

Article

Microplastics in Vegan Foods from Spain, France, and Italy: Quantification and Characterization Across Dairy Alternatives, Meat Substitutes, and Sauces

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Abstract

The market rise in innovative vegan food products has been driven by global dietary trends moving toward plant-rich models. Nevertheless, new xenobiotics, such as microplastics (MPs), may be introduced via plastic packaging and multi-step industrial processing. Five commercial vegan items—seitan, quinoa burgers, soy desserts, vegan “Parmesan,” and vegan pesto sauce—gathered from Spanish, French, and Italian retail outlets (N = 15 commercial products, evaluated in technical triplicate, n = 3 per batch) were statistically assessed in this pilot study for MP contamination. Rather than reflecting national market averages, MP contamination levels in the analysed samples were primarily governed by processing intensity and primary packaging. While liquid/semi-solid matrices indicated significantly lower concentrations (0.3–4.7 MPs/10 g), solid ultra-processed meat substitutes had the most significant MP burdens (5.3–9.3 MPs/10 g). Particles measuring < 100 µm represented 85–91% of the total counts of recovered MPs across all samples. Polymer analysis is a combination of thermoplastics (such as PE, PP, PET) and engineering polymers (including PTFE, PU), implying possible influences from manufacturing equipment and packaging substances. Mean MP concentrations across product categories ranged from 0.03 to 0.93 MPs/g (0.3–9.3 MPs/10 g). According to standard European serving sizes, the individual estimated daily intakes (EDIs) varied from 0.12 MPs/kg_{bw}/day for vegan pesto to 1.20 MPs/kg_{bw}/day for plant-based burgers. Based on existing illustrative scenario assumptions, the total daily exposure resulted in an annual intake of around 43,000–46,000 MPs/year. This first pilot study provides preliminary baseline data on MP contamination in specific commercial vegan food items from three Southern European retail locations, underscoring the necessity for enhanced risk analysis and larger market-representative studies in the plant-based food supply chain.



Received: 19 August 2026

Revised: 15 October 2026

Accepted: 15 October 2026

Published: 20 October 2026

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Keywords: microplastics; vegan food; food ultra-processing; food packaging migration; dietary exposure risk

1. Introduction

Global food systems have been under enormous pressure in recent years to evolve to paradigms that are solid, sustainable, and health-promoting. Rich in meat products, sodium, and saturated fats, traditional Western dietary patterns are a major contributor to environmental degradation worldwide, accounting for up to one-third of greenhouse gas emissions (GHGE) and extensive land exploitation. They are also strongly associated with non-communicable diseases (NCDs) [1–3]. As a result, influencing consumer behaviour to adopt plant-based diets (such as vegetarian, vegan, and flexitarian) has become a viable strategy to reduce climate change and improve public health. Adopting plant-rich diets is becoming increasingly crucial in national and international dietary frameworks. In particular, mathematical optimisation models applied to national dietary guidelines indicate that plant-dominant diets may substantially decrease GHGEs and land use while meeting essential nutritional requirements [1–3].

The transition to plant-based diets is prompted by a variety of complicated sociocultural factors that differ geographically. Structural limitations (such as product availability, price point, and market accessibility), self-efficacy, individual ethical beliefs, and sociocultural identities all have a significant impact on consumer acceptance of plant-based products. Emerging economies are usually constrained by practical access and structural availability restrictions, whereas established Western markets commonly indicate value-driven and identity-focused consumer preferences toward plant-based products. The demand for plant-based meat substitutes and plant-based food alternatives, which range from grains and legumes to structured meat and dairy analogues, is nevertheless growing rapidly worldwide despite these different regional factors [4–6].

Anthropogenic demand on the environment continues to increase within the framework of advancing toward circular economy models and the urgent requirement to minimise the environmental impact associated with human production and consumption chains; this trend is highlighted by the production of 430.9 million tonnes of plastics in 2024 [7]. Ironically, the multi-step processing required to create these ultra-processed formulations from agricultural raw ingredients (such as soy, wheat gluten, quinoa, nuts, herbs, and plant fats) involves constant exposure to industrial machinery, synthetic packaging materials, and international supply chains, even though the rapid industrial expansion of novel plant-based food alternatives has emerged as a key sustainability strategy [8–11]. Consequently, these specific vegan formulations might be significant carriers for emerging chemical and physical xenobiotics, including microplastics (MPs). The widespread detection of emerging contaminants, such as MPs, pharmaceuticals, pathogens, and heavy metals, within waste streams including sewage sludge [12–15], which severely restricts their agricultural or energetic valorisation if not subjected to strict quality and safety management, is similar to this exposure pathway [16,17].

A key strategy for achieving sustainability in the worldwide ecological transition is the substitution of plant-based matrices for animal proteins. Quinoa (*Chenopodium quinoa*), cañihua (*C. pallidicaule*), and amaranth (*Amaranthus caudatus*) are examples of Andean pseudocereals that have balanced amino acid profiles and high crude protein levels (15.0–16.3% dry weight) that are comparable to animal sources while significantly lowering environmental consequences. For instance, GHGE (27.0 kg CO₂ vs. 0.7–0.9 kg CO₂). Quinoa and cañihua have substantially smaller water footprints (850–1200 L/kg vs. 15,400 L/kg and eq/kg) than beef [11]. In terms of nutrition, studies indicate that limiting animal food consumption improves cardiometabolic health and weight reduction regardless of the degree of NOVA processing; processed plant foods do not appear to be associated with weight gain [10,18–21]. Despite these benefits, commercial vegan meals may be exposed to new xenobiotics due to rigorous industrial processing, high-shear emulsification, and

plastic packaging, which might result in MP contamination levels that are on a level with or higher than those observed in foods derived from animals.

