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MICROPLASTIC CONTAMINATION IN SEA SALT PRODUCTION USING GEOMEMBRANE PLASTIC

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ABSTRACT

The raw material for making salt is seawater. The global issue is that seawater has been polluted by plastic waste, over time the plastic waste is degraded into microplastics. Apart from the polluted water, entering the salt production area in the crystallization pond is lined with plastic geomembrane. This study is to examine the quantity and kind of microplastics in four different crystallization pond locations (salt crystal) in Rembang, Central Java, Indonesia. The procedure used to determine the kind of plastic (FTIR), the amount of microplastic particles (number) using a microscope, and the morphology (SEM-EDX). The variables used include sampling location (four locations) and crystallization procedure (with and without geomembranes). The results showed no significant distinctions between treatments involving the deployment of geomembrane plastics and those lacking geomembrane materials regarding microplastic concentration. The mean distribution of microplastic contamination within the selected salt fields has been quantified at 326 and 337 microplastic particles per kilogram without and with geomembrane. FTIR analyzed on the salt with Geomembranes was more contaminated than that without Geomembranes. PS, HDPE, PP, PET, Nylon, Polyamide, and Latex, are the plastic contaminants, whereas PS, HDPE, PP, HDPE, LDPE, PET, PE, PVC, Acrylic, Ethylene vinyl Acetate, and Latex are the plastics that use Geomembranes.

Keywords: Degradation, Geomembrane Plastic, Microplastic Contamination, Sea Salt, FTIR, SEM EDX

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INTRODUCTION

Plastic pollution, especially in oceanic habitats, is a rapidly worsening environmental problem, with microplastic (MPs), defined as plastic particles smaller than 5 millimeters, contamination becoming a growing concern in various ecosystems, including those related to food production. Among the food products, table salts have been found to contain MPs, which raises alarms for public health and environmental sustainability.[1] The presence of MPs in marine and coastal areas, where salt production is prominent, has become a critical issue.[2] Addressing this issue is crucial, as microplastics can have detrimental impacts on marine ecosystems and the overall health of the environment. Developing strategies to mitigate the release of microplastics from salt production sites and implementing effective monitoring and management practices are essential steps toward a more sustainable and environmentally responsible salt industry. The salt production process can be carried out through various methods, such as evaporation, geomembrane, valve, and prism house. Among these, the geomembrane method involves direct contact with plastic. The application of plastic geomembranes, also known as geo-isolators, in salt field production, involves their use as protective barriers to safeguard the underlying soil in salt ponds. This approach utilizes High-Density Polypropylene sheets installed in salt fields to create a waterproof barrier between the soil

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and other elements. Geomembrane plastics are commonly used in salt production facilities to prevent saline solution seepage and maintain production efficiency. Moreover, the dark color of the geomembrane allows for better absorption of solar heat, which in turn accelerates the crystallization process. Salt production facilities, particularly those utilizing plastic geomembranes, may be inadvertently contributing to MP contamination due to the degradation of these materials over time. Geomembranes, used for their excellent barrier properties, prevent the intrusion of contaminants and conserve water. However, as these geomembranes degrade, they release MPs into the environment, exacerbating pollution.[3] The degradation of plastic geomembranes, which are commonly used in salt fields, is a key source of MP contamination in salt. A study has shown that salt produced with geomembranes contains higher concentrations of MPs.[2] However, another study revealed that the traditional method of salt production resulted in the highest levels of MPs contamination (up to 403 MPs/kg), while the geomembrane method showed lower contamination levels (154.4 MPs/kg on average).[4] Environmental factors like sunlight and chemical exposure accelerate the degradation of these geomembranes, particularly in the case of atactic polypropylene, leading to surface delamination and the release of MPs.[5]

Consequently, this contamination poses potential health risks to consumers and affects the sustainability of salt production.[4] MPs are not only a concern in salt production but have also been detected in various salt products globally. These include sea, lake, rock, and well salt, with concentrations ranging from 0 to 1674 MPs/kg[6]. While the estimated intake of MPs through salt consumption in countries like Indonesia is currently considered low—ranging between 60 to 1142 MPs per year for adults[5]—the presence of MPs in salt continues to raise significant concerns about potential long-term health risks and environmental impacts. Further research is needed to enhance extraction protocols and assess the full extent of MPs contamination in salt.[7] In salt fields, plastic geomembranes, typically made of High-Density Polyethylene (HDPE), have played a crucial role in increasing salt production efficiency. These geomembranes serve as protective barriers, preventing soil contamination and saline solution seepage while improving sodium chloride levels from 94% to 96% in harvested salt.[8]

