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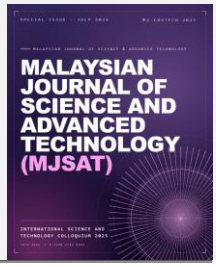

Comparative Analysis of Microplastic Release from Plastic and Biodegradable Food Containers Under Thermal and Food Simulant Conditions

Nur Alyana Shazana Mat Saad[1], and Khairunnisa Ahmad Kamil*[2]

[1]*Fakulti Sains Gunaan, UiTM Cawangan Perlis, Kampus Arau, 02600, Arau, Perlis, Malaysia.*

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ABSTRACT

Microplastics released from food containers have posed significant environmental and health concerns. Since traditional plastics like polystyrene and polypropylene are already known as the contributors to this pollution, most research has focused only on these types of plastic. There are still limited studies about the potential of biodegradable containers like cornstarch and sugarcane bagasse to release microplastics under certain conditions while they may also contain microplastic components. Besides, the knowledge about the influence of food properties such as acidity and oil content on microplastic release remains limited due to a lack of research focusing on their impact. Due to these concerns, this study aims to identify and compare the abundance of microplastics released between plastic food containers and biodegradable containers when exposed to different environmental conditions, including temperatures of 40°C, 70°C and 100°C, as well as food simulants such as 3% acetic acid and vegetable oil. A total of 24 food containers derived from plastic and biodegradable materials were subjected to these treatments. The released microplastics were then collected via vacuum filtration setup and analyzed by using stereo microscopy and Fourier-Transform Infrared (FTIR) Spectroscopy. The results indicate that all container types released microplastic particles under all treatments. Polystyrene materials consistently exhibiting highest amount with total of 176 particles released especially under combination condition between 3% acetic acid and 100°C. Notably, under certain treatments, cornstarch materials showed a comparable amount of microplastic released as polypropylene highlighting those biodegradable materials not entirely exempt from contributing to microplastic pollution despite their eco-friendly claims.

1. INTRODUCTION

Microplastics can be categorized as plastic particles are smaller than 5 mm in size [1]. Due to their persistence and ability to penetrate food chains, they are becoming an increasingly significant issue in environmental concerns [2]. Microplastics are divided into two types which are primary and secondary microplastic. Primary and secondary microplastic can be referred as those that are intentionally added into products as those used in personal care and cleaning agents. However, since people have become more aware about their effects on the nature, water soluble polymers has been the substitute solutions for many companies as "microplastic-free" alternatives [3]. Otherwise, primary microplastic can be categorized as those that are directly released into the nature due to abrasion. For example, tires particles or synthetic fibers that detach from garments during laundry [4]. On the other hand, secondary microplastics arise due to degradation of large objects that influences by UV radiation, microbial activity or physical abrasion. This process has progressively fragmented the objects into smaller particles that can contaminate the environment [5].

The probability of microplastics released being ingested by organisms increases due to their smaller sizes, which make them more bioavailable. The absorption rate for these particles can be influenced by several factors, including particle hydrophobicity, surface charge, and functionalization. Microplastics that have low hydrophobicity and negative surface charge are more likely to be absorbed by the organisms

*Corresponding author:
E-mail address: Khairunnisa Ahmad Kamil < khairunnisakamil@ uitm.edu.my >.
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[6]. Humans can also ingest the microplastic through the food chains when other organisms, like fish, mistakenly consume microplastic particles, frequently through non-selective feeding or accidental consumption [7].

Nowadays, people are already anxious about widely contamination of microplastic particles released from conventional plastics like polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET). According to research findings, heat and exposure to acidic or oily foods might accelerate the released of microplastic into food [8]. In response to this challenges, biodegradable and compostable containers made from plant-based materials such as polylactic acid (PLA) or bagasse are gaining popularity among users as an eco-friendly alternative. However, some studies suggest that despite their claims, these materials could still release microplastics in certain conditions [9]. This process may happen particularly if they possess synthetic coatings or fail to decompose completely.

In recent studies, the released of microplastic from food packaging materials has been influenced by several external factors specifically thermal and food simulant conditions which mimic real-world food storage and consumption scenarios. Heat exposure increases the rate of plastic polymers degradation leading to fragmentation acceleration and microplastic shedding [10]. Thus, high temperatures can significantly disrupt the structural integrity of common food packaging materials such as PE, PP and PS by inducing polymer chain scission and oxidation [11]. Otherwise, the released of microplastic can be influence by food simulants conditions like acidic and oily substances. In acidic conditions, the high concentration of hydrogen ions protonates the polymer chain of the food containers, increasing its reactivity and making it more susceptible to chain scission by hydroxide ions [2]. Similarly, the interaction between hydrophobic plastic surfaces and oily food simulants like vegetable oil can influence the rate of microplastic release. Oily substances may alter the surface charge and functionalization of the microplastic particles making them more prone to detach from the container's surface [11]. These findings are aligned with the studies on environmental microplastic contamination which indicate that surface charge and hydrophobicity properties influence their bioavailability and absorption by organisms. In this study, different temperature conditions were selected to represent realistic food contact scenarios and varying degrees of thermal stress on food containers. A temperature of 40°C represents warm food storage or exposure to ambient heat, while 70°C simulates contact with hot food during takeaway or food serving conditions. The temperature of 100°C was selected to represent extreme conditions such as boiling water or high-temperature food contact. Polymer degradation was expected to accelerate due to the increasing temperatures through enhanced molecular mobility and chain scission which leads to a higher release of microplastic particles.