In comparison to fresh animal products or unprocessed agricultural supplies, structured plant-based substitutes (such as meat alternatives and dairy replacements) require comprehensive multi-stage processing. The production of these products entails high-shear dry milling, high-moisture thermal extrusion (HMTE), continuous automated transport, and thermoformed vacuum encapsulation. Every mechanical phase subject the food matrix to synthetic polymers originating from machinery elements (such as drive belts, gaskets, scrapers, and non-stick coatings) and plastic container interfaces, serving as a significant conduit for possible MP contamination.

Although plant-based convenience and specialty items are widely distributed commercially throughout the European Union, there is still an absence of thorough empirical evidence on MP contamination in specific, renowned commercial vegan categories. There is a significant analytical gap with regard to processed plant-based matrices due to the vast majority of the environmental and food safety literature currently in publication having concentrated on marine creatures, drinking water, or items produced from animals. In order to satisfy this knowledge gap, the present study provides a systematic quantitative analysis of MP contamination in five different commercial vegan product categories that are commonly consumed in South-Western Europe (Spain, France and Italy): seitan with vegetables, quinoa burgers with tomato, soy-based desserts, vegan “Parmesan”-style cheese, and vegan pesto sauce. Due to their extremely varied physicochemical matrices—which include fermented dairy analogues, emulsified plant fat-and-oil systems, high-protein wheat gluten networks, and mixtures—evaluating these specific products is essential. Each of these matrices presents unique physical and chemical mechanisms for MP uptake, migration, and retention during industrial processing, handling, and packaging. Consequently, the primary aim of this study is to isolate, quantify, chemically characterise and identify MPs in these five product categories that were collected from three important Southern European markets. The parameters analysed include abundance, size distribution, polymer composition, and morphology. Additionally, this study aims to identify critical contamination hotspots in vegan food processing, assess potential human dietary exposure risks associated with plant-based diets, and provide crucial empirical data to inform future food safety regulations and quality assurance standards within the rapidly growing plant-based sector by providing preliminary analytical baseline information across selected Southern European markets. To the best of our knowledge, this exploratory pilot study is among the first targeted investigations to quantify and chemically characterize MP contamination across multiple commercially available vegan food categories in Southern European markets. The findings may help generate hypotheses for future food-safety studies and inform the design of broader monitoring studies in the rapidly expanding plant-based food sector.

2. Materials and Methods

2.1. Gathering Samples

Samples were acquired between June and August 2026. We acquired a range of vegan food products from different retail establishments in Oviedo (Spain), Bayonne (France), and Pavia (Italy) that represented the most common commercial vegan items in the Spanish, French, and Italian markets. As many distinct firms as feasible were chosen for analysis in each location. The chosen brands included a variety of formulas and packaging styles, as well as the primary providers of vegan items. A single production batch could contain up to three different packages. Considering this represented an exploratory study, the sampling strategy gave industry representativeness precedence over brand exhaustiveness. Therefore, rather than focusing on batch variability, the current study analysed technical

replication (in triplicate) within a single batch. Moreover, the selection was not intended to be representative of the whole market. In particular, five distinct commercial products were investigated in each of the three regions (Table S1). Every product came in factory-sealed packaging. Each of the five products' sampling concentrated on a single production batch, which underwent triple analysis ($n = 3$ per batch, total analytical samples = 45). Accordingly, the present sampling design should be interpreted as an exploratory pilot sampling framework rather than as a market-representative survey. The observations are intended to characterize the selected products and to generate hypotheses for subsequent multi-brand and multi-batch studies. Due to the selection of each product category by a single commercial brand/batch in each analysed nation, assessed in technical triplicate ($n = 3$), the study design is exclusively exploratory ($N = 5$ independent items per country, totalling $N = 15$). The findings pertain to these particular samples and are intended to formulate hypotheses rather than reflect national market averages.

2.2. Sample Preparation

All reagents and double-filtered distilled water were filtered using a glass microfibre filter ($0.7\ \mu\text{m}$ particle size, Whatman, Florham Park, NJ, USA) to guarantee the total absence of background MPs and prevent MP cross-contamination. Every sample was preserved in a beaker. The solid samples (10 g each) were combined with 500 mL of double-filtered distilled water to render stirring easier. The samples were stirred for 30 min at 120 rpm using a flocculation analyser (JLT6, VELPS Scientifica, Usmate Velata, MB, Italy) with a digital display, six glass beaker settings, an electric speed control mechanism (10–300 rpm), and a programmable timer (0–99 h). Each sample was subsequently combined with 80 mL H_2O_2 50% v/v solution (VWR Chemicals, Briare, France) and incubated for 24 h at room temperature continuously stirring. Subsequently, all samples were left to oxidise with 80 mL of Fenton's reagent. Fenton's reagent was prepared by dissolving iron(II) sulfate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 0.05 M final concentration, Sigma-Aldrich, Germany) in double-filtered distilled water adjusted to pH 3.0 with dilute H_2SO_4 (Sigma-Aldrich, Germany). Digestion was performed sequentially and continuously within the same glass beaker without intermediate filtration: samples were first incubated with 80 mL of 50% v/v H_2O_2 for 24 h at room temperature under constant stirring (120 rpm), followed immediately by the addition of 80 mL of Fenton's reagent and incubated for an additional 24 h. A stainless steel module (CISA Sieving Technologies, Barcelona, Spain) with overlapping sieves sized 500, 250, 100, and $20\ \mu\text{m}$ was then used to filter each sample. The sieving column consisted of a vertical system of stainless steel mesh with successively decreasing apertures (500, 250, 100, and $20\ \mu\text{m}$). The residual eluent passing through the finest sieve (liquid fraction $< 20\ \mu\text{m}$) was systematically collected in a solid stainless steel tray at the base of the column. This sub- $20\ \mu\text{m}$ fraction was also recovered, density-separated using ZnCl_2 solution (Sigma-Aldrich, Germany), and vacuum-filtered onto glass microfibre filters ($0.7\ \mu\text{m}$ pore size) for visual and chemical screening.