However, the durability of these materials, although beneficial for productivity, leads to challenges related to waste management. HDPE geomembranes are resistant to natural degradation processes and can persist for hundreds of years.[9,10] Their resistance to degradation raises concerns about the accumulation of plastic waste in salt production areas, presenting both environmental and disposal challenges. Although the use of geomembranes has improved salt yields by up to 60%, contributing to an increase in production capacity from 92 to 140 tons per hectare, it also introduces the risk of MPs contamination as the geomembranes degrade.[2] The disposal of these plastic geomembranes presents a significant challenge for salt farmers, especially in areas where plastic waste management is inadequate.[11]

Sustainable solutions, including improved recycling methods and policies to prevent harmful disposal practices, are essential to address the environmental impact of plastic geomembranes.[10] Despite these challenges, plastic geomembranes remain essential for modern salt production. However, their degradation and the resultant release of MPs must be carefully managed to ensure environmental protection and food safety. In contrast to this, research conducted by Dwiyitno *et al.* presented a different result.

The discrepancy between these studies may be due to differences in the environmental context, the condition and age of the geomembranes used, and the specific production processes applied. Research also noted that the geomembranes in their study had been in use for less than a year, which might explain the lower MPs contamination levels observed.[12] This highlights the need for further research into the long-term effects of geomembrane degradation on MPs release, as well as the importance of production context in determining contamination levels.

This study seeks to further investigate the degradation mechanisms of plastic geomembranes in salt fields, with an emphasis on understanding the factors contributing to MPs contamination. Using advanced analytical techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), and Fourier Transform Infrared (FTIR) spectroscopy, this work aims to assess the degradability of plastic geomembranes and their implications for salt production.

EXPERIMENTAL

Material and Methods

The research involved sampling from salt crystallization ponds equipped with geomembrane liners and control sites without such materials. Geomembrane samples were analyzed for physical degradation indicators, while salt samples were processed to quantify MPs particles using microscopy and spectroscopic techniques. The instrumental apparatus encompassed a Baume meter, plankton net, microscope, petri dish, scale, vacuum filter, and spectrophotometer. The research was conducted in a salt field in Rembang, Central Java Province, Indonesia, and involved sampling from salt crystallization ponds equipped with geomembrane plastic liners and without geomembrane plastic. The sampling locations were in 4 salt pond locations, each location having a crystallization pond without using a geomembrane and using a geomembrane plastic. Geomembrane plastic samples were analyzed for physical degradation indicators, while salt samples were processed to quantify MPs particles using microscopy and spectroscopic techniques. The materials used in this research were geomembrane plastic, plankton net, Baume meter, Beaker glass, Duran bottles with lids, Petri dish filter paper, and jar containers for samples. The instrumental apparatus encompassed were a vacuum pump, microscope, and spectrometer. All equipment used in the laboratory and for sampling was non-plastic glassware that had been previously cleaned. All distilled water used in cleaning and analyses was prefiltered using cellulose nitrate Whatman membrane pore size 0.5 µm, to produce free particle water.

General Procedure

Sampling points were designated at salt crystallization ponds situated in Rembang, Central Java, Indonesia, and salt from industry. The study employed geomembrane plastic material and seawater brine with a concentration of 25^0 Bé, sourced from evaporation ponds in the proximity, ready to undergo crystallization. The last pond typically serves as the location for the salt crystallization process. The instrumental apparatus encompassed a Baume meter, plankton net, microscope, petri dish, scale, vacuum filter, and spectrophotometer. Sampling points were designated at salt crystallization ponds at 4 locations and sampling salt raw material from industry. The salt crystal in the crystallization pond becomes from evaporation pond seawater brine with a concentration of 25^0 Bé, sourced from evaporation ponds in the proximity, ready to undergo crystallization. The last pond typically serves as the location for the salt crystallization process. Salt samples were taken in the salt fields using purposive sampling. One kilogram of each sample was taken at five points (four points at the corners of the crystallization pool and one point in the middle) and then composited so that the total sample was approximately five kilograms for each crystallization pond. The samples were tested in the laboratory at the Center for Industrial Pollution Prevention Technology Semarang, Diponegoro University, Indonesia.

Detection Method

The research primarily focused on the investigation of plastic geomembrane degradation. This investigation encompassed the analysis of plastic geomembranes both pre- and post-deployment in salt fields. For microplastic analysis, samples from salt fields are collected and examined using microscopy and spectroscopy (Trimolecular Zoom stereo microscope) to quantify and characterize the microplastics present.[13] Visual count on MPs in salt conducted as described elsewhere.[1] The characterization involved the utilization of SEM (Phenom Pro X Desktop SEM with EDX, Nederland) to scrutinize the surface morphology of plastic geomembranes, EDX for the identification of inorganic compounds, and FTIR spectroscopy using a Nicolet iS 10 (Thermo Fisher Scientific, Waltham, MA, USA) for the analysis of MPs. Advanced methods such as Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM) are used to identify chemical changes and microstructural damage in the geomembranes.[14] 250 g of salt and 100 ml of 30% H2O2 (Hydrogen Peroxide) were combined in a bottle and sealed. The bottle containing the liquid was then placed in the oscillation incubator and left there for 24 hours at 650 C and 80 rpm. After being taken out of the incubator, it was let to sit at ambient temperature for 48 hours. Add 800 ml of prefiltered distilled water after that. Stir until it dissolves completely. The solution was then filtered using a vacuum pump using cellulose nitrate filter paper with a 47 mm diameter and a pore size of 5 μm. The filter paper was placed on a glass Petri dish and dried at room temperature before being examined using a digital Trimolecular Zoom stereo microscope for MP analysis. The Universal ATR-FTIR (UATR) device was used to identify the type of polymer microplastic particles, while SEM examination was used to identify the surface of both used and unused plastic geomembranes. EDX test to determine inorganic compounds of geomembrane plastic and salt crystals.