Consequent to these issues, this study aims to systematically assess and compare the microplastic particles released from conventional plastic and biodegradable food containers by analyzing their response to different environmental conditions. Specifically, the study investigates the influence of varying temperatures, acidic and oily food simulants on degrading the microplastics by using membrane filtration for particle collection and analysis via stereo microscope and FTIR spectroscopy, providing valuable insights into the potential risks associated with these packaging materials.

2. METHODOLOGY

2.1 Sample Collection and Preparation

Experiments were performed according to the methodology shown in Figure 1. Two types of food containers including conventional and biodegradable were collected by purchasing them from various supermarkets and online stores. The purchased food containers were sealed and kept before being used. The conventional containers are made up from polypropylene and polystyrene while biodegradable containers are made up from sugarcane and cornstarch bagasse. To ensure no contamination occurs, these containers were cleaned thoroughly using a 7% ethanol solution, rinsed three times with distilled water and air-dried before being used.

2.2 Environmental Temperature and Treatments

Two treatments were conducted to assess the release of microplastics under different temperature conditions including 40°C, 70°C and 100°C. The temperature conditions of 40°C, 70°C and 100°C were selected to simulate different levels of thermal exposure commonly encountered during food storage, handling and consumption. These temperatures were applied to evaluate the effect of increasing thermal stress on microplastic release from food containers. For the warm water temperature treatment (40°C), each of the food containers were filled with distilled water up to their capacity and covered with the container lid. The containers were left standing for two days at room temperature. For the other temperature treatment, the containers were filled with hot water (70°C) and boiling water (100°C) respectively and then covered with aluminium foil.

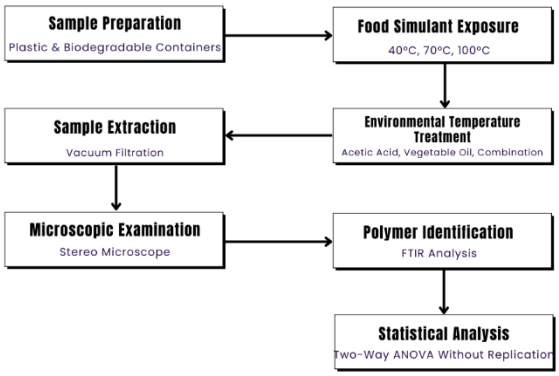

Fig 1. Experimental workflow for evaluating microplastic release from food packaging materials.

The containers were placed on magnetic hotplate stirrer for 30 minutes to simulate agitation and left for two days before filtration [12].

2.3 Exposure to Acidic and Oily Food Simulants

In order to mimic real-world food conditions, two different food simulants were prepared. Acidic and oily food simulants in this study were represented by 3% acetic acid (CH3COOH) and vegetable oil. The food simulants were prepared first before undergone further procedure. Acidic food simulant was prepared by diluting with 3mL of acetic acid with 97 mL of distilled water to produce 100 mL of 3% CH3COOH. The total volume of the 3% CH3COOH used depends on the total volume needed for each of the containers. Each of the containers were

filled to their capacity with either the acidic or oily simulant, and glass beakers containing the simulants were used as the controls [8]. The containers were then covered with aluminium foil and placed on a magnetic stirrer and stirred at a moderate speed setting of 6-8 for 30 minutes. After the agitation, the containers were stored at room temperature before filtration. The containers were also subjected to additional heat exposure by being placed in boiling water (100°C) for 30 minutes to simulate heating of food, followed by cooling at room temperature.

2.4 Sample Extraction

After all the treatments has been conducted, the containers were undergone filtration process. The contents in each of containers were filtered through 0.47 µm pore size of glass microfiber filter disc (Whatmann®). The effluent from each of the containers were collected by flushing the inner surface of the containers three times with distilled water. The filter discs were placed in clean, covered Petri dishes to dry at room temperature before further analysis [8].