The MPs were collected in beakers after being held on each sieve and cleaned with distilled water that had been double-filtered. Lastly, a density separation technique utilising a ZnCl_2 solution ($d = 1.5\ \text{g/mL}$, 97% purity, VWR Chemicals, Briare, France) was used to separate the polymers from inorganic contaminants. By adding a saturated ZnCl_2 solution that had been adjusted to a reasonable density of $1.5\text{--}1.6\ \text{g/cm}^3$, density separation was achieved. The mixture was completely homogenised and left to remain at room temperature for a whole day in order to enable full flotation of the low- and high-density polymers. To maximise analytical recovery and reduce any physical entrapment inside the remaining matrix, this density separation approach was carried out in duplicate ($2 \times 24\ \text{h}$) for each sample. Before filtering, the supernatant containing MPs was quantitatively separated by

carefully aspirating the top layer, which was restricted to 10–20% of the fluid volume. After this operational control guaranteed full capture of the floating particle fraction without disturbing or resuspending the thick sediments at the bottom of the vessel, the combined supernatant was then directed straight to the vacuum filtration unit. Glass microfibre filters (Whatman, Florham Park, NJ, USA) with a pore size of 0.7 μm were used to filter the MP concentration.

2.3. Microplastic Analysis

The MPs in the filters were counted using a stereomicroscope (Leica M205FA, Wetzlar, Germany) and a high-resolution digital camera (Leica DFC310FX; 1.4 Mpixel, Leica Microsystems, Wetzlar, Germany). The sizes of the MPs were determined using the Confocal UniOvi ImageJ software (Version 1.54p). A scanning electron microscope analysis (SEM) (JEOL-6610LV, Tokyo, Japan) with a resolution of up to 3.0 nm and an operating voltage of 0.5–30 kV was used to further analyse MPs. The magnifications were between $5\times$ and $50,000\times$. Backscattered and secondary electron detectors were used to apply low- and high-vacuum modes as necessary. The files were automatically saved as JPG, TIFF, or BMP.

To chemically identify the separated MPs, sample spectra were compared to reference polymer databases using a strict automatic match criterion of $\geq 80\%$. To ensure analytical rigour, ambiguous matches—that is, those that produced transmission/reflection quality scores between 70% and 79% or exhibited clear atmospheric/baseline anomalies—were often referred to human expert verification. For this post-analysis cross-examination, the main diagnostic infrared absorption bands (such as the C=O stretching at about 1700 cm^{-1} for polyesters (PES) or the characteristic doublet at about 2900 cm^{-1} and about 1450 cm^{-1} for polyolefins) must be visually correlated against standard spectra. Any particle having a spectral match score of less than 70% or whose core structural peaks could not be definitively reconciled with reference baselines during human auditing was conservatively removed from the final dataset in order to avoid Type I mistakes (false positives). The operational size range for quantified microplastics was defined as 10–5000 μm , with the smallest size fraction categorized as 10–50 μm . All MPs are categorised as fragments, fibres, microbeads, etc. A μFTIR spectrophotometer (Perkin Elmer Spotlight 200i FTIR spectrophotometer, Springfield, IL, USA) from the Autonomous University of Madrid (UAM) Molecular Spectroscopy Unit was used to determine the chemical composition of MPs. For transmission analysis, MPs were set up atop infrared light-transparent supports (KBr pellets). The results of an automatic analysis of the produced infrared spectra were compared with a spectral database that was kept in the device. The instrument's spectrum library included over 36,000 chemical spectra of organic and inorganic materials, polymers, fibres, paints and their derivatives, solvents, pharmaceuticals, etc. The following measurement settings were used to analyse MPs: infrared beam aperture ($20 \times 100\text{ }\mu\text{m}$ for MP fibres and $50 \times 50\text{ }\mu\text{m}$ for MP fragments), spectral range ($550\text{--}4000\text{ cm}^{-1}$), resolution (16 cm^{-1}), and number of scans (30).

To eliminate any natural or semi-synthetic interferences (such as cotton and cellulose), cross-validation using micro-Fourier transform infrared spectroscopy (μFTIR) was essential. Throughout the whole study, all clearly separated particles were subjected to μFTIR analysis. Polymeric confirmation was strictly allowed when the spectral library match score (Hit Index) was more than 0.85; spectra below this threshold exhibiting ambiguous signals due to low signal-to-noise ratios were classified as unconfirmed and eliminated from the final counts. Although MPs in the $<20\text{ }\mu\text{m}$ fraction were collected in the stainless steel base tray and subjected to preliminary examination, $10\text{ }\mu\text{m}$ was set as the operational lower size limit for reliable quantification and chemical identification. This boundary was established due to the mesh aperture of the smallest sieve ($20\text{ }\mu\text{m}$) and the spatial

resolution/optical aperture limitations of the μ FTIR spectrophotometer ($10 \times 100 \mu\text{m}$ for fibres and $50 \times 50 \mu\text{m}$ for fragments), which preclude unambiguous spectroscopic identification of sub- $20 \mu\text{m}$ particles without higher-resolution techniques.

An Euromex Edu Blue (v2.4.9.0) magnifying lens (Duiven, Netherlands) with $20\times$ and $40\times$ magnification was used to evaluate MP particles; each plate's sample count and approximate size, shape, and colour were determined (data collected prior to analysis). Colour classification was only utilised as qualitative and descriptive criteria to assist the operator during manual sorting and prevent particle miscounting; it was not subjected to quantitative statistical modelling. The samples were physically placed on the surface of a manufactured KBr pellet, which is transparent in the mid-infrared band, after being recognised. They were then stored in an infrared microscope sample container. For this important procedure, a magnifying lens was always utilised as visual assistance. Electrostatically charged microfibre were transferred by handling isolated particles with tungsten needles or absorbent paper tips. Individual particles were carefully applied to the surface of a potassium bromide (KBr) pellet substrate. Before the KBr pellet was put on the motorised stage of the infrared microscope, each target was first identified using visible light microscopy. After determining the optical aperture and measurement settings, mid-infrared spectroscopic acquisition was performed. The generated spectra were automatically matched to reference polymer profiles kept in the device's software database in order to achieve chemical identification.