RESULTS AND DISCUSSION

Visual Count of Microplastics in Salt

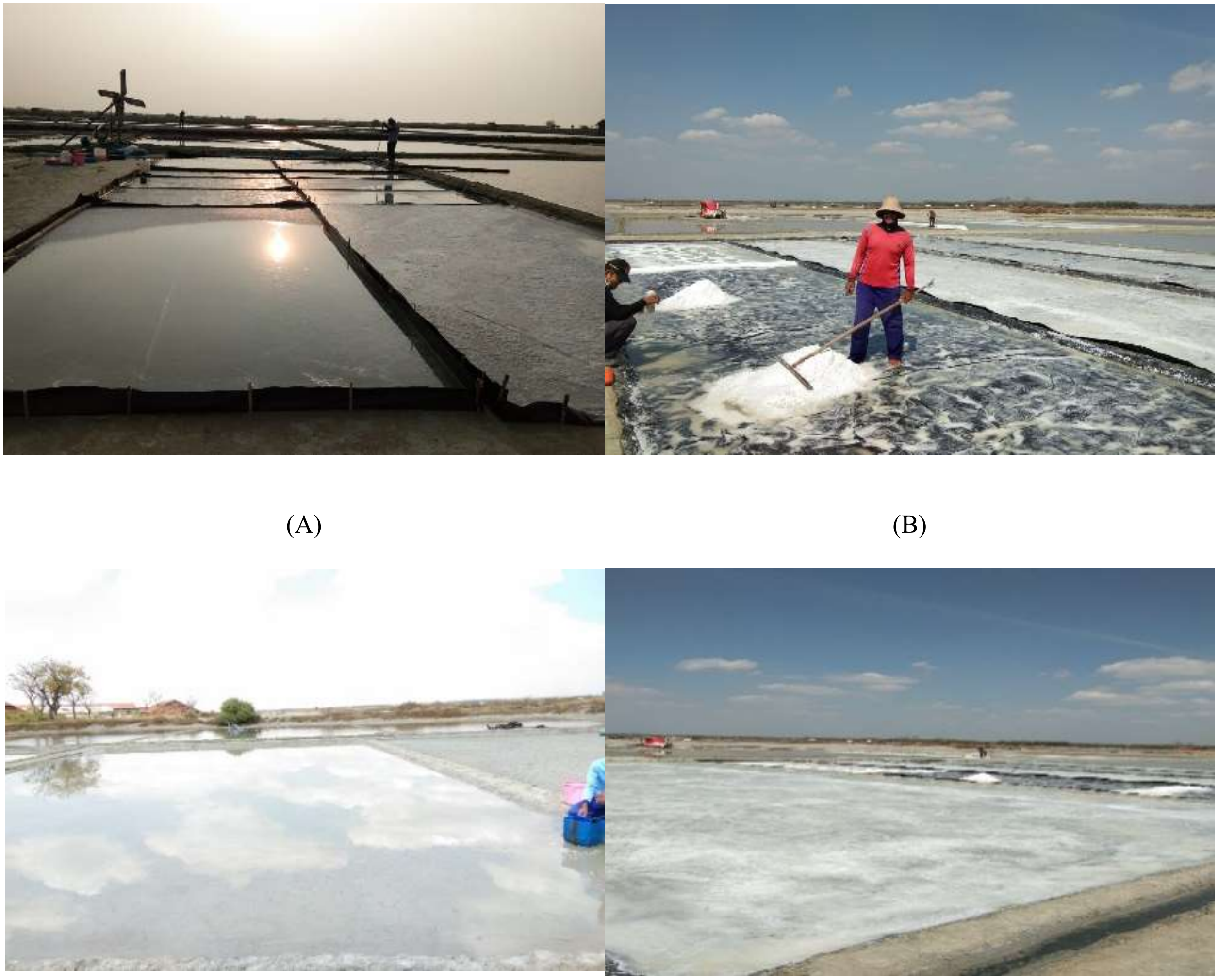
The presence of microplastics in salt derived from smallholder farmers can be seen in Table-1. Recent studies have revealed that the amount of microplastic contamination in salt is notably lower when no geomembrane plastic is used. Specifically, the contamination level is at 326 particles per kilogram of salt. In contrast, when geomembrane plastic is employed, the contamination level rises slightly to 337 particles per kilogram of salt. This difference, while seemingly small, has significant implications for environmental health and safety.