2.5 Sample Inspection and Examination

A stereo microscope was used to observed and identify the microplastics for visual quantitative and qualitative analysis. The microplastic were divided into three categories which are fibers, fragments and films [12]. The sample inspection and examination process referred to the study by [8]. This study recorded the amount of microplastics visible on each filter disc. Additionally, the photos of all particles were captured by using Redmi Note 14 5G smartphone with 108 megapixels back camera. All samples were photographed with stereo microscope under 5x10 magnification with 3.5 zoom in. This technique did not alter the microplastics chemical composition. Then, the microplastic particles was counted manually using naked eyes.

2.6 Identification of Microplastic with Fourier-Transform Infrared (FTIR) Spectroscopy

FTIR spectroscopy was used to confirmed the polymer composition of microplastic release isolated from food containers after each treatment [2]. The potential particles were carefully picked using micro forceps and placed onto the ATR crystal of the FTIR instrument. The analysis was carried out by using ATR mode with scan range between 4000-600 cm^{-1} and 32 scans per sample following a previous study to ensure an outstanding signal-to-noise-ratio [12]. The recorded spectra were analyzed with the Spectrum™ 10 spectroscopy software. The resulting spectrum were interpreted by comparing the peaks to standard polymer libraries to identify the specific types of microplastics found in the samples. Common peaks corresponding to functional groups such as C-H stretching or C=O bonds were matched to determine the specific polymer such as PS or PP.

2.7 Statistical Analysis

The collected data were processed using Microsoft Excel 2019. A two-way ANOVA without replication was performed to assess the influence of two independent factors, which are types of food containers and treatment conditions, on the microplastic abundance. This statistical approach was selected due to the presence of only one observation per treatment-container combination. The analysis aimed to determine whether there is a significant difference between the microplastic release based on container material, treatment condition, or their interaction. A p-value of less than 0.05 ($p<0.05$) was considered statistically significant, following the standard threshold for significance [12].

3. RESULTS AND DISCUSSION

3.1 Microplastic Abundance Across Different Types of Food Containers

This study investigated the release of microplastic from four types of food containers including polystyrene (PS), polypropylene (PP), cornstarch bagasse and sugarcane bagasse under various thermal and simulated food conditions. The results revealed that all types of food containers tested in this study exhibited the release of microplastic particles under all treatment conditions. Based on Figure 2, PS container exhibited the highest total of microplastic with 176 particles, followed by cornstarch bagasse container with 141 particles, PP container with 134 particles and the least microplastic released in total were from sugarcane bagasse with 105 particles.

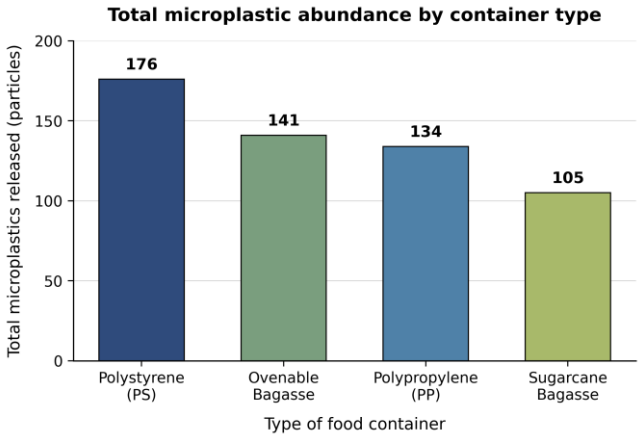

Fig 2. Abundance of microplastics in different types of food containers

The observed differences in microplastic abundance across different types of food containers significantly stem from their material composition and inherent structural properties, which the manufacturing process directly influences. For instance, PS containers are typically manufactured through a gas injection foaming technique that creates a lightweight structure with a porous and rough surface [12]. The foamed morphology results in a brittle and fragile material with low mechanical strength, making the container more susceptible to physical fragmentation and surface flaking. The PS rigidity and lack of elasticity contribute to its high propensity for microplastic shedding even when exposed to slight stress. This structural vulnerability is aligning with the findings from [12], who highlighted the correlation between the porous and irregular texture of PS containers and the highest abundance of microplastic released compared to other containers.

On the other hand, PP containers are manufactured through high-pressure injection molding, resulting in a denser, more compact material with a smooth surface and higher mechanical resilience. PP's tighter molecular structure and relatively non-porous surface make it stronger and more resistant to fragmentation, which explains the lower microplastic abundance observed from this type of plastic under similar conditions [12].

Interestingly, this study results showed that under certain treatments, the biodegradable cornstarch-based containers demonstrated an unexpected degree of microplastic release, which was often comparable to or even greater than PP containers. This phenomenon can be explained by the inherent properties of cornstarch polymers which are hydrophilic and structurally less stable. Due to natural polysaccharide structure, starch-based materials tend to absorb moisture easily which leads in disrupting the intermolecular forces, maintaining the polymer chains in a stable conformation [13]. This leads to a reduction in material integrity, making this type of container become prone to softening, cracking or even premature degradation. Furthermore, cornstarch containers commonly lack the compact, crystalline structure found in synthetic plastic, making them inherently vulnerable and prone to particle detachment [14].