2.4. Quality Assurance and Quality Control (QA/QC)

From the time of collection until their quantification, the MP samples underwent quality assurance and control (QA/QC) [13]. Important QA/QC processes included filtering chemical reagents before use, eliminating polymeric contaminants from the lab, and using glass microfibre filters with a pore size of $0.7 \mu\text{m}$. During the collection and analysis process, secondary contamination from MPs detected in the air, on surfaces, and eventually on the equipment was decreased by using good field and laboratory practices (GLPs). As little plastic as feasible was used during sampling and sample processing. When this was not feasible, procedural blanks were employed.

To assess analytical matrix effects, spike experiments were performed in triplicate by introducing known quantities ($n = 50$) of conventional polyethylene (PE) and polystyrene (PS) particles ($50\text{--}100 \mu\text{m}$) into clean, pre-analyzed matrices. Average recovery rates varied from $82\% \pm 5\%$ for semi-solid matrices to $89\% \pm 4\%$ for solid matrices. Procedural blanks ($n = 5$, lacking a food matrix) were simultaneously subjected to all analytical procedures, yielding an average background count of 0.4 ± 0.2 MPs per filter. To adjust for background contamination, the average blank particle count was removed from the raw particle count of each analytical sample prior to converting the data to net concentration per mass (MPs/10 g and MPs/g). The morphotype and polymer distributions of uncoated particles were observed to ensure that certain external factors were considered before the overall data compilation.

Sample counts were adjusted by deducting the appropriate mean blank value. To assess the efficacy of the particle-transfer method from glass microfibre filters to KBr pellets, transfer trials were performed using conventional PE and PS particles ($n = 30$ for each size fraction). Utilising stereomicroscopic oversight, the manual transfer with tungsten needles yielded an average recovery rate of $91.3\% \pm 3.2\%$ for particles beyond $50 \mu\text{m}$ and $83.5\% \pm 4.1\%$ for the $10\text{--}50 \mu\text{m}$ range.

Polymer interaction was inevitable in two particular situations, despite the analytical workflow's strong preference for glass and metallic equipment: (i) the main commercial plastic packaging of the vegan food items themselves. To systematically detect and remove

any background contamination or particle shedding originating from these specific plastic interfaces, full procedural blanks ($n = 5$, including no food matrix) were included in the process. These blanks were processed concurrently through every subsequent analytical stage, from the initial opening of the sealed vessels and chemical digestion to density separation, wet sieving, and final vacuum filtration, to guarantee that any external polymer contribution was fully quantified and mathematically corrected. To accurately assess any background and airborne contamination, each extraction batch was processed alongside parallel procedural blanks ($n = 5$, including no food matrix) using the same methods. MPs produced by the Falcon tubes used for sample handling and sampling were therefore deemed insignificant, according to [13,22]. This background blank number was carefully subtracted from each final sample count to get actual net abundances. In the ISO 5 laminar flow cabinet, filter exposure times were restricted to fewer than 15 min in order to minimise airborne fallout during microscopic counting (see Supplementary Materials File).

2.5. Statistical Analysis

R and SPSS (24.0 v, IBM, Armonk, NY, USA) for Windows were used to evaluate the data. The technical triplicates ($n = 3$) obtained from each manufacturing batch were averaged to generate a single value for each commercial product, thereby avoiding pseudoreplication. The independent statistical unit was therefore the commercial product ($N = 5$ per country; total $N = 15$). Statistical comparisons were regarded as exploratory rather than confirmatory due to the small number of independent products. Where parametric assumptions were reasonably satisfied, ANOVA and Tukey's HSD were used to characterize observed differences among product categories and countries. Results are primarily reported using means, standard deviations and 95% confidence intervals (CIs). Effect-size estimates were calculated as complementary descriptive measures, but given the small sample size, they were interpreted cautiously and not used as standalone evidence of biologically meaningful differences.

3. Results

3.1. Comparative MP Analysis Among All Vegan Foods for Each Country

As detailed in Table S2, the evaluation of MP contamination across the 15 commercial vegan food items—where technical triplicates ($n = 3$) were averaged into individual statistical units per product ($N = 5$ per country; total $N = 15$)—indicated detectable contamination across all evaluated categories and geographical markets. Levene's test for homoscedasticity ($p > 0.05$) and Shapiro–Wilk normality tests ($p > 0.05$) confirmed that parametric assumptions were met. Exploratory evaluation of the three markets revealed descriptive patterns in overall mean MP abundance, with the highest mean concentration observed in the Italian samples (5.8 ± 0.5 MPs/10 g, equivalent to 0.58 ± 0.05 MPs/g), followed by France (4.9 ± 0.4 MPs/10 g, or 0.49 ± 0.04 MPs/g) and Spain (4.6 ± 0.6 MPs/10 g, or 0.46 ± 0.06 MPs/g). Given the limited number of independent commercial products analysed per country ($N = 5$), these cross-country variations represent descriptive trends rather than evidence of robust country-level effects. The vegan food product category had, within the evaluated samples, rather than statistically robust, market-wide national differences.