Table-1: Microplastics in Salt with and Without Geomembrane Plastic

Crystallization pond location	Unit	No Geomembranes	Geomembranes
1	Mps/kg	300±3	318±6
2	Mps/kg	271±53	315±27
3	Mps/kg	380±108	338±23
4	Mps/kg	352±36	379±9
Average	Mps/kg	326±50	337±16

The results revealed that the average concentration of MPs particles in the salt treatment involving a geomembrane was slightly higher, albeit not significantly different. In the treatment without the use of a geomembrane, the count of particles was 326 MP/kg of salt, whereas in the treatment utilizing a geomembrane, it measured 337 MP/kg of salt. The observed slight increment in MPs presence in the geomembrane-treated samples suggests the potential for contamination originating from geomembrane plastic. Nevertheless, these results are much lower than those reported in studies of the MPs content of commercial consumption salt[13] and sea salt.[12] Figure-1 shows the salt field with geomembrane plastic and without geomembrane plastic. The degradation of plastics, including the formation of MPs, is a complex process influenced by various factors. Dimasi *et al.,*[14] found that in salt marsh habitats, plastic degradation occurs relatively quickly, with surface delamination being a key mechanism. This process is further influenced by factors such as UV radiation, mechanical abrasion, and chemical processes. However, Liu *et al.,*[3] and Zhang *et al.*[15] both highlight the challenges in plastic degradation, including the difficulty in breaking down plastics due to their hydrophobicity and stable covalent bonds.[14,15] They also emphasize the need for further research to understand the methods, mechanisms, and environmental impacts of plastic degradation. Lin et al.,[16] further explore the effects of physicochemical factors on plastic degradation, including mechanical comminution, UV radiation, high temperature, and pH value, as well as the role of enzymes in biodegradation. These studies collectively underscore the importance of understanding the degradation of plastics, including MPs, in order to mitigate their long-term environmental impact. Apart from the degradation of plastic geomembranes, another contribution comes from waste disposal by farmers and communities around the salt fields. So, there is a need for counseling for salt farmers. This is supported by opinions of Filipe[10] and Borg & Camilleri-Fenech.[11]

Initial findings revealed a measurable presence of MPs in both geomembrane-protected and control salt fields. Visual and chemical analyses of geomembrane samples highlighted observable structural changes indicative of degradation. These included surface cracking, loss of flexibility, and alterations in chemical composition, potentially influencing their effectiveness as barriers over time. In this study, the seawater sampled, ranging from 2.5 to 30 Be, contained 11.5 x 10^3 MPs particles/m^3 (inlet, prior to entering the storage pond). The source of pollution from seawater may also potentially emanate from plastic geomembranes or plastic materials in the proximity of the salt fields. These results show the need for further investigation into the specific sources and pathways of MPs contamination in salt production processes involving geomembranes (Fig.-1).



(A) (B)

(C) (D)

Fig.-1: Salt Field with Geomembrane Plastic (A, B) and without Geomembrane Plastic (C, D)

FTIR Analysis

The analysis by FTIR spectroscopy was done as the analytical tool for the identification of polymer types and the discernment of alterations in their molecular structure based on the distinctive functional groups constituting the fundamental elements of plastic materials.[17] The FTIR analysis (Fig.-2) was conducted on two sets of plastic geomembranes: one set serving as a control, having never been utilized, and another set that had undergone three growing salt production seasons, equivalent to an aging period of 21 months. In interpreting the FTIR spectrum, the initial step involves scrutinizing the presence of a carbonyl group (C=O), localized within the wavelength range of 1810-1630 cm^{-1}. Vibrations observed at peak frequencies of 1450 cm^{-1} and 1400-1300 cm^{-1} are indicative of carboxyl and alkyl groups, respectively. Additionally, at wavelengths spanning 1050-1000 cm^{-1}, signals associated with CO, CC, and OH groups were detected, signifying the presence of ethers, esters, and hydroxyl polysaccharides.

Figure-2 depicts the FTIR spectra revealing the presence of the carbonyl functional group within the wavelength range of 1725-1700 cm^{-1}. This region encompasses distinctive peaks associated with the C=O group at 1725-1700 cm^{-1}, ketone at 1725-1705 cm^{-1}, and aldehyde at 1740-1720 cm^{-1}. The carbonyl group exhibits subcategories, including aldehyde (1740-1720 cm^{-1}), ketone (1725-1705 cm^{-1}), carboxylic acid (1725-1700 cm^{-1}), ester (1750-1730 cm^{-1}), amide (1680-1630 cm^{-1}), and anhydride (1810 and 1760 cm^{-1}).

