by the Salt Trading Corporation Limited from various locations and city areas. Additionally, 9 salt samples packaged from neighboring India. These samples representing various brands were randomly collected from local shops across different districts and states. In total, we documented five salt companies, with one originating from Nepal and four from the neighboring country, India. One kg "Aayo Nun" package is available in the market and is packaged in plastic material by both Nepalese and Indian companies. The thickness of the packaging materials for salt varies slightly.

In this study, above sample ID were further categorized as follows: A(Indian), B (Indian), C (Nepalese company), D(Indian) and E (Indian). A, B, D, E stands for different salt packaging companies of India.

During sampling, information such as the collection date, packaging date, sampling site, batch number, storage conditions, and packaging companies were recorded. The salt samples were carefully collected, placed in clean cloth bags to prevent contamination, and then transported to the lab.

2.2. Extraction of microplastics

Microplastics in the table salt samples were extracted using a slightly modified version of the method developed by Yang et al. [50]. A salt sample weighing 50 g was treated with 30 mL of Fenton's reagent (20 mL of 30 % hydrogen peroxide + 10 mL of Fe^{2+} catalyst) in a beaker. After settling for 30 min, the solution underwent an additional 15 min of stirring using a magnetic stirrer. Following this, 250 mL of filtered distilled water were added to completely dissolve the salt, forming a saturated solution. The solution was then left to incubate overnight at 50 °C to ensure thorough dissolution. Subsequently, the solution was sieved through steel sieves with apertures

Table 1
Salt sample collected from different districts with required information.

Sample ID	Location (Sample collection district)	Packaging Date	Storage during sale	Packaging Countries
S1	Kailali	October 2023	Outdoor	Nepal
S2	Surkhet	November 2023	Indoor	Nepal
S3	Salyan	September 2022	Indoor	India
S4	Kapilvastu	June 2023	Indoor	India
S5	Dang	March 2023	Indoor	India
S6	Rupandehi	April 2023	Indoor	India
S7	Humla	Aug 2022	Outdoor	Nepal
S8	Ramechhap	June 2022	Indoor	India
S9	Bara	December 2023	Outdoor	Nepal
S10	Parsa	December 2023	Outdoor	Nepal
S11	Nawalparasi	December 2023	Outdoor	Nepal
S12	Makwanpur	December 2023	Outdoor	Nepal
S13	Gorkha	March 2023	Outdoor	Nepal
S14	Tanahu	September 2022	Indoor	India
S15	Chitwan	March 2023	Indoor	India
S16	Chitwan	October 2023	Outdoor	Nepal
S17	Dhading	March 2023	Indoor	India
S18	Sindupalchowk	May 2023	Outdoor	Nepal
S19	Kathmandu	December 2023	Outdoor	Nepal
S20	Bhaktapur	February 2023	Indoor	India
S21	Lalitpur	May 2023	Outdoor	Nepal
S22	Sunsari	January 2024	Outdoor	Nepal
S23	Morang	November 2023	Outdoor	Nepal
S24	Doti	November 2018	Outdoor	Nepal

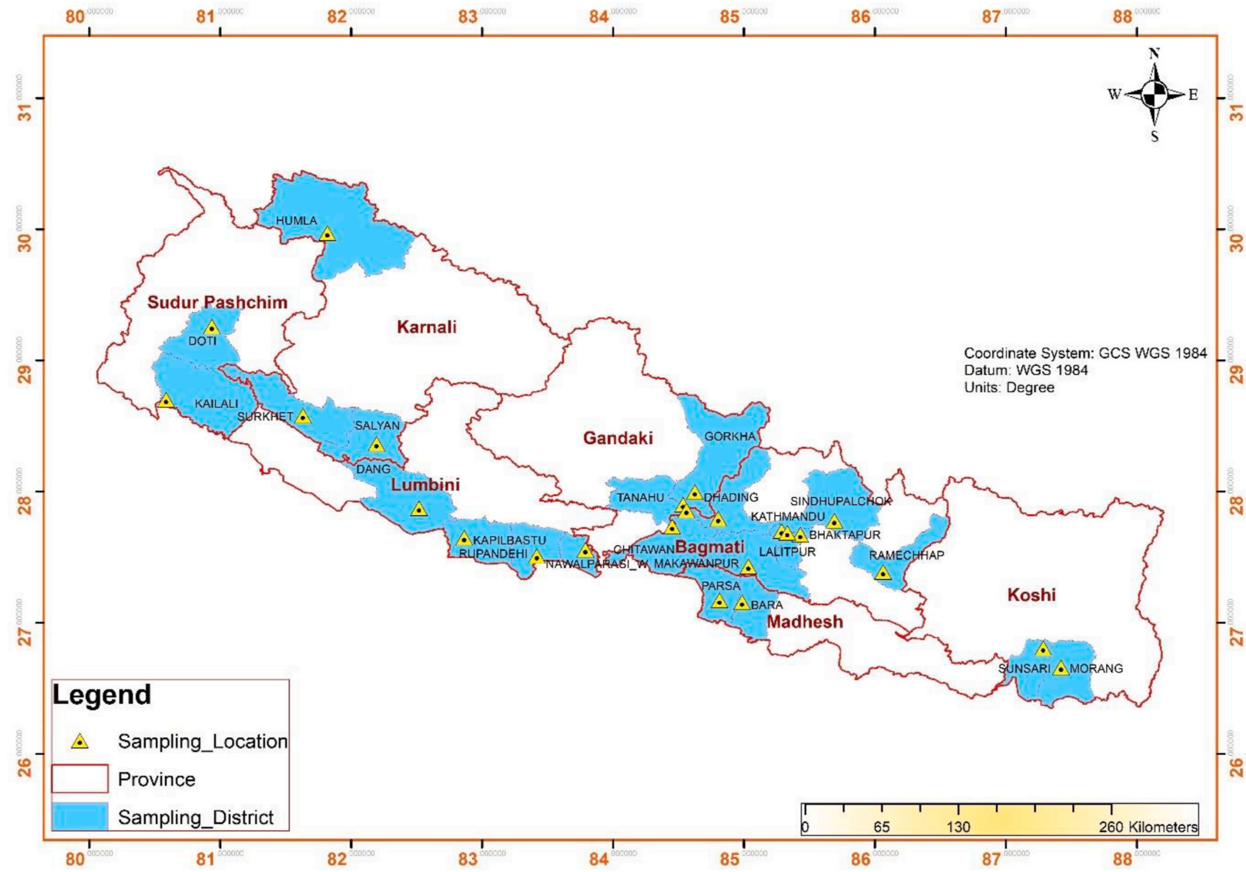

Fig. 1. Salt sample collected from different district.

of 5 mm and 44 μm, limiting the size of the microplastics under study to between 5 mm and 44 μm. Particles retained in the 44 μm sieve were washed with distilled water and collected in a glass beaker. The collected material then underwent filtration using a vacuum filtration setup with a glass microfiber filter paper of pore size 1.2 μm and a diameter of 47 mm. In the process of density separation and filtration, the filter paper containing the residue was washed with a 20 mL solution of Zinc Chloride ($ZnCl_2$) into a beaker, ensuring no residue remained. The solution was left to settle for 1–2 h, after which the supernatant was carefully filtered to separate the particles from the $ZnCl_2$ solution.