Food category type exercised a prominent influence on MP concentrations across all analyzed products ($p < 0.001$). Solid ultra-processed meat substitutes exhibited the highest MP burdens in all three markets; specifically, plant-based quinoa burgers presented peak mean concentrations in Italy (9.3 ± 1.5 MPs/10 g, or 0.93 ± 0.15 MPs/g) and Spain (9.3 ± 2.3 MPs/10 g, or 0.93 ± 0.23 MPs/g), while French quinoa burgers showed 6.7 ± 1.5 MPs/10 g (0.67 ± 0.15 MPs/g) (Table S2). No clear country-level sta-

tistical differences were detected across markets for either seitan ($p = 0.24$) or burgers ($p = 0.08$). Similarly, gluten-based seitan with vegetables yielded elevated MP burdens ranging from 5.3 ± 1.2 MPs/10 g (0.53 ± 0.12 MPs/g) in France to 7.0 ± 1.7 MPs/10 g (0.70 ± 0.17 MPs/g) in Spain and 7.3 ± 1.2 MPs/10 g (0.73 ± 0.12 MPs/g) in Italy (Table S2).

The MP concentrations of vegan “Parmesan”-style cheese alternatives were remarkably uniform across all three markets ($p = 0.82$), with Spanish samples averaging 4.7 ± 1.2 MPs/10 g (0.47 ± 0.12 MPs/g) and Italian and French samples averaging 5.3 ± 1.5 MPs/10 g and 5.3 ± 0.6 MPs/10 g (0.53 MPs/g), respectively (Table S2). Conversely, MP burdens were lower in liquid and semi-solid matrices; vegan pesto sauce exhibited a descriptive declining pattern from Italy (4.7 ± 0.6 MPs/10 g, or 0.47 ± 0.06 MPs/g) to France (3.7 ± 1.2 MPs/10 g, or 0.37 ± 0.12 MPs/g) and Spain (1.7 ± 1.2 MPs/10 g, or 0.17 ± 0.12 MPs/g) (Table S2). Finally, soy-based desserts recorded the lowest overall MP contamination, yielding 3.3 ± 0.6 MPs/10 g (0.33 ± 0.06 MPs/g) in France, 2.6 ± 0.6 MPs/10 g (0.26 ± 0.06 MPs/g) in Italy, and 0.3 ± 0.6 MPs/10 g (0.03 ± 0.06 MPs/g) in Spain (where MPs were identified in only one of the technical triplicates). Table 1 summarizes these cross-country descriptive comparisons and reported exploratory metrics.

Table 1. Cross-country descriptive comparison of mean MP concentrations for commercial vegan food categories analysed in Italy, France, and Spain.

Vegan Food Item	Cross-Country Descriptive Comparison Mean Concentration (MPs/10 g) *	Equivalent Mean Concentration (MPs/g) **	Exploratory Statistical Comparison (p -Value) ***
Seitan with vegetables	Italy (7.3) $\approx$ Spain (7.0) > France (5.3)	0.53–0.73	No clear difference detected ($p > 0.05$)
Plant-Based/Quinoa Burgers	Italy (9.3) = Spain (9.3) > France (6.7)	0.67–0.93	Exploratory trend ($p = 0.08$)
Vegan “Parmesan”-Style Cheese	Italy (5.3) = France (5.3) $\approx$ Spain (4.7)	0.47–0.53	No difference detected ($p = 0.82$)
Vegan Pesto Sauce	Italy (4.7) > France (3.7) > Spain (1.7)	0.17–0.47	Descriptive variation ($p < 0.05$) (Italy vs. Spain)
Soy-based Dessert	France (3.3) $\approx$ Italy (2.6) > Spain (0.3)	0.03–0.33	Descriptive variation ($p < 0.01$) (France/Italy vs. Spain)

* Values represent the arithmetic mean of MPs recovered per 10 g of sample ($n = 3$ technical triplicates per batch). ** Values expressed in MPs/g are provided for direct standardized comparison and alignment with dietary exposure models. *** p -values are reported as exploratory indicators from a two-tailed ANOVA and post-hoc Tukey’s HSD test ($N = 5$ independent commercial products per country). Given the pilot sampling framework ($N = 15$ total products), observed variations represent descriptive trends within the sampled products rather than confirmed market-level differences.

3.2. Size Distribution and Morphological Characteristics of Recovered MPs

Table S3 describes the physical and morphological characteristics of MPs identified in all 15 commercial vegan food items. Technical triplicates ($n = 3$) were combined into arithmetic means to represent distinct statistical units ($N = 5$ per nation; total $N = 15$). Levene’s test for homoscedasticity ($p > 0.05$) and Shapiro–Wilk normality tests ($p > 0.05$) verified that all datasets met parametric criteria. Particle size distribution and shape morphotypes were strongly biased toward small fragments throughout all investigated countries, with minimal overall variation between geographical areas ($p > 0.05$), according to a two-tailed analysis of variance (ANOVA). Particles smaller $<100 \mu\text{m}$ dominated MPs

in all assessed samples, accounting for more than 85–91% of all recoverable MPs in Italy, France, and Spain (Table S3). In particular, the 51–100 μm size fraction represented $51 \pm 11\%$ in Italy, $38 \pm 16\%$ in France, and $47 \pm 11\%$ in Spain, whereas the 20–50 μm size fraction accounted for overall mean abundances of $40 \pm 14\%$ in Italy, $49 \pm 17\%$ in France, and $46 \pm 14\%$ in Spain (Table S3). All nations had a small percentage of particles larger $>100 \mu\text{m}$; Italy, France, and Spain did not vary statistically significantly in the 101–150 μm (4–7%), 151–250 μm (2–5%), or $>250 \mu\text{m}$ (0–1%) fractions ($p > 0.05$, $d < 0.3$). With an average of $83 \pm 7\%$ in Italy, in France, and $81 \pm 9\%$ in Spain, fragments were the most common particle morphotype across all food types and nations (Table S3). With $11 \pm 6\%$ in Italy, $11 \pm 6\%$ in France, and $10 \pm 6\%$ in Spain, films constituted the second most common MP shape. Fibres ranked second with $6 \pm 3\%$ in Italy, $8 \pm 5\%$ in France, and $9 \pm 4\%$ in Spain. Microbeads were almost nonexistent in all matrices (0–1%), with only a few small occurrences observed in pesto sauce (1%) and French quinoa burgers (2%) (Table S3). Different morphological, size, and polymer profiles were observed when particular food categories were assessed separately throughout each nation (Table S3).