The results reveal subtle variations in peak wavelengths, indicating the degradation of the geomembrane plastic that has been in use for three growing seasons (dry season), equivalent to a 21-month utilization period. This degradation is likely attributed to factors such as the abrasive effects of salt crystals, salt dredging tools, and the impact of wind speeds. Additionally, the degradation process may be influenced by the presence of microorganisms in concentrated saltwater exceeding 200 Be, particularly by *halophilic* bacteria. *Halotolerant* bacteria isolated from saline environments have shown the potential to decompose MPs.

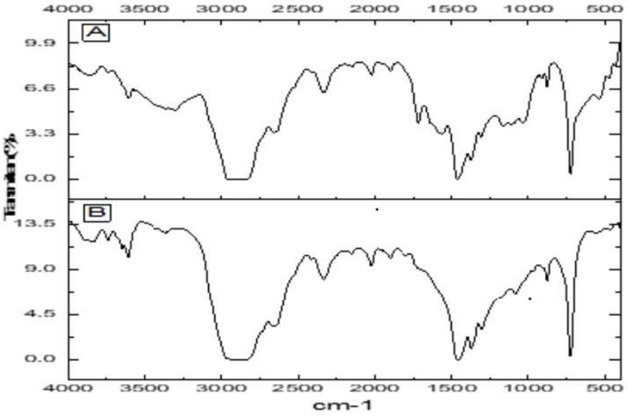
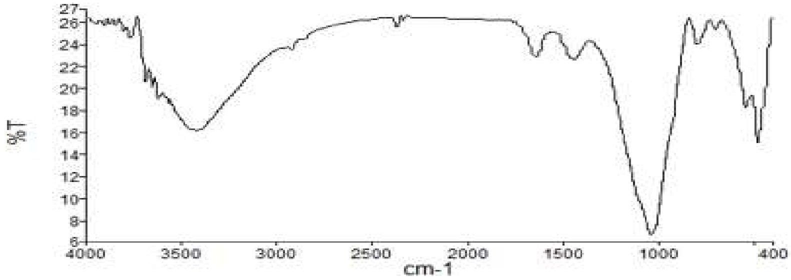


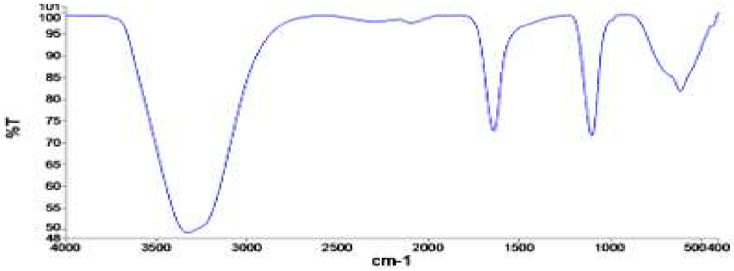
Fig.-2: FTIR Analysis for Geomembrane Plastic that has Been Used for 21 months (A) and Unused Plastic Geomembrane (B)

Stenotrophomonas maltophilia BK1 and *Enterococcus sp.* ZK3 shows the ability to degrade LDPE in artificial seawater.[18] Similarly, Pseudomonas species isolated from wastewater demonstrated plastic degradation capabilities, reducing plastic mass by 25% over 120 days.[19] These findings underscore the ubiquity of MPs pollution and the potential for bacteria-mediated remediation in a variety of environments. *Halophilic* bacteria, also known as archaebacteria, represent a category of bacteria capable of thriving and enduring in saline environmental conditions. These bacteria demonstrate their resilience in environments characterized by elevated salinity levels, such as seawater. In tandem with halophilic bacteria, other microorganisms known as halotolerant organisms coexist, exhibiting the capacity to adapt to high-salinity environments without necessitating exceptionally elevated salt concentrations for sustenance. The EDX analysis shows a reduction in the carbon element content within the plastic, implying its consumption by microorganisms. Conversely, there was a significant increase in the oxygen content attributable to the presence of *Halophilic* bacteria, characterized by their red coloration, which absorbs heat for their photosynthetic processes. Further elemental analysis encompassing Mg, K, Fe, Si, Al, and Cl compounds indicated an augmentation in their concentrations. These compounds originate from the plastic substrate itself, contributing to an accumulation of these elements. Various types of MPs were discerned through FTIR analysis conducted on salt samples obtained from all salt fields. The FTIR results exhibited consistent graph patterns across samples, characterized by multiple sharp peaks, as illustrated in Fig.-3 and Fig.-4. Notably, the FTIR spectra revealed the presence of distinct plastic types, including nylon (3500-3100 cm^{-1}), PETE (1680-1630 cm^{-1}), PP (1000-650 cm^{-1}), PS (900-690 cm^{-1}), and PVC (608 cm^{-1}). We note that where a geomembrane was absent, the identified plastic types in the salt samples encompassed PS, PP, Nylon, PETE, PE, and PVC. This result in accordance with another study that stated plastic-type PE, PS, PVC, PTFE, and PC in sea salt pan.[20] The salt crystal analysis by FTIR using geomembrane plastic employed at each site can be seen in Fig.-4.