Following the initial washing steps, a secondary washing with distilled water was conducted to ensure the thorough removal of any remaining residue in the beaker. The beaker was carefully rinsed with distilled water, and after allowing it to settle for an additional 20 min, the supernatant was passed through the same glass microfiber filter paper. This process was repeated once more to guarantee the comprehensive extraction of all residue. Subsequently, the filter paper containing the microplastic residue was air dried in a laminar air flow for approximately 30 min.

2.3. Identification and characterization of microplastics

Once completely dried, the microplastics present in the filter paper were examined under a stereoscope at 30× magnification using an OMAX microscope from China, and images were captured using an OMAX A3503S microscope digital camera. Each microplastic in the salt samples was carefully identified and quantified. In cases where confusion arose due to the presence of organic matter, and transparent microplastics, the hot needle method was employed to distinguish microplastics. Additionally, identified microplastics were carefully collected and individually wrapped in aluminum foil for Fourier Transform Infrared Spectroscopy (FTIR) analysis. For identifying microplastic polymers, ATR-FTIR (IRAffinity, 1S, SHIMADZU, Japan) was utilized, covering wavelengths from 400 to 4000 cm^{-1}.

2.4. Quality control and quality assurance

To prevent contamination, the distilled water, hydrogen peroxide and zinc chloride used were carefully filtered using a 1.5 μm pore size glass fiber microfilter. All required glassware were thoroughly rinsed with filtered distilled water. Additionally, samples were properly covered with aluminum foil when not being processed. To prevent procedural contamination, a set of procedural blanks (control) was used which included filtered water used for the extraction process. All experimental procedures were conducted in Biosafety cabinet and a 100 % cotton laboratory coat was worn throughout the process. Moreover, researchers adhered to strict protocols, including wearing nitrile gloves and cotton masks, and ensuring that the windows remained closed to prevent dust particles from entering the environment.

2.5. Measurement of thickness of salt packaging material

The thickness of each plastic material was measured using a micrometer (Insize 3109-25a 0–25 mm digital outside micrometer. The meter has a resolution of 0.001 mm and can measure within a range of 0–25 mm. The accuracy of the gauge is within ± 2 μm.

2.6. Microplastic ingestion from table salt in a year

The annual microplastic ingestion from salt consumption was determined using a modified equation derived from Ref. [56].

$$MP_{ISY} = \frac{\propto \times \beta \times 365}{1000}$$

In this equation, MP_{ISY} represents the microplastics ingested from salt per year (MPs/year), ∝ signifies the mean microplastic concentration (particles/kg) in salt samples, and β indicates the daily salt consumption (g) for adults. Daily salt consumption data were based on the World Health Organization recommendation of 5 g daily salt intake for humans [53]. The daily salt consumption (g) for Nepalese people was sourced from a study conducted by Neupane et al. [54].

Salt intake by Nepalese people was recorded 13.3 (±4.7) g/person/day.

2.7. Statistical analysis

To determine the relationship between the abundance of microplastics in salt samples and various independent factors, we employed correlation analysis and independent t-tests. The correlation analysis was employed in between microplastic level and potential influencing factor such as thickness of packaging material. Independent *t*-test was used to compare the mean abundance of microplastics between different groups within these factors, such as packaging date and storage environment (Indoor and Outdoor).

2.8. Ethical approval

Review and/or approval by an ethics committee was not needed for this study because it does not involve human or animal experiments, nor does it include questionnaire surveys, interviews, or focus group discussions.

3. Results and discussion

This research aims to quantify and analyze the presence of microplastics in salt samples, a concern due to potential health risks associated with microplastic ingestion.

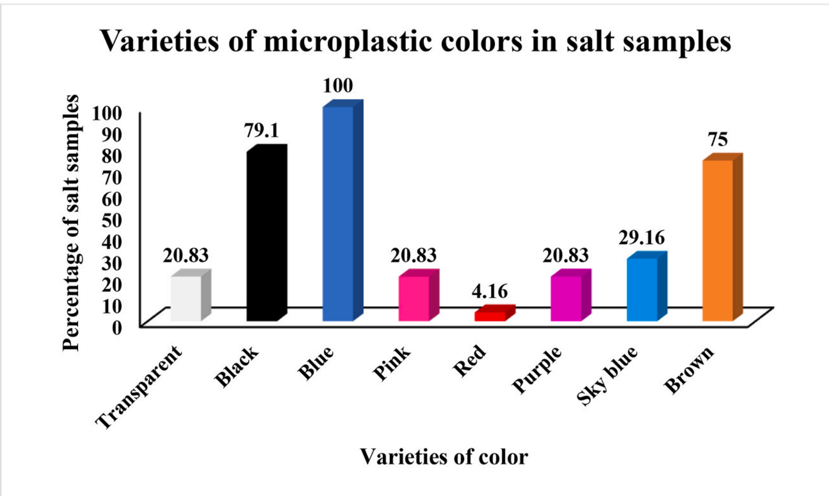

Fig. 2. Color of microplastic recorded in salt samples. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.1. Physical and chemical characteristics of microplastics

3.1.1. Color of microplastics

The presence of microplastics in salt samples can be identified through their various colors. Each color represents a different type of plastic polymer or a result of environmental exposure and degradation. The color distribution of microplastics in a salt sample reveals diverse sources and widespread contamination. In the present study, eight different colors of microplastics were recorded in the salt sample (Fig. 2).

A total of 24 salt samples were analyzed for microplastic content. Blue microplastics were present in all samples (S1 to S24), indicating a 100 % occurrence rate (Fig. 2). This suggests that blue-colored plastics are either widely used and discarded or more prone to breaking down into microplastics, making them ubiquitous in the environment. Black microplastics were found in 19 (79 %) out of the 24 samples (except S4, S5, S6, S12, S15). Brown microplastics were identified in 18 samples (75 %) (except S2, S3, S5, S8, S11, S17) closely following black, indicating another common type of microplastic in the environment. Sky blue microplastics appeared in 7 samples (29 %) (S4, S6, S9, S12, S13, S16, S18) which, while less frequent than blue, black, and brown, still represent a noticeable presence. Others colors were pink, red, purple and transparent. The variability in the occurrence of different colored microplastics could be due to differences in the production, usage, and degradation of various plastic products. The study found that the specific blue, green, and red pigments were significantly degraded [57].