MPs recovered from the five vegan food matrices were examined for texture, surface topography, and physical degradation patterns using SEM analysis (JEOL-6610LV) (Figure 1) [23]. The SEM images verified a definite prevalence of heterogeneous and irregular fragments in all the samples, which is consistent with the previous optical characterisation [24].

- Extremely processed foods (vegan seitan with veggies and a vegan quinoa burger): The MPs recovered from these solid matrices demonstrated the greatest rates of structural damage and topological degradation [17]. SEM images indicated complex microfractures, localised porosity, ragged angular edges, and longitudinal cracks [25]. The extreme heat and mechanical stress (cereal/legume grinding, high-speed mixing, and thermo-mechanical extrusion) needed to texturize the plant proteins cause these topographic flaws [26].
- Analogous fat and dairy matrix (vegan “Parmesan” cheese): Film-like morphotypes (lamellar films) and clustering fragments in the 51–100 μm range were significantly present in MPs recovered from vegan “Parmesan” cheese [27,28]. SEM analysis revealed thin sheets with damaged edges, fractures, and folds [29]. This pattern shows how friction and the negative pressure of vacuum packaging on the lipid-rich surface (coconut oil) induce tiny layers to mechanically separate from the plastic wrapper [30] (Figure 1).
- Emulsified semi-solid matrix (vegan pesto sauce): Smaller fragments ($<50 \mu\text{m}$) were indicative of MPs isolated in the vegan pesto sauce [31]. When processing hard botanical components (nuts, pine nuts, and basil), hydraulic shear and abrasive cutting of the crushing blades resulted in angular and uneven surfaces, as illustrated in SEM images [26] (Figure 1).
- Liquid/semi-solid matrix (Vegan soy dessert): The majority of the MPs identified in the vegan soy dessert belonged to the fine particle size fraction (20–50 μm) [31]. Due to fluid friction and high-speed pumping in the pasteurization/UHT treatment and packaging processes, SEM analysis revealed MPs with abrasive shapes [32] (Figure 1).

SEM confirmed the virtual absence of identical or polished microbeads (0–1%) in the five matrices [26]. This verifies that MP contamination comes from degradation and mechanical friction during industrial processing and packaging, and not from the direct addition of primary plastic microbeads [17].

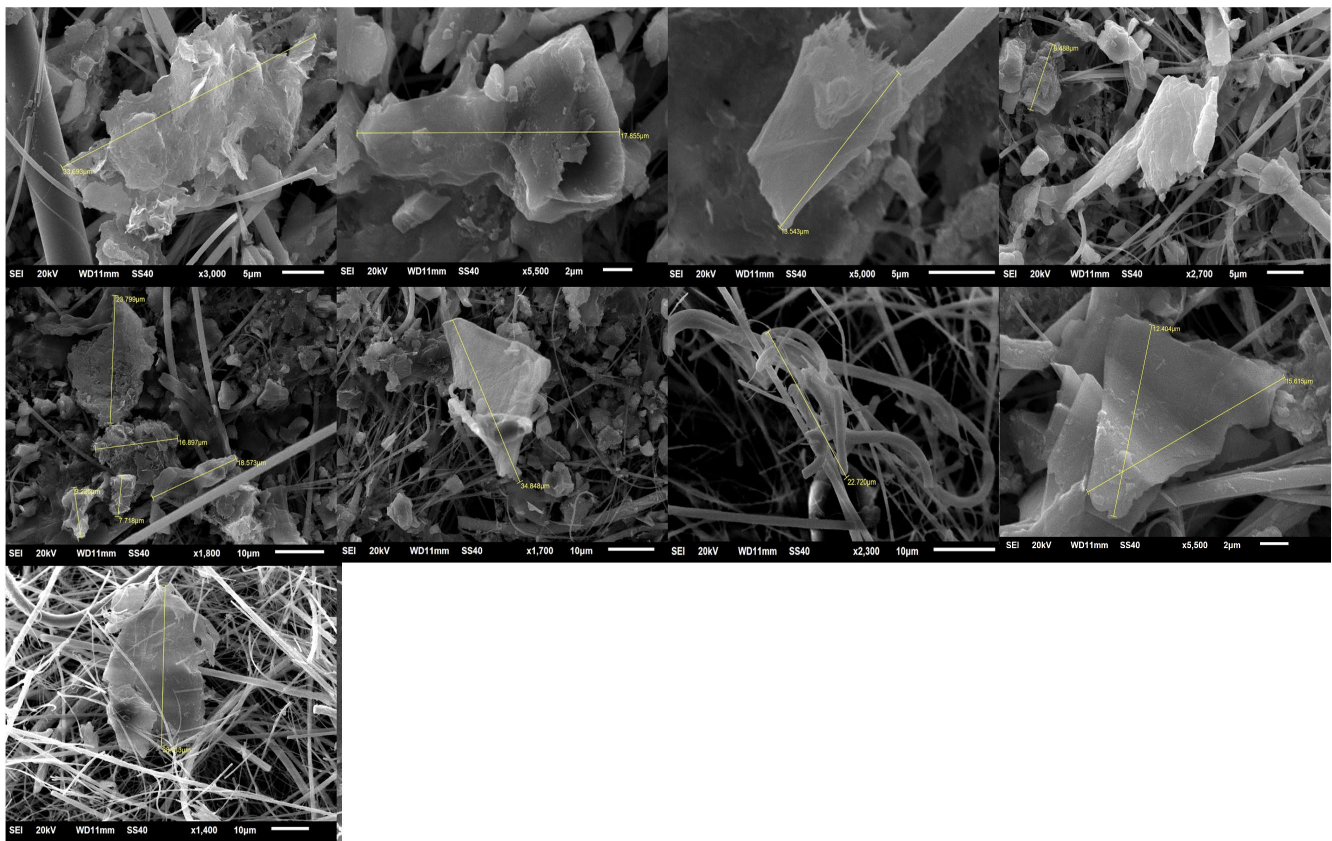


Figure 1. SEM images of the all-vegan food samples (France, Spain and Italy).