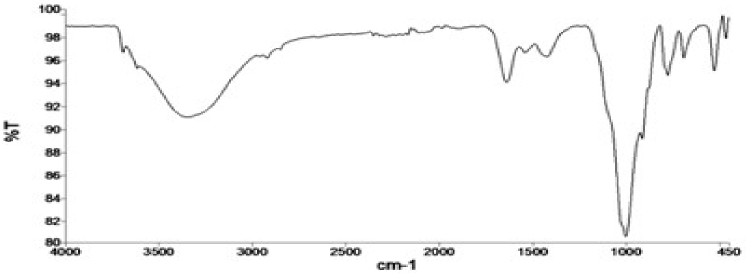
Factors contributing to geomembrane degradation in salt fields were explored, including exposure to UV radiation, saline water chemistry, mechanical stress from salt harvesting activities, and biological interactions. Salt harvested using geomembranes has been found to be contaminated by various plastic types, including Nylon (3500-3100 cm^{-1}), PETE (1680-1630 cm^{-1}), PP (1000-650 cm^{-1}), PS (900-690 cm^{-1}), and PVC (608 cm^{-1}). Analyzing individual sampling locations reveals distinct compositions: Location 1 exhibits PS, PP, PE, PETE, and Nylon plastic types; Location 2 contains PS, PP, PETE, Nylon, and PVC; while Location 3 comprises PS, PP, Nylon, and PVC.



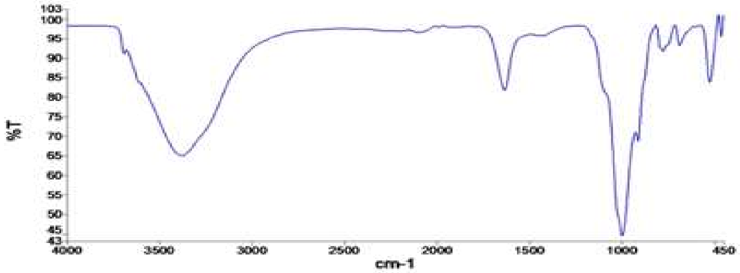
Location 1



Location 2

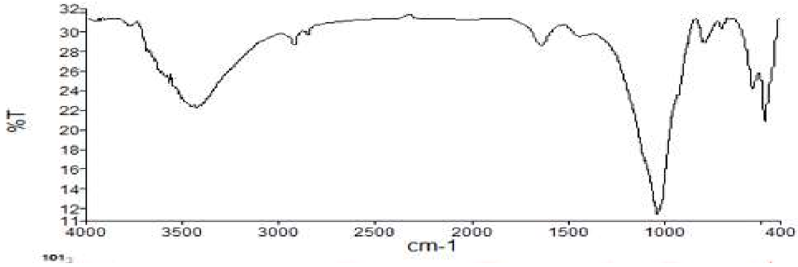


Location 3

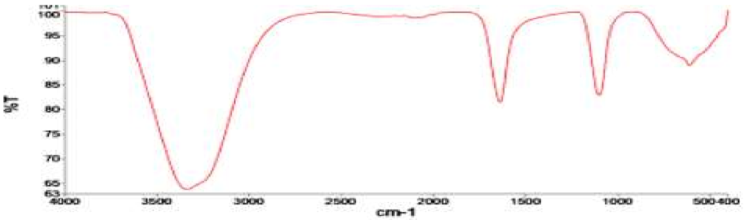


Location 4

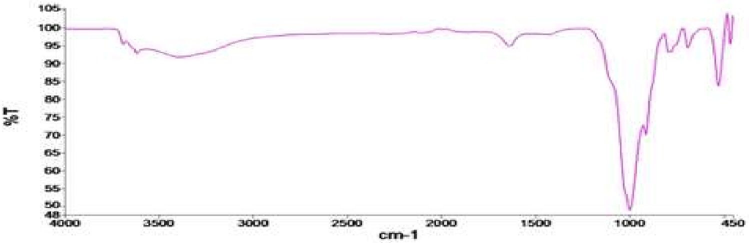
Fig.-3: FTIR Spectra of Salt Crystal without Geomembrane Plastic (Location 1, 2, 3, 4)