The color of microplastics were also noticed by various researchers [58,58–60] in their salt samples. They reported black, red, blue, green, brown, white, grey, pink, purple, and transparent. The salt sample predominantly contained microplastics of a blue color, with white and black being the subsequent most prevalent colors in their study. The present study is less or more similar to their findings as blue and black color is also dominant in our study.

In Nepalese salt samples, the most common microplastic colors are blue (all samples), black (present in almost all samples except S12 sample) and brown (except S2 and S11). Transparent, pink, red, purple, and sky blue microplastics are less prevalent. For Indian salt samples, blue microplastics are also prevalent, appearing in all samples, black was also present in the maximum samples except S4, S5 and S6. However, brown and sky blue microplastics are less common, each appearing in 56 % of samples. This comparison shows that black and blue microplastics are the most prevalent colors in both countries, while the presence of other colors varied.

3.1.2. Shape of microplastics

Microplastics exhibit diverse shapes, including fibers, fragments, films, pellets, and irregular particles. The shape can be influenced by the original plastic product, environmental weathering, and degradation processes. The particles exhibit surface morphology indicative of continuous weathering, mechanical fracture, and oxidation processes [61]. In our study, various shapes including fiber, fragment, film and pellets of microplastics were observed in the salt samples (Figs. 3 and 4). The majority of microplastics are in the form of fibers, comprising 56 % of the total. This suggests that fibrous microplastics are the most prevalent shape observed in the samples. Following fibers, films constitute 17 % of the total, indicating thin, sheet-like microplastics present in the samples. Fragments make up 16 % of the total, indicating that broken pieces of larger plastic items contribute to a significant portion of the microplastic pollution. Pellets account for 11 % of the total, representing small, rounded plastic particles often used as raw material in plastic manufacturing processes. Fibers, often originating from textiles, represent a significant proportion, highlighting potential sources and pathways of microplastic pollution [62,63]. The origins of the microplastic fibers are likely from the processing and packaging facilities of salt-producing firms, potentially accompanied by airborne particles. The packaging materials used for the salt consisted mainly of polyethylene, as stated by Vidyasakar et al. [64]. Microplastic fibers enter the environment by detaching from clothing and textiles, primarily due to friction occurring at various stages of a garment's life cycle. This includes the manufacturing of fabric, garment production, and subsequent wearing and washing. Throughout these processes, millions of microplastic fibers are released into water and air. Moreover, the potential source of microplastics in the form of fibers is the fishing industry, where fishing nets and ropes were utilized [65]. Fragment shaped are derived from broken-down pieces of larger debris, such as plastic bottles which ultimately mixed with aquatic environment. They are a common type of plastic waste derived by breakdown by UV light, wind, and waves [66].

Various researchers have examined the shape of microplastics found in salt, revealing a range of characteristics and distributions.

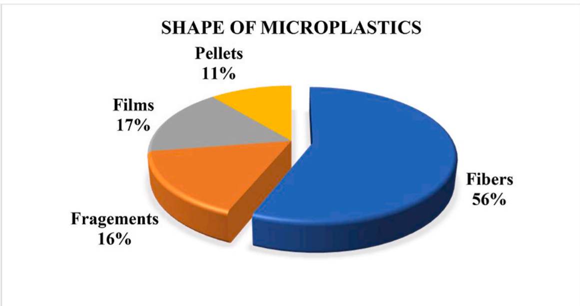

Fig. 3. Shape of microplastics recorded in salt samples.

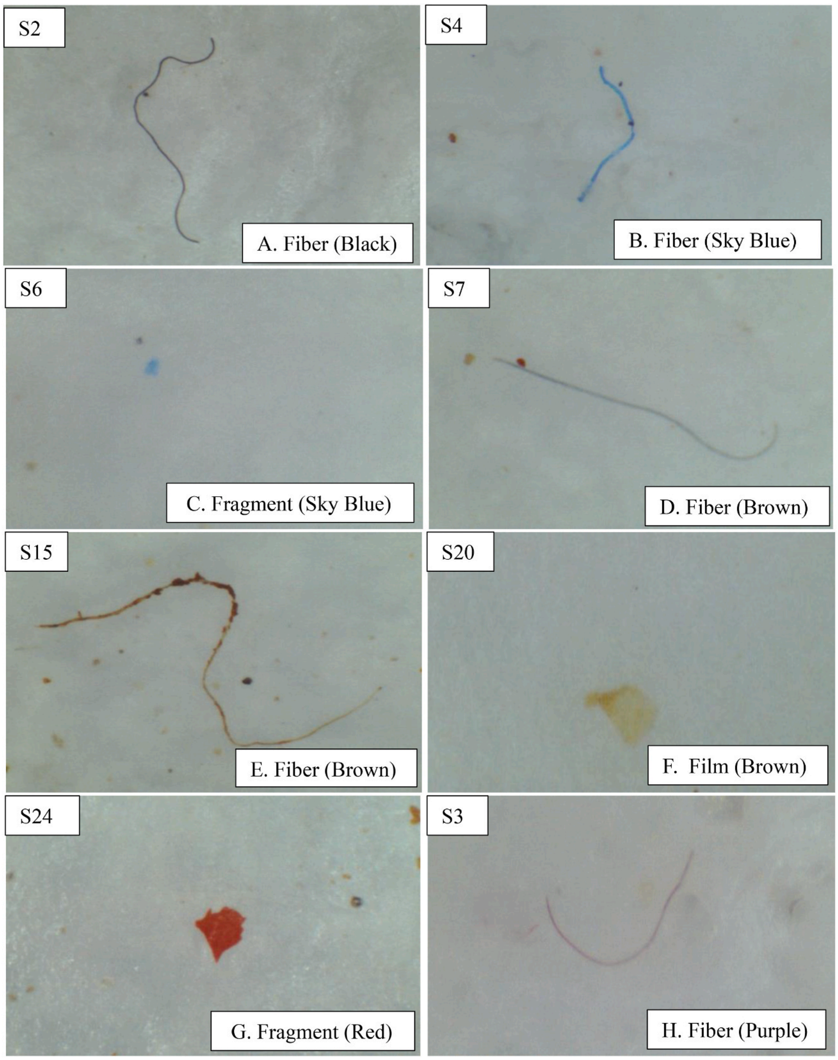

Fig. 4. Different shape of microplastics recorded in salt sample.

Fiore et al. [67] observed fibers as the predominant shape, followed by fragments and spherical particles. Similarly, Shokunbi et al. [60] recorded fibers as the most common shape, followed by fragments. Lee et al. [68] found that 93 % of recorded microplastics were fragments, with only 7 % being fibers. On other hand, Nithin et al. [58] documented exclusively fibers in their samples. Mazumder et al. [69] reported a higher prevalence of fibers (79 %) compared to fragmented particles (19.9 %). Additionally, Makhdoumi et al. [24] observed a majority of fragments (78.57 %) with a smaller proportion of fiber-shaped microplastics (21.43 %).