These findings suggest that while biodegradable containers are designated to decompose upon exposure to environmental conditions, their material fragility may make them susceptible to mechanical wear and microplastic shedding even before full degradation occurs. Therefore, both the conventional, like thePS container and the biodegradable, like the cornstarch container, have intrinsic material vulnerabilities that can facilitate microplastic release irrespective of any external influences.

3.2 Influence of Treatments on Microplastic Abundance in Food Containers

This study results also revealed that the abundance of microplastic released from all types of food containers were significantly influenced by the treatment conditions including thermal and food simulants. There are six treatments applied in this study including various thermal conditions and food simulant such as warm water temperature (40°C), hot water temperature (70°C), boiling water temperature (100°C), 3% acetic acid (CH_3COOH), vegetable oil at room temperature and combination treatment of 3% CH_3COOH with 100°C. The combination treatment was selected based on previous studies' results, which indicate that 100°C exhibited the greatest microplastic release among the temperature conditions, while in the context of the food simulant applied in this study, acidic condition (3% CH_3COOH) caused the highest release of microplastic particles at room temperature. In order to ensure the precision of microplastic quantification and minimize the risk of false positive, three control samples were prepared and analyzed alongside the experimental samples. These controls including distilled water, 3% CH_3COOH and vegetable oil which were subjected to the same filtration and analysis procedures. The purpose of these controls was to detect any potential microplastic contamination baseline and helps in differentiate between true microplastic release from food containers and background laboratory or procedural contamination [8]. No signs of microplastics presence in all three controls (Figure 3).

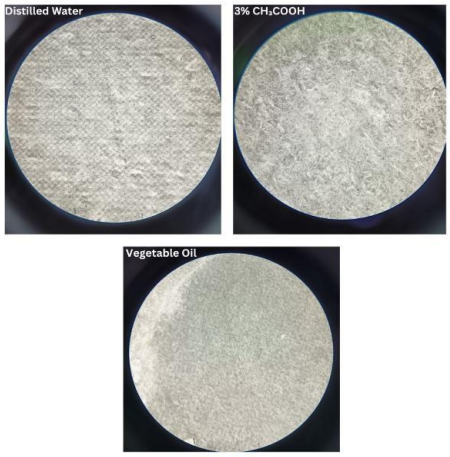

Fig 3. Control samples as filtered with distilled water, 3% CH_3COOH and vegetable oil

Table 1. Microplastic particles released from each container type under specific temperature and food simulant conditions.

Treatment Conditions	Type of Containers			
	PS	PP	Sugarcane	Cornstarch
40 °C	17	11	6	13
70 °C	25	26	23	22
100 °C	38	20	22	23
3% CH_3COOH	24	22	17	27
Oil	21	15	10	16
3% CH_3COOH+ 100 °C	51	40	27	40

Based on Figure 4, among these six treatments, the combined treatment of 3% CH_3COOH with 100°C showed the highest microplastic released from all treated food containers. PS container showed the highest abundance with 51 particles, followed by PP and cornstarch bagasse with 40 particles and sugarcane bagasse with 27 particles. The combination treatment between acidic food simulant and high temperature had creates a significant synergistic effect that dramatically accelerates the degradation of food container materials. Under this condition, the rate of acid-catalyzed hydrolysis had significantly increase, particularly in polymers that are more susceptible to chemical breakdown like polylactic acid (PLA) [15]. The high temperature acts as a catalyst that enhances the mobility and reactivity of molecules involved in the degradation process. Diffusion of acid molecules into polymer matric had increase due to the elevated heat, which allows the acid molecule to penetrate deeper and initiate further chemical reactions within the material [15]. Since the structure of the polymer is already compromised by thermal stress, this condition is particularly significant in making the polymer more vulnerable to acid attack. This trend provides valuable insights on how different environmental stressors can collaborate to significantly accelerate the degradation process of plastic and biodegradable materials into environment.

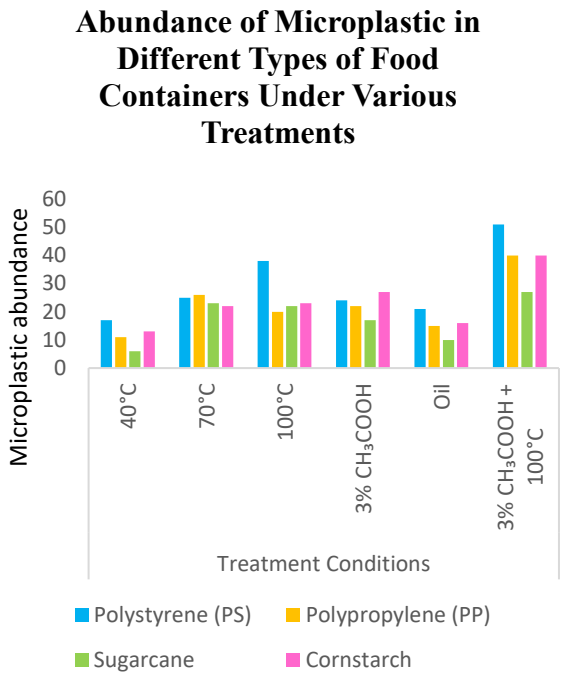

Fig 4. Microplastic abundance of different types of food containers under various treatment conditions