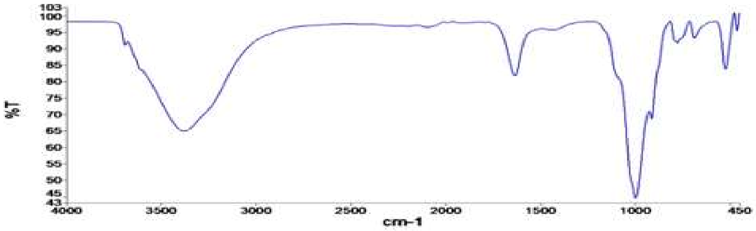
Location 1



Location 2



Location 3



Location 4

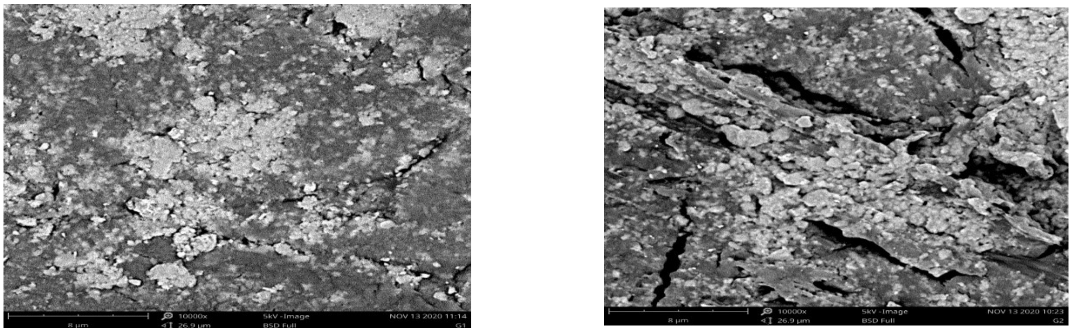
Fig.-4: FTIR Spectra of Salt Crystal with Geomembrane Plastic (Location 1, 2, 3, 4)

It is noteworthy that salt harvested with the aid of geomembranes incorporates a broader spectrum of plastic types, encompassing PS, PP, HDPE, PETE, LDPE, PE, PVC, Acrylic, and Latex. In contrast, salt harvested without plastic geomembranes exhibits a comparatively reduced variety of plastic polymers. The result indicates the potential influence of geomembranes on the types and extent of plastic contamination in harvested salt. The comparison indicates that the utilization of geomembranes may introduce a broader range of plastic types into the harvested salt, necessitating attention to mitigate environmental and health concerns associated with diverse plastic pollutants.

SEM and EDX Analysis

One of the most crucial techniques for analyzing the morphology of microplastics is scanning electron microscopy.[21,22] SEM analysis was conducted to characterize the morphology of the plastic geomembrane both before and after utilization. The results from SEM analysis show the morphology of the geomembrane plastic (Fig.-5A and Fig.-5B). Notably, after employing geomembrane plastic for 21 months of actual use, significant defects, particularly long scratches, were identified as indicative of geomembrane plastic degradation. Plastic degradation can manifest more rapidly in the presence of aquatic ecosystem bacteria, such as *Rhodococcus rhodochrous* ATCC 29672 (known for its ability to degrade high-density polyethylene (HDPE) and low-density polyethylene (LDPE)), *Serratia marcescens*, *Bacillus sp.*, *Staphylococcus sp.*, *Streptococcus sp.*, *Diplococcus sp*., *Micrococcus sp*., *Pseudomonas sp*., *Moraxella sp*., and *Bacillus cereus*. Additionally, certain strains of *Pseudomonas sp*. are capable of degrading polyethylene (PE). The degradation of plastic geomembranes can be attributed to various factors, including mechanical influences such as scratches incurred during salt harvesting using wooden stakes and friction arising from interactions with the salt crystals. Additionally, wind-induced friction plays a role, with observed wind speeds ranging from 2.6 to 6.0 m/s in the vicinity of the salt fields.

SEM analysis reveals distinctive characteristics in salt crystals utilizing geomembranes. Specifically, the MPs present in these crystals exhibit a morphology characterized by fibers and fragments. In contrast, salt crystals without geomembranes display MPs in the form of fibers, fragments, and films. The SEM characterization was done by EDX analysis, providing evidence of alterations in the content of inorganic compounds. The EDX analysis for geomembranes and salt crystals indicates the presence of elements including C, O, Mg, Si, Cl, Ca, Na, K, Fe, Al, and Si, as summarized in Table-2. A distinction is observed between unused (control) geomembrane plastic and those utilized for three growing seasons (21 months). In used geomembrane plastic, there are substantial changes in carbon and other compounds, with a decrease in carbon compounds from 72.02% to 44.64%. This reduction is attributed to the degradation of carbon compounds due to physical factors such as scratches from salt dredgers, friction from salt crystals, and environmental factors like temperature and wind speed.