The distribution of various shapes of microplastics (MPs)- fibers, fragments, pellets, and films were recorded across 24 different samples (S1 to S24). Our findings revealed a predominance of fibers across most samples, with counts ranging from 60 (S12) to 420 MP/kg salt samples (S15), indicating that fibers are the most frequently encountered shape in these samples. Fragments show a significant presence in several samples, particularly in S13 (160 MP/kg), S14 (180 MP/kg), S17 (300 MP/kg), and S24 (180 MP/kg). Pellets, though less common than fibers and fragments, appear notably in samples like S5 (80 MP/kg), S7 (60 MP/kg), S10 (120 MP/kg), and S17 (200 MP/kg). Films are highly variable across samples, with some samples showing no films (S1, S3, S4, S6 and S18), while others have high counts such as S5 (140 MP/kg), S12 (120 MP/kg), S14 (180 MP/kg), and S17 (180 MP/kg).

The distribution of shape of microplastics in table salt samples from Nepalese packaging companies and Indian companies is relatively similar, a slightly higher number of fibers in the Nepalese samples and pellets in Indian companies (Fig. 5)

3.1.3. Type of polymers

The prevalence of certain polymers in salt, particularly polyethylene, polypropylene, and polyethylene-terephthalate, aligns with their widespread global usage and common presence in the marine environment [48,70,71]. Moreover, polyethylene and polypropylene are the predominant forms of plastics, constituting 60 % of the total worldwide plastic production. These polymers have a

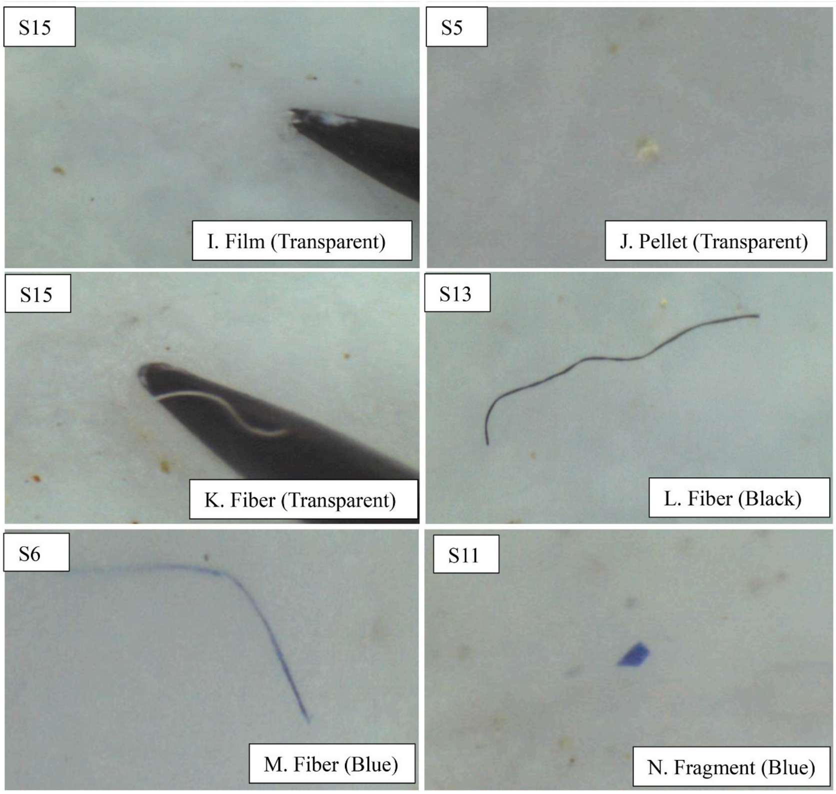

Fig. 4. (*continued*).

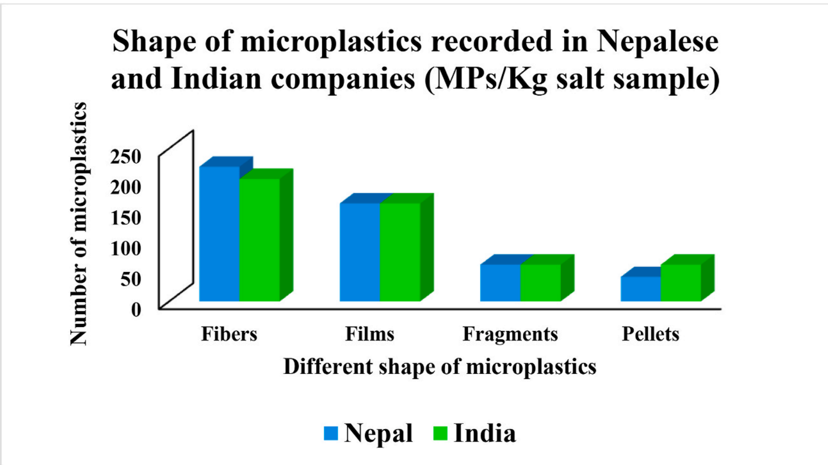

Fig. 5. Different shape of microplastics recorded in salt samples packaged by Nepalese and Indian companies.

low density, measuring less than 1 g/cm^3, which causes them to float on the surface of the sea [72,73]. In the present study, only two types of polymers were identified: polyethylene (PE) and polypropylene (PP) (Fig. 6a and 6b). Among the samples analyzed, polyethylene was the dominant polymer, comprising 80 % of the total polymer content. Polypropylene was less prevalent, accounting for 20 % of the polymers identified. This distribution suggests that polyethylene is the most common polymer contaminant in the environment being studied, possibly due to its widespread use in packaging, containers, and various consumer products. Several studies conducted in different countries have investigated the presence of specific polymer types in commercial salt samples. In Turkey, Gundogdu [74] examined 16 brands of commercial salts and identified the presence of polyethylene (PE) and polypropylene (PP) polymers. Similarly, in Spain, Yang et al. [50] analyzed 21 brands of commercial salts and found polymers such as polyethylene terephthalate (PET), polypropylene (PP), and polyethylene (PE). In Nigeria, Fadare et al. [75] investigated 4 table salts and detected