Furthermore, the result clearly demonstrated that increasing temperatures significantly impact microplastic release from food containers. As stated in Figure 4, among the thermal conditions applied, boiling water temperature (100°C) released the highest abundance of microplastic compared to warm water temperature (40°C) and hot water temperature (70°C). This trend aligns with the understanding of higher temperature might accelerate the kinetics polymer by increasing the molecular mobility and energy within the polymer matrix. As the temperatures approaches or exceeds the glass transition (Tg) or melting temperature (Tm) of the material, the polymer softened where their polymer chains experience structural relaxation, chain scission and reduced molecular weight [2]. These changes weaken the polymer's internal structure, making it more vulnerable to mechanical stress and chemical attack, which enhancing microplastic release. Hence, the diffusion of small molecules and additives from polymer matrix were also enhances by the elevated temperature, contributing to microplastic [16]. These factors reflected in the study findings presented in Figure 4, where PS container released the highest microplastic abundance at 100°C with 38 particles, followed by cornstarch bagasse with 23 particles, sugarcane bagasse with 22 particles and PP container with 20 particles. Besides, this result not only confirm the temperature-dependent nature of microplastic release but also provide valuable insights to the differ materials respond to thermal stress with PS container being the most affected, suggesting that PS is more thermally unstable to degradation under high heat than the other materials.

In terms of food simulant, this study revealed that both food simulant applied, acidic and oily plays a vital role in influencing the release of microplastic from food containers by interacting chemically and physically with the material's polymer structures. However, when comparing these two conditions, acidic food simulant tends to release a bit higher microplastic of abundance in all food containers tested. According to Figure 4, cornstarch bagasse released the highest particles at 3% CH_3COOH with 27 particles, followed by PS container with 24 particles, PP container with 22 particles and sugarcane bagasse with 17 particles. This finding aligns with the facts that certain polymer materials, especially biodegradable ones, are highly vulnerable to degradation, proving the reason why cornstarch releases more microplastic compared to conventional materials. As known, cornstarch bagasse is primarily composed of polylactic acid (PLA) where it contains ester linkages that are particularly susceptible to acid-catalyzed hydrolysis. Served as a catalyst, the acid was accelerating the polymer backbone degradation, resulting in a higher release of microplastics [17]. Thus, although PS and PP are more chemically resistant, acidic exposure can still weaken their outer structure. The acidic environment promotes protonation of the polymer chains, increasing their susceptibility to chain scission and fragmentation [2]. This is reflected in the observed trend, where acetic acid treatment consistently led to increases of microplastic release, especially in cornstarch bagasse, highlighting the PLA's sensitivity to acidic environment.

Meanwhile, at room temperature of vegetable oil, PS showed the highest abundance of microplastic released with 21 particles, followed by cornstarch bagasse with 16 particles, PP container with 15 particles and sugarcane bagasse with 10 particles. Even the degradation mechanism differs from the acidic condition, but it is still equally significant. Oils serve as plasticizers, penetrating the polymer matrix and increasing the mobility of polymer chains. This softening effect decreases the mechanical properties of the material making it more susceptible to wear and fragmentation [18].

Furthermore, the presence of oil can cause polymer swelling and introduce internal stresses that weaken the polymer structure [12]. Oils may also extract small polymer fragments as well as additives embedded within the material, contributing to microplastic release. These factors suggest that even an oily environment is not aggressive as an acidic or high-temperature environment, but it still poses a significant threat for microplastic contamination through more subtle but continuous degradation processes.

3.3 Polymer Identification and Composition of Released Microplastics

In this study, FTIR spectroscopy was employed to identify the polymer composition of the microplastic particles collected from the treated food containers. The analysis confirmed the presence of polymers consistent with the original container materials, validating that the released particles originated from the containers themselves. In an FTIR spectrum, the x-axis represents the wavenumber (cm^{-1}), which indicates the infrared light frequency absorbed by the sample and is inversely proportional to wavelength. Higher values appear on the left while lower values appear on the right. The y-axis indicates the intensity of the absorption [19]. The FTIR spectra were recorded 4000 cm^{-1} to 400 cm^{-1}, with a resolution of 4 cm^{-1} and 32 scans per sample to ensure an excellent signal-to-noise ratio. As illustrated in Figure 5 , aliphatic C-H stretching between 2923.69 cm^{-1} and 2854.11 cm^{-1} representing polystyrene polymer type. Otherwise, there are also aromatic C=C stretching vibrations of the benzene ring appearing at 1459.48 cm^{-1}. Above all, the out-of-plane C-H bending vibrations highly diagnostic of mono-substituted benzene literally in polystyrene was clearly presented at 717.36 cm^{-1}. This

combination of these characteristics peaks unequivocally identifies the polymer material as polystyrene [20].