In addition to having the highest concentration of fragments (91–93%), the lowest fibre contribution (2–4%), and polymer signatures dominated by polyethylene (PE), polypropylene (PP), and polystyrene (PS), soy-based desserts continually demonstrated the highest proportion of the finest size fraction (20–50 μm), reaching 63% in Italy, 77% in France, and 66% in Spain (Table S3). Similar high concentrations of 20–50 μm particles (44% in Italy, 46% in France, and 51% in Spain) and increased fragment percentages (75–87%) were observed in vegan pesto sauce; polymer identification confirmed polyamide (PA), PE, polyethylene terephthalate (PET), and PP (Table S3, Figure 2).

Conversely, vegan “Parmesan”-style cheese showed a shifted size distribution that increased in the 51–100 μm range (58% in Italy, 38% in France, and 60% in Spain). This was supported by a significant film morphotype fraction (14% in Italy, 7% in France, and 15% in Spain) that was triggered by direct contact with vacuum cling film packaging. Polymer analysis identified ethylene-vinyl acetate (EVA), PE, PET, and PP (Table S3). While polymer characterisation revealed complex synthetic blends including PA, PE, PET, polytetrafluoroethylene (PTFE), and polyurethane (PU), Seitan with vegetables demonstrated a predominant size clustering in the 51–100 μm range (53% in Italy, 55% in France, and 49% in Spain), with fragments (69–78%) and films (16–18%) dominating the morphotype profile. Finally, plant-based and quinoa burgers demonstrated the most varied morphological profiles and particle sizes, with 51–100 μm MPs recovered representing an up 48–62%, along with significant film contributions (11–18%), the highest fibre counts (7–11%), and a polymer composition that included PE, PET, PP, PS, and styrene-butadiene rubber (SBR) (Table S3).

Particle morphology is primarily determined by food processing mechanisms and primary packaging types rather than geographical origin, as confirmed by cross-country statistical comparisons of identical products, which revealed no statistically significant

differences in particle size or morphotype distribution between Italy, France, and Spain ($p > 0.05$, Cohen's $d < 0.4$). Inter-product comparisons within each nation, nevertheless, indicated that the food category had a highly significant impact on morphotype breakdown ($p < 0.01$, $d = 1.18$) and size distribution ($p < 0.01$, $d = 1.32$). Specifically, burgers, seitan, and vegan cheeses had significantly higher proportions of MP-film morphotypes (11–18%, $p < 0.05$, 95% CI [8.2,16.4]) and larger particle sizes (μm), which directly reflected high-shear mechanical processing and flexible plastic film encapsulation, while semi-solid desserts and pesto sauces had significantly higher proportions of $<50 \mu\text{m}$ fragments compared to solid extruded alternatives ($p < 0.01$). Due to the small number of independent products, effect-size estimates should be regarded carefully as exploratory measures of magnitude.

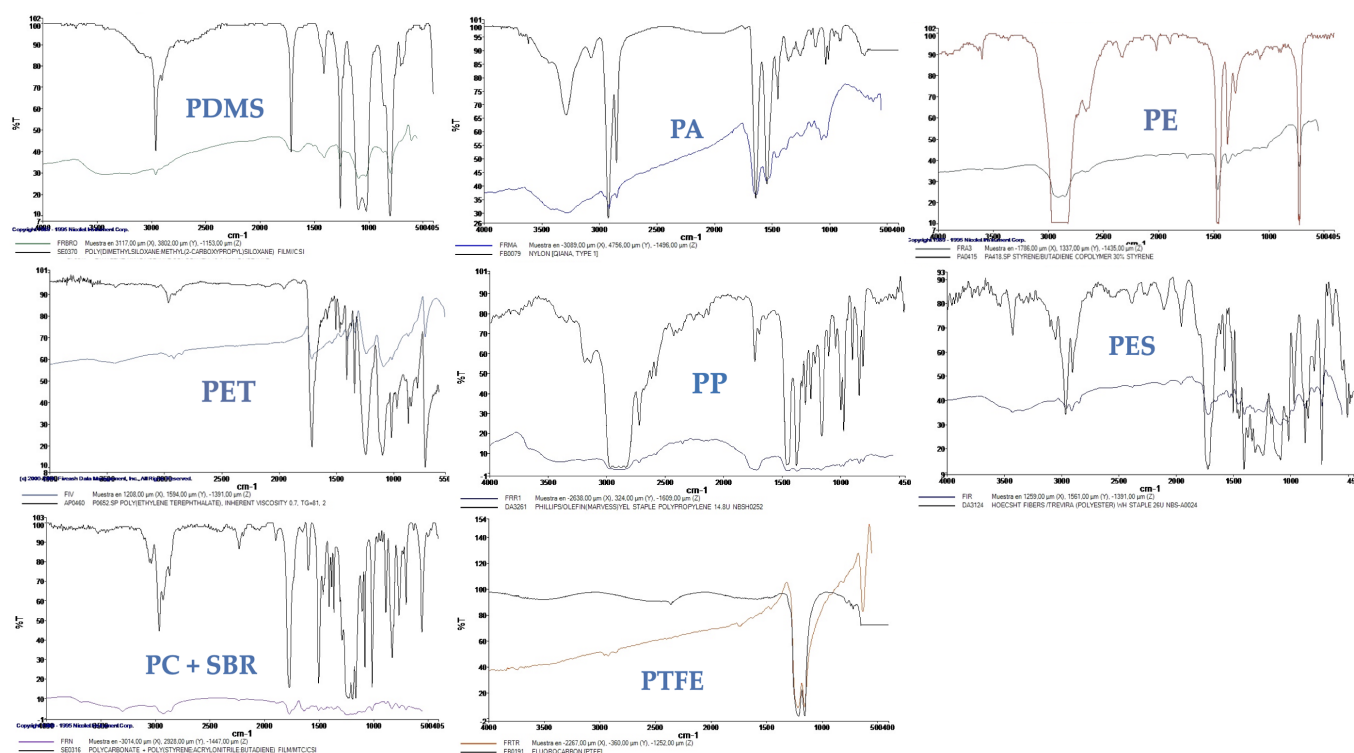


Figure 2. μFTIR images of the all-vegan food samples (France, Spain and Italy).