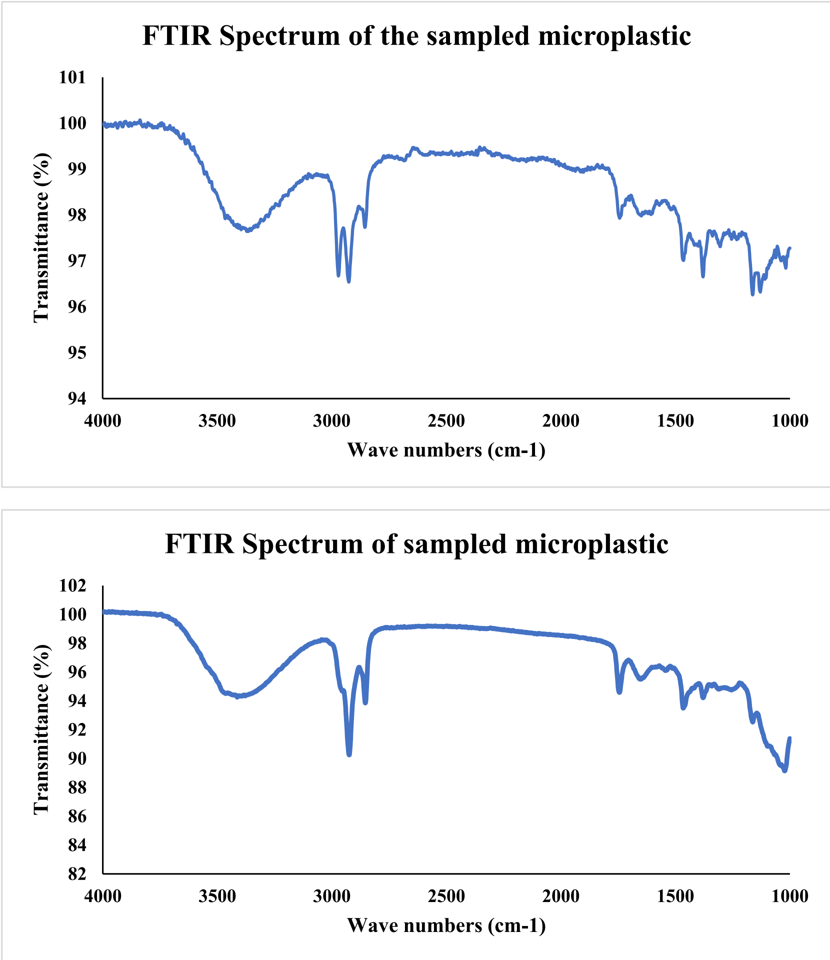

Fig. 6a. 6a Type of polymer (polypropylene) in sample (S23).
6b Type of polymer (polythene) in sample (S10).

polymers including fluorinated polypropylene (FPP), polyethylene (PE), and polyvinyl acetate. Furthermore, Kosuth et al. [76] studied commercial salt samples from Italy and Croatia, identifying the presence of polypropylene (PP) and polyethylene terephthalate (PET) polymers. Similarly, Makhdoumi et al. [24] obtained the result that polypropylene (PP) and polyethylene (PE) were present in table salts. Lee et al. [68] in their review found that 94 % of salt products tested globally contained microplastics, with the majority of particles being PET, PP, and PE. Research conducted across various countries has consistently revealed the presence of specific polymer types in commercial salt samples.

3.2. *Abundance of microplastic in table salt*

The concentration or abundance of microplastics in a given environment is a critical characteristic. It reflects the density of these particles within a specific area or sample. The abundance of microplastics varies spatially, depending on factors such as location, hydrodynamic situation, environmental stress, and duration [77]. The abundance of microplastics is normally dependent upon anthropogenic and environmental factors including the surrounding ecosystem, ocean currents, and weather conditions [78,79]. Rising sea levels and altered ocean currents facilitate the widespread distribution of microplastics globally. These environmental changes, coupled with the impact of extreme weather events like hurricanes and storms, contribute significantly to the dispersion of plastic debris across marine ecosystems [80]. Since the marine ecosystem is the primary source of salt production, it is vulnerable to microplastic contamination Microplastic contamination in salt originates from environmental pollution as well as during the production and packaging processes [61].

The abundance of microplastics varies across the samples, ranging from 80 to 1040 microplastics per kg of salt (Fig. 7). The average microplastic concentration is 382 ± 219 particles per kilogram of salt sample. Some samples, such as S5 (Dang), S10 (Parsa), S14 (Tanahu), S15 (Chitwan), S17 (Dhading) and S22 (Sunsari) have relatively high abundances of microplastics, exceeding 500 microplastics per kg of salt. On the other hand, samples like S3 (Salyan) and S4 (Kapilbastu), have lower abundances, less than 100 MPs per kg of salt.

The distribution of microplastic concentrations across the salt samples, with the majority falling within the 301–400 microplastics per kg salt range, comprising 33 % of the total samples (Figs. 8 and 9). It also shows the presence of both lower and higher concentrations of microplastics, indicating varied levels of contamination among the samples.

Microplastic contamination in salt samples packaged by different companies in India reveals varying levels of concern regarding the presence of these harmful particles. Among the companies listed, two Indian companies (categorized A and B) exhibit relatively low average abundances of microplastics in their packaged salt, with 107 and 120 microplastics per kg salt sample, respectively. These lower levels may indicate more stringent quality control measures or manufacturing processes that minimize contamination. However, the situation becomes more alarming with Nepal Salt Trading Corporation Limited (Categorized as Company C), which shows a significantly higher average abundance of microplastics at 369 per sample. This suggests a potential issue with the sourcing, processing, or packaging of the salt, leading to increased contamination levels compared to the previous companies. The concerns worsen further with Indian company (Categorized as Company D, where the average abundance of microplastics in their packaged salt skyrockets to 760 per sample and maximum was recorded 1040 per kg salt sample. This alarming figure indicates a substantial contamination level, raising questions about the company's production practices and the overall safety of their products for consumption. Similarly, another Indian Company E also presents a high average abundance of microplastics at 450 per sample (Fig. 10). The present findings need to suggest for comprehensive measures to address microplastic contamination in packaged salt across various companies in India. However, average microplastic contamination levels in salt packaged by Nepalese company tend to be slightly higher (369 per kg salt) compared to salt packaged in India (359 per kg salt) (Fig. 11). Nevertheless, there is no significant difference in the abundance of microplastics in salt samples between Nepalese and Indian companies, as indicated by a p-value greater than 0.05 ($p = 0.730$). This suggests that both sources contribute similarly to microplastic contamination in the studied samples.

Microplastics contamination in table salt has been extensively studied by various researchers, revealing diverse levels and characteristics of pollution. Li et al. [31] documented microplastics ranging from 20 to 125 particles per kilogram, while Nakat et al. [33] observed contamination in 81.3 % of brands, with packed and coarse salt exhibiting higher pollution levels than bulk or fine salt.