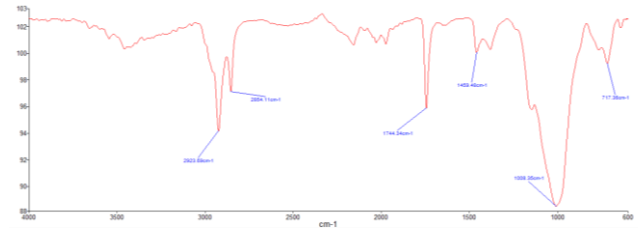

Fig 5. Fourier Transform Infrared (FTIR) Spectroscopy spectrum results for polystyrene at 100°C.

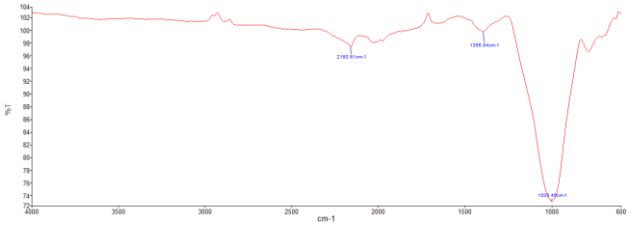

Fig 6. Fourier Transform Infrared (FTIR) Spectroscopy spectrum results for polypropylene at 100°C.

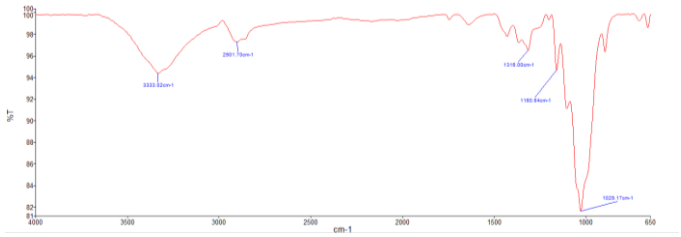

Fig 7. Fourier Transform Infrared (FTIR) Spectroscopy spectrum results for sugarcane bagasse at 40°C

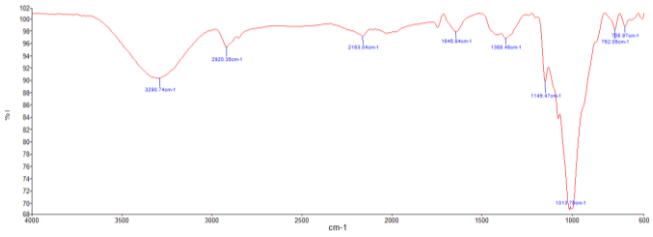

Fig 8. Fourier Transform Infrared (FTIR) Spectroscopy spectrum results for cornstarch bagasse at 100°C

Based on Figure 6, C-H bending vibrations at 1395.84 cm^{-1} is a definitive indicator of polypropylene. Other characteristic peaks were noted at 1000.48 representing C-C stretching which is a key skeletal vibration of the polypropylene chain. The overall spectral pattern distinctly identifies the material as polypropylene [20]. In terms of sugarcane bagasse, referring to the Figure 7, there was a broad and strong O-H stretching band in the region of 3300-3400 cm^{-1}, specifically at 3333.02 cm^{-1}. This peak signifies cellulose which is a primary component of sugarcane fiber. Peaks related to C-H stretching vibrations were observed at 2901.70 cm^{-1}. Hence, there were C-O stretching peaks showed at 1160.64 cm^{-1} and 1029.17 cm^{-1}. These peaks are highly indicative of the glycosidic linkages and the polysaccharide structure of cellulose. In general, the spectral pattern confirms the cellulosic nature of the sugarcane material [21]. Figure 8 clearly shows a prominent and broad O-H stretching band around 3290.74 cm^{-1}, which is a range for hydroxyl (-OH) groups that is abundant in starch due to hydrogen bonding and a fundamental feature of polysaccharides. In another case, there was a distinct peak shown at 2920.35 cm^{-1} corresponding to the C-H stretching vibrations within the starch glucose units. The most diagnostic region for cornstarch characterization lies below 1500 cm^{-1} where there were strong and distinct peaks visible at 1149.47 cm^{-1} and intensively sharp at 1013.75 cm^{-1}. These peaks represented the characteristic of the C-O stretching vibrations of the glucose units and C-O-C asymmetric stretching of the glycosidic linkages that form the starch polymer. The trend and intensity of these bands clearly confirm the material as cornstarch [19].