(A) (B)

Fig.-5: SEM of Unused Geomembrane Plastic (A) and used Geomembrane after 21 Months (B)

Table-2: EDX Results of Unused and used Geomembrane, as well as Salt Samples with and Without Geomembrane

Element	Plastic geomembrane control	Geomembrane used 3 harvestings (21month)	Industry salt	Industry salt	Salt + Geomembrane	Salt + Geomembrane	Salt without geomembrane	Salt without geomembrane
C	72.06	44.64	13.93	14.18	15.47	2.79	28.07	10.21
O	24.05	45.25	66.02	69.97	52.85	50.28	43.78	70.82
Mg	1.41	0.76	0.94	2.59	2.85	2.41	3.09	4.30
Si	0.83	4.38	7.58	4.00	13.43	8.16	4.81	7.14
Cl	0.61	0.76	0.23	0.17	3.80	12.16	7.17	1.96
Al	0.72	2.95	6.82	2.76	6.01	4.37	2.75	3.83
Fe	0.24	0.94	3.83	0.27	1.59	-	-	-
K	0.09	0.31	0.14		0.86	-	-	-
Na	-	-	0.24	1.43	3.14	19.82	10.33	1.75
Ca	-	-	0.11	4.64	-	-	-	-

The study underscores the importance of monitoring geomembrane integrity to mitigate potential MPs contamination risks in salt production environments. Understanding degradation mechanisms aids in developing strategies to enhance geomembrane longevity and minimize environmental impact. Biological influences also play a role, particularly the presence of *Halophilic* bacteria thriving in high-salinity environments. These bacteria, identified as *Haloferax spp*, contribute to an increase in other elements such as oxygen through photosynthesis. This biological activity results in the production of oxygen by red *Halophilic* bacteria, further impacting the elemental composition observed in the geomembranes. This causes an increase in oxygen compounds in the geomembrane used. To sustain the life of *Halophilic* bacteria, essential nutrients such as Mg, Fe, and K are required. The results indicate an increase in the concentrations of these elements. Al from 0.72% to 2.95%, Fe from 0.24% to 1.91%, and K from 0.09% to 0.31%. Notably, in the crystallization pond, no external nutrients are introduced, implying that the bacteria rely on the compounds present in the degraded plastic for their nutritional needs (these compounds are naturally available from raw materials and media/soil in crystallization ponds). Plastics, particularly MPs, pose a significant challenge due to their hydrophobicity and stable covalent bonds, which hinder their degradation.[3] The slow fragmentation of plastics into MPs further exacerbates this issue.[23] Despite the potential for environmental harm, the full impact of MPs remains unclear.[24] Research is needed to understand the methods, mechanisms, and environmental impacts of plastic degradation, with a focus on sustainable strategies such as microbial degradation.[25] The observed increase in elemental concentrations, coupled with the absence of nutrient additions in the crystallization pond, suggests that *Halophilic* bacteria in this environment rely on the degradation products of plastic geomembranes as a nutrient source. The results obtained from the EDX analysis of salt crystals revealed a carbon content of 15.47% when employing geomembranes, 10.21% in the absence of geomembranes, and 13.93% in the case of industrial salt. Notably, the carbon content is higher in scenarios involving geomembrane application, indicative of carbon degradation originating from the plastic geomembrane. This elevation in carbon levels may be attributed to the presence of MPs, which serve as a source of inorganic carbon that is amenable to microbial absorption. Apart from that, the carbon concentration in salt is greatly influenced by the origin of the salt, so salt originating from one area will have a different carbon content compared to that originating from another area. This explains why the carbon concentration in industrial salt is higher than in non-geomembrane salt. Furthermore, there is a discernible increase in the concentrations of various micro compounds, including Mg, Fe, Al, and K, when geomembranes are utilized (Mg concentration in salt with geomembrane is lower than in salt without geomembrane treatment). This phenomenon can be attributed to the plausible degradation of the plastic geomembrane facilitated by *Halophilic* bacteria, alongside influences stemming from mechanical stress and environmental factors, as mentioned above.

CONCLUSION

We have successfully identified and characterized MPs contamination in selected salt fields, comparing those with and without geomembrane plastic application. The results reveal that all the salt fields under investigation exhibit MPs particles, averaging 331.5625 MPs particles/kg. Notably, there is no statistically significant difference ($p<0.05$) in the concentration of MPs particles between salt fields treated with and without geomembrane plastic. The MPs particles found to contaminate salt crystals in fields without geomembranes include polystyrene, polypropylene, high-density polyethylene, nylon, polyethylene terephthalate, polyamide, and latex. In contrast, MPs in salt crystals from fields using geomembrane plastic exhibit a similar composition as those without geomembrane plastic, but with the additional presence of low-density polyethylene, polyethylene, polyvinyl chloride, acrylic, and ethylene vinyl acetate. Characterization through scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) reveals morphological differences between salt crystals contaminated in fields with and without geomembrane applications. Future research should focus on longitudinal studies to track geomembrane degradation trends over extended periods. Additionally, investigating the effectiveness of alternative geomembrane materials or protective coatings could offer sustainable solutions to mitigate microplastic release into salt fields.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

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