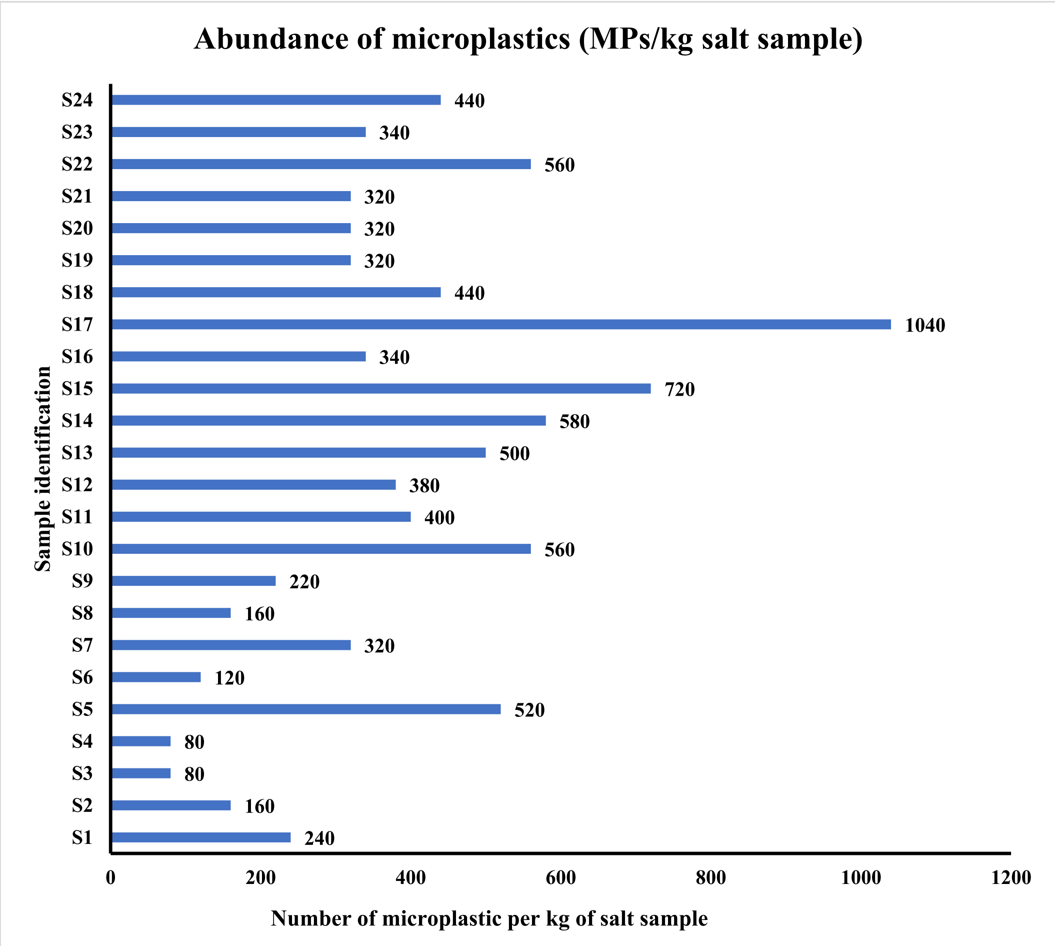

Fig. 7. Abundance of Microplastics in salt samples.

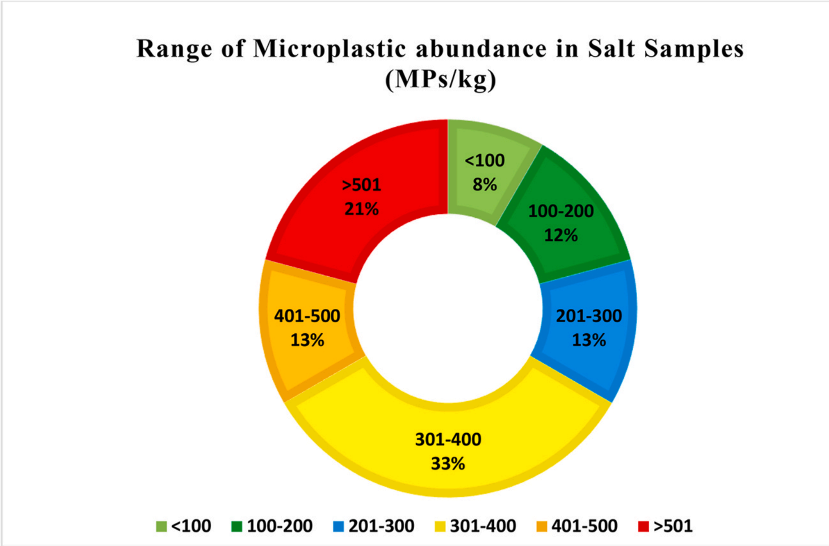

Fig. 8. Range of microplastic recorded in salt samples.