3.4 Statistical Analysis

A Two-Way ANOVA Without Replication was conducted to determine whether there were statistically significant differences in abundance of microplastic released based on container types and treatment conditions applied in this study (Table 2). This analysis was appropriate as each data combination of container types and treatment conditions had only a single observation, allowing for the assessment of the main effects of both factors.

Table 2. Two-way ANOVA without replication results

Factor	Experimental Condition	Significant Level	P-value
Treatment	40°C 70°C 100°C 3% CH_3COOH Vegetable Oil 3% CH_3COOH + 100°C	p = 0.05	p = 2.14E-06
Container Type	Polystyrene Polypropylene Sugarcane Bagasse Cornstarch Bagasse	p = 0.05	p = 0.00168

The analysis revealed that both treatment conditions and container types had a statistically significant effect on the abundance of microplastic released as both p-values were lower than the significance threshold of 0.05. From Table 2, the treatment factor (p = 2.14E-06) significantly influenced the release of microplastic suggesting that different environmental conditions including high temperature and food simulant exposure may greatly influence the extent of microplastic released from food containers Likewise, the type of food container material also significantly affected the release of microplastic with p-value of 0.00168, indicating that the material composition plays a vital role in effecting the microplastic released under stress conditions. As a result, we reject the null hypothesis of this study whose p-value of the study was smaller than their significance threshold.

Biodegradable containers are generally considered as safer alternatives compared to the conventional ones, but according to the statistical analysis it was confirmed that under certain conditions, especially at high temperature or exposure to acidic simulant, biodegradable containers might release microplastic

into the environment. This implies that while biodegradable containers offer environmental benefits in decomposition, their performance under food-use conditions may not always align with expectations.

Beyond the material degradation mechanisms discussed above, the environmental and health implications of these findings warrant further attention. Microplastics released from food containers under thermal and acidic conditions can be ingested directly by consumers, particularly when hot beverages or acidic foods are stored or served in these containers. Once ingested, microplastic particles in the micrometre range have been associated with potential translocation across the gastrointestinal barrier, raising concerns about bioaccumulation and long-term exposure risk. Furthermore, when discarded, these containers continue to fragment under environmental weathering, contributing microplastics and associated additives such as plasticizers and stabilizers into soil and aquatic ecosystems. Given that both plastic and biodegradable containers demonstrated measurable microplastic release under the tested conditions, the results suggest that migration risk should be assessed as a standard criterion for food-contact material approval, rather than relying solely on material origin or biodegradability claims.

Several limitations of this study should also be acknowledged. Microplastic quantification relied on stereo microscopy for visual counting, which, while effective for identifying particles above the optical resolution limit, may underestimate the abundance of sub-micron particles that require more sensitive techniques such as scanning electron microscopy or pyrolysis gas chromatography-mass spectrometry. In addition, the exposure durations and simulant concentrations used in this study, while representative of common food-contact scenarios, may not fully capture the cumulative effect of repeated or prolonged use typical of household and food-service settings. Future studies should therefore incorporate longer-term migration assays, a wider range of food simulants and real food matrices, and complementary analytical techniques capable of detecting nanoplastics, to provide a more comprehensive risk assessment. Investigating the toxicological effects of the identified polymer fragments on human cell lines or model organisms would also strengthen the evidence base linking microplastic release from food containers to actual health outcomes.

From a practical standpoint, these findings carry implications for both consumers and food-packaging manufacturers. Consumers should be encouraged to avoid exposing plastic and biodegradable food containers to prolonged high heat or highly acidic or oily contents whenever possible, particularly for reheating or extended storage. Manufacturers, meanwhile, may need to reconsider formulation strategies, such as incorporating more thermally stable polymer blends or protective coatings, to reduce microplastic shedding under realistic use conditions. Regulatory bodies could also consider revising food-contact material standards to include migration testing under a broader range of thermal and chemical stress conditions, ensuring that biodegradable alternatives are evaluated with the same rigour as conventional plastics before being marketed as safer substitutes.

Taken together, the comparative behaviour of plastic and biodegradable containers observed in this study also raises broader questions about how “single-use alternatives” are positioned in sustainability discourse. Sugarcane and cornstarch bagasse products are frequently marketed as environmentally friendly substitutes precisely because they are compostable and derived from renewable feedstocks, yet the present results show that, under acidic or high-temperature conditions typical of everyday food handling, these materials can shed microplastic particles at levels comparable to, or in some treatments exceeding, those released by polystyrene and polypropylene. This does not diminish the end-of-life advantages of biodegradable packaging, but it does indicate that biodegradability and microplastic safety are independent properties that must each be verified rather than assumed. Policymakers, certifying bodies, and consumers alike would therefore benefit from clearer labelling that distinguishes compostability claims from migration or shedding performance, so that material choices for hot, acidic, or oily food applications are guided by demonstrated performance data rather than by general perceptions of “bio-based” materials as inherently safer.