4. Discussion

The quantitative assessment of MP contamination in commercial vegan foods provides significant data on the processes controlling particle transfer in contemporary plant-based diets. Although plant-based items are often thought of as more sustainable environmental alternatives, the empirical evidence collected in France, Spain, and Italy reveals notable differences resulting from production paradigms. MP burdens are intrinsically connected to technological transformations, matrix physical states, and polymer-packaging interfaces rather than representing the origins of basic ingredients. The main structural and operational factors influencing these contamination profiles are explained in subsequent subsections, which also compare them to recognised non-vegan dietary assessment findings.

4.1. Impact of Food Matrix Complexity, Industrial Processing, and Packaging on MP Abundance

The findings of the present study demonstrate that MP contamination in plant-based food items is primarily dictated by the degree of industrial processing and the nature of primary packaging rather than the intrinsic plant origin of the raw materials [24–26]. Regional differences, as well as additive complexity, are primary reasons for the observed geographical variation in MP burdens, with Italy exhibiting the highest contamination

levels (5.8 ± 0.5 MPs/10 g sample), followed by France (4.9 ± 0.4 MPs/10 g sample) and Spain (4.6 ± 0.6 MPs/10 g sample) [17,31]. Highly multi-layered formulations (such as pre-gelatinized wheat flour, brown rice, oat flakes, and vegetable blends) requiring extensive industrial mixing, conveying, and extrusion—where mechanical friction against synthetic machinery belts, scrapers, and seals promotes particle shedding—are observed in the elevated MP concentrations in Italian samples [26].

Spanish products, conversely, had lower overall MP contamination due to their simpler, less processed formulations. For example, a soy-based dessert with 99.5% soy extract and no thickening gums or modified starches yielded nearly zero MP levels (0.3 ± 0.6 MPs/10 g sample) [17,31]. While high-pressure extrusion and vacuum sealing continue to be the main sources of contamination, French items exhibited an intermediate contamination profile where the use of certified organic ingredients in products like quinoa burgers may slightly decrease baseline agricultural contamination.

Based on the matrix structure interface, a clear hierarchy of MP risk emerges across different food categories [17]: solid meat substitutes (burgers and seitan) generated higher MP concentrations (5.3–9.3 MPs/10 g sample, or 0.53–0.93 MPs/g), which we hypothesize may be attributed to potential mechanical wear of machinery components during thermo-mechanical extrusion, along with potential shedding from flexible vacuum packaging. Similarly, for lipid-dense matrices such as vegan ‘Parmesan’-style cheese (4.7–5.3 MPs/10 g sample, or 0.47–0.53 MPs/g), the observed contamination is consistent with possible particle transfer from synthetic film wrapping under vacuum conditions [26,31,32]. In contrast, reduced concentrations were identified in liquid and semi-solid matrices, indicating that decreased mechanical shear during processing and the utilisation of inert glass containers may mitigate particle introduction. In summary, these trends indicate that the intensity of industrial processing and packaging interactions—rather than the source of raw materials being plant or animal—are likely contributors to MP contamination [17,24–26,31,32].

4.2. Size Distribution, Morphological Characteristics, and Polymer Signatures as Indicators of Contamination Pathways

Important mechanistic data regarding the specific operational pathways of contamination during food processing and packaging are provided by the physical dimensions, morphological profiles, and recovered MPs (Table S3) [26,31]. The severe physical degradation processes currently taking place within industrial processing lines are demonstrated by the significant dominance of small particle size fractions across all three geographical markets, where MPs < 100 μm consistently accounted for over 85–91% of the total burden [26,33]. The high frequency of fluid mixing, homogenisation, and pumping of fluid ingredients, which breaks down synthetic polymers into microscopic debris without triggering larger particles, can be observed in the high prevalence of the finest 20–50 μm fraction in liquid and semi-solid matrices, especially in soy-based desserts (63–77%) and vegan pesto sauces (44–51%) [31]. Conversely, solid extruded matrices exhibited a clear distributional shift toward the 51–100 μm range, including plant-based burgers (48–62%), gluten-based seitan (49–55%), and lipid-dense vegan cheeses (38–60%) (Table S3). This modification is consistent with the strong thermo-mechanical shear stress applied during high-moisture extrusion and protein texturization, when abrasive contact with equipment walls produces both tiny microscopic dust and bigger particle debris [26,34,35].

These contamination pathways resulting from processing are further supported by a morphological analysis (Table S3). The majority of obtained MPs across all items and nations (69–93%) were irregularly shaped fragments. The presence of irregular fragments across all categories is hypothesized to originate from potential mechanical wear of polymer-based processing elements, such as gaskets, seals, scrapers, or conveyor belts subjected to friction during processing. The occurrence of film morphotypes (3–18%), particularly in seitan,

vegan cheeses, and burgers, is consistent with possible shedding from primary flexible packaging during vacuum sealing and handling [31,32]. Additionally, the identification of chemical polymers provides credible insights into possible contamination pathways. The identification of SBR fragments in burgers might be correlated with possible mechanical abrasion with rubberised seals or drive mechanisms, whilst the