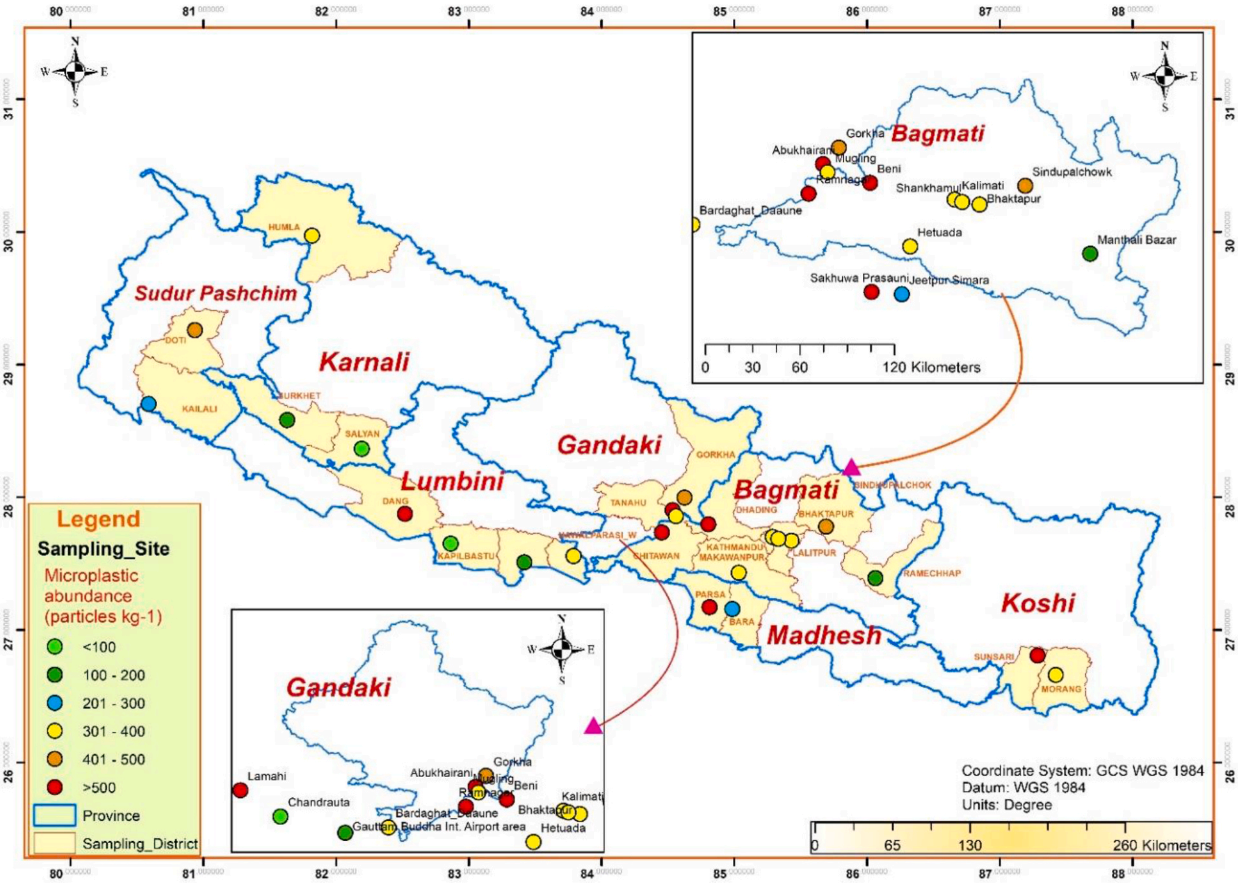

Fig. 9. Range of microplastic recorded in different districts.

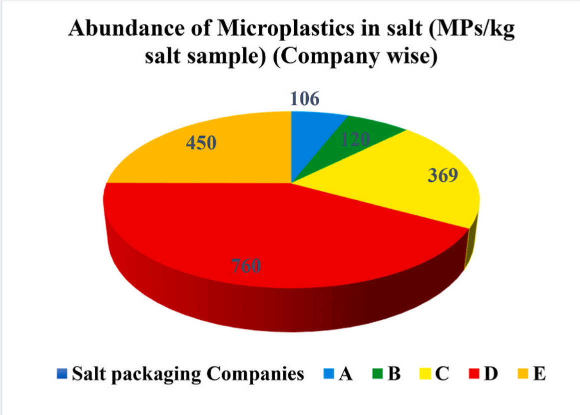

Fig. 10. Abundance of microplastic recorded in five companies.

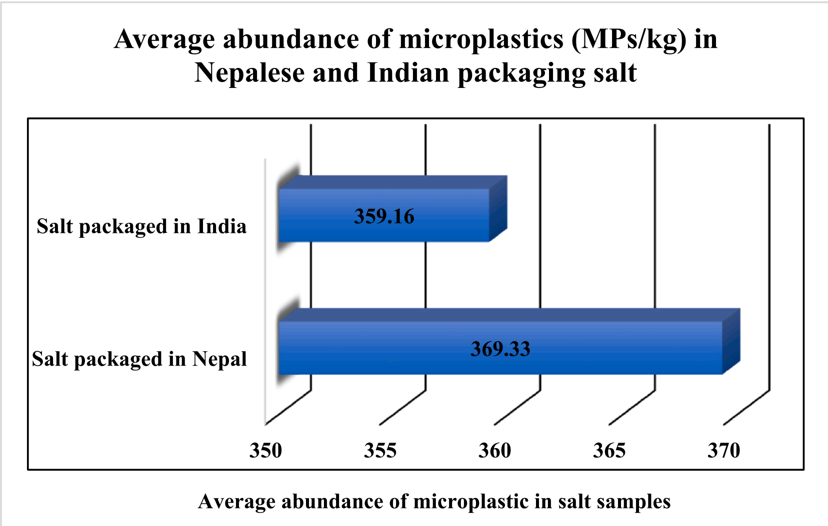

Fig. 11. Microplastic contamination in Nepalese and Indian packaging salt.

Similarly, Sivagami et al. [32] reported an average microplastics abundance of less than 700 particles per kilogram across all commercial brands. Rakib et al. [81] detected microplastics in all samples, with the average abundance ranging from 78 ± 9.33 to 137 ± 21.7 particles per kilogram. Parvin et al. [82] found an average of 2676 microplastics per kilogram of salt, with contamination levels varying from 390 to 7400 particles per kilogram. These findings collectively emphasize the widespread presence and variable abundance of microplastics in table salt.

4. Association between abundance of microplastics and date of packaging

In the present study, we investigated whether the abundance of microplastics in salt samples depends on the age of manufacturing. The statistical analysis yielded a p-value of 0.535. Since this p-value is greater than the commonly used significance level of 0.05, we conclude that there is no statistically significant difference in the abundance of microplastics based on the age of the salt. In general, salt packages with older packaging dates have had more time to be exposed to environmental factors such as air, moisture, and handling. This prolonged exposure can increase the risk of microplastic contamination as packaging materials may degrade over time.

Association between abundance of microplastic contamination and Storage during sale (Indoor and Outdoor).

The storage conditions of salt during sale can potentially influence its quality, safety, and shelf life. Proper storage conditions are crucial. Salt stored in controlled environments is less likely to experience packaging degradation compared to salt stored in less controlled conditions. The independent samples *t*-test revealed no statistically significant difference in the abundance of microplastics in salt samples based on storage conditions (indoor vs. outdoor) during sale ($p = 0.73$). This indicates that the storage method does not significantly impact the level of microplastics in the salt samples. The findings showed regardless of indoor or outdoor storage, using robust and salt purification method is essential to safeguard the salt from microplastic contamination.

4.1. Association between thickness of packaging material and abundance of microplastics

Packaging materials for salt play a crucial role in preserving its quality, ensuring its safety, and minimizing contamination. The relationship between packaging materials and the presence of microplastics in salt samples is an important area of study. Salt, being a staple in many diets, often undergoes extensive packaging and distribution processes, which can influence its purity and safety.

The minimum thickness of packaging material of salt recorded is 41 μm, and the maximum is 95 μm (Fig. 12), resulting in a range of 54 μm. This indicates substantial variability in the thickness of the packaging materials. Average thickness of packaging material was recorded 51.73 ± 11.21. In the remote reaches of Karnali (Humla) and Sudurpaschim (Doti), far removed from Kathmandu city, lies an area where salt is carefully sealed in thick plastic packaging. This vital task is carried out by the Salt Trading Corporation Limited in Nepalgunj, renowned for its branded salt, "Bhanu nun." Notably, in Humla, the packaging material stands out with a remarkable thickness of up to 95 μm.

The relationship between the abundance of microplastics in salt and the thickness of the salt packaging materials is weak, as indicated by a low correlation coefficient ($r = 0.126$). This suggests that there is only a slight, practically negligible association between the two variables. Variations in the thickness of packaging materials do not significantly predict or relate to the amount of microplastics found in salt. This weak correlation implies that other factors are likely more influential in determining the presence of microplastics in salt, and that the thickness of the packaging material plays a minimal role.