The observed differences in microplastic release among the four container materials can also be interpreted in light of their intrinsic structural and chemical properties. Polystyrene, being a brittle amorphous thermoplastic with a relatively low glass transition temperature, is prone to surface cracking and fragmentation once softened by heat, which explains its consistently higher particle counts across nearly all treatment conditions. Polypropylene, in contrast, is a semi-crystalline polymer with greater thermal and chemical resistance, and its comparatively lower release rates in this study are consistent with its higher resistance to hydrolytic and thermal attack. The two biodegradable materials, though structurally distinct from conventional plastics, are held together largely by hydrogen bonding and ester linkages that are intrinsically more hydrolysable, which is consistent with the pronounced sensitivity of cornstarch bagasse to acidic and combined acid-heat treatments observed in this study. Sugarcane bagasse, being predominantly fibrous and cellulose-based, showed comparatively lower particle release than cornstarch bagasse across most conditions, suggesting that its fibre-reinforced structure confers somewhat greater mechanical integrity under the tested stress conditions, although it remained more susceptible than polypropylene overall.

These structure-property relationships are also consistent with the shape distributions noted qualitatively during microscopic examination, where fragments dominated across all four materials while fibres were more prevalent in the bagasse-based containers, reflecting their fibrous internal architecture, and films were occasionally observed from the thinner wall sections of the plastic containers. Collectively, these observations reinforce the conclusion that microplastic release is governed by an interaction between the intrinsic polymer chemistry of the container material and the severity of the external thermal and chemical stressors it is exposed to, rather than by either factor alone. This mechanistic understanding is important for guiding the design of next-generation food packaging materials, as it suggests that simply substituting a conventional plastic with a biodegradable alternative, without addressing its hydrolytic sensitivity under realistic thermal and food-contact conditions, is unlikely to eliminate the risk of microplastic exposure to consumers.

When compared with previous studies on microplastic migration from food-contact materials, the abundance levels observed here are broadly consistent with the trend reported for polystyrene-based tableware exposed to hot liquids, where particle release increased sharply once the water temperature approached or exceeded 90°C. However, the finding that biodegradable bagasse-based containers can approach or, in the combined acid-heat treatment, even exceed the particle counts of some conventional plastics adds a distinct contribution to the existing literature, much of which has focused predominantly on conventional plastics such as polyethylene, polypropylene and polystyrene. Relatively few studies have systematically compared plant-fibre-based biodegradable packaging with conventional plastics under an identical set of thermal and food-simulant conditions, which limits direct benchmarking of the present results against prior work. This gap underscores the value of the present comparative design, which applied a consistent testing protocol across all four container types, thereby allowing the relative microplastic release behaviour of plastic and biodegradable materials to be assessed on an equal basis rather than inferred indirectly from separate studies conducted under different experimental conditions.

The present findings, therefore, contribute new comparative evidence to the growing body of literature on microplastic contamination from food packaging and provide a basis for more targeted future research. In particular, they highlight the need for standardized testing protocols that specifically account for the combined effects of heat and food simulants, rather than assessing thermal and chemical stressors in isolation, since the present results show that their combined effect can be substantially greater than either stressor alone. Establishing such standardized, combined-stressor protocols would allow more reliable cross-study comparisons and support the development of evidence-based guidelines for the safe use of both plastic and biodegradable food containers in everyday food handling and food-service applications.

4. Conclusion

In the nutshell, the objectives of this study were achieved successfully by proving that all food container types including biodegradable materials have potential in releasing microplastics under thermal and food simulant conditions. The findings showed that polystyrene container was consistently released the most abundance microplastic particles particularly under combination treatment of high temperature and acidic exposure. Surprisingly, this study also indicates that biodegradable containers, specifically sugarcane and cornstarch bagasse, can also contribute to microplastic pollution under realistic usage conditions, challenging the common assumption that these materials are inherently safer. In terms of shape distribution, fragments were the most dominant shape founds followed by fibers and films, indicating that mechanical and thermal degradation were the main degradation mechanism. Moreover, through the FTIR analysis, this study confirms that all the microplastics released totally correspond to the chemical signatures of the respective polymer materials, validating the accuracy of the results and absence of contamination. The two-way ANOVA without replication revealed that both treatment conditions and container types significantly influenced the microplastic released, where both p-values are significantly different. This finding emphasizes the vital role of both external factors, including heat, acidity and oil, and internal material properties, like polymer structure and thermal stability, in microplastic generation. Ultimately, this study underscores the importance of evaluating food contact materials not only based on their biodegradability claims but also by their actual performance and resistance under typical usage conditions, especially when exposed to heat and acidic environments.

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