4.2. Microplastic ingestion from table salt by nepalese people

Based on our study findings, it was revealed that Nepalese individuals ingest an estimated annual average of 1853 microplastics. This equates to a daily intake of approximately 5 microplastics per person. Numerous researchers documented the consumption of salt by individuals across various countries. Özçifçi et al. [59] have determined that individuals aged 15 or above may be exposed to microplastics through table salt consumption, with daily, annual, and lifetime exposures calculated at 0.41 per day, 150 per year, and 10,424 per 70 years, respectively. Nigerian people are expected to ingest an average of 21.9 microplastic particles annually [60]. Adults and children were found to be exposed to varying levels of microplastics through salts and sugars, indicating potential health risks associated with additives in the food chain [24]. In Spain, consumers of Spanish salt may ingest around 510 plastic particles annually, although microplastics can also enter the body through alternative sources such as seafood [48]. Sea salt consumption contributes significantly to the absorption of microplastics in the human body, with Australians estimated to ingest about 155.47 microplastics per year [83]. Minimal intake of particles from salts, with a maximum of 37 particles per individual per year, was reported in a study by Karami et al. [84]. Sathish et al. [85] found that individuals ingest around 216 microplastic particles per year through sea salt and 48 particles per year with bore-well salt. Lebanese adults are predicted to receive 2372 microplastic particles annually from salt consumption [33]. In Iran, human dietary intake of microplastics ranges from 5 to 59 particles per capita per day,

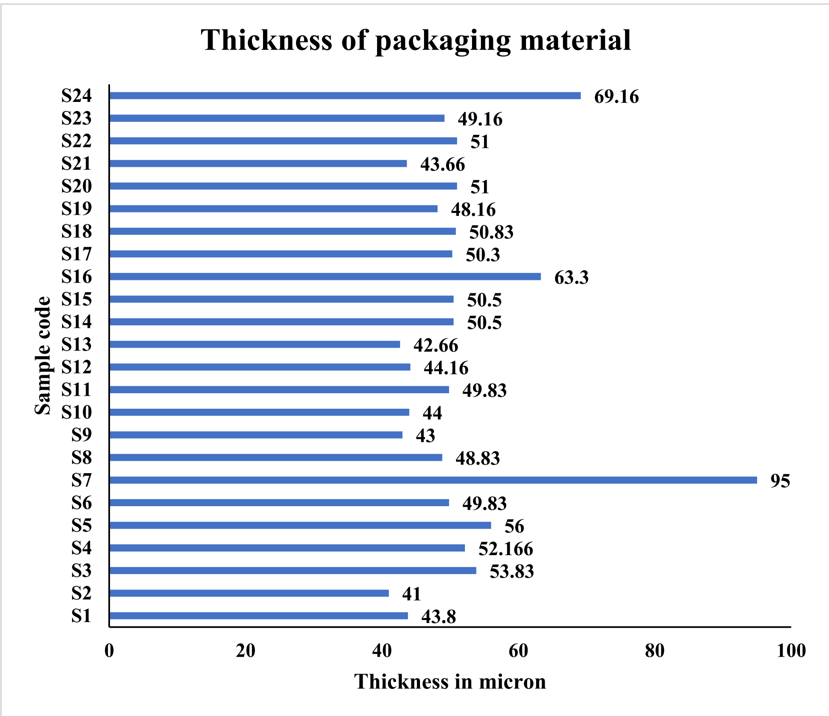

Fig. 12. Thickness of packaging material.

with estimated annual intake ranging from 1967 to 21563 microplastics per capita per year [61]. Finally, considering salt consumption rates in Bangladesh, individuals may be exposed to microplastics at a concerning rate of 13,088 particles per year, posing potential threats to public health [82].

In terms of microplastic ingestion, Nepal's annual consumption of 1853 microplastics per person stands at a moderate level compared to the other countries listed. While Nigeria has a notably lower intake at 21.9 microplastics per person annually. Countries like Lebanon, Iran, and Bangladesh exhibit considerably higher microplastic ingestion rates, suggesting a greater prevalence of microplastics in their environments or food sources. Nepal's microplastic ingestion is relatively moderate compared to some countries, the issue remains a global concern with varying levels of exposure and potential health implications across different regions.

5. Conclusion

In conclusion, the study of microplastic contamination in salt samples uncovered significant findings across multiple parameters. The average abundance of microplastics varied widely among packaging companies, with some districts and states showing higher levels of contamination, indicating regional differences in production and handling practices. Color analysis showed diverse types, predominantly blue, black, and brown, suggesting varied sources of contamination. The shapes of microplastics included fibers (56 %), films (17 %), fragments (16 %), and pellets (11 %), each potentially originating from different plastic products and environmental degradation processes. Polymer type analysis identified polyethylene (80 %) and polypropylene (20 %), confirming that a variety of plastic materials contribute to the overall microplastic burden in salt.

The factors that could potentially affect the abundance of microplastics in salt, such as storage conditions (whether indoor or outdoor), location, salt packaging date, and sampling time, do not show a significant difference in the presence of microplastics in the samples. This suggests that these variables are not the primary contributors to microplastic contamination in present study. Therefore, we conclude that the manufacturing process is likely the main cause for the high levels of microplastics found in the salt samples. The consistent presence of microplastics in all samples indicates the need for a thorough examination and improvement of production methods to reduce contamination. Efforts to mitigate and monitor microplastic contamination in food products, including salt, are crucial to safeguarding public health and environmental well-being.

Our study found that Nepalese individuals ingest an estimated annual average of 1853 microplastics, equating to a daily intake of approximately 5 microplastics per person. These findings indicate the considerable exposure to microplastics from salt consumption.

Nepalese people are increasingly using loose salt that is neither properly packaged nor stored. Typically, this salt is kept outside shops, making it susceptible to various contaminants, including microplastics that can originate from airborne sources. The exposure to environmental elements without adequate protection significantly raises the risk of contamination. Therefore, future investigations should focus on assessing the extent of microplastic contamination in loose salt.

Our study focuses on snapshot sampling, which provides a limited view of microplastic contamination in salt. To gain a comprehensive understanding, it is crucial to implement regular monitoring of microplastic abundance in salt samples. Continuous surveillance will help track trends over time, identify sources of contamination, and assess the effectiveness of mitigation strategies. Some companies exhibit a high presence of microplastics in their salt products, it is imperative for government authorities to take action to ensure the purity of salt.

Our findings can help consumers, salt industries, and policymakers reduce microplastic levels. Consumers can make informed choices to minimize exposure, salt industries can implement better filtration and production methods, and policymakers can create and enforce regulations to ensure safer production practices. Regulatory measures should be introduced to set strict limits on permissible microplastic levels in consumable salt. Collaborative efforts among these groups can significantly decrease microplastic contamination in the food supply and environment.

Data availability statement

The data are included in article.

CRediT authorship contribution statement

Kishor Kumar Maharjan: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Ram Prasad Dhungel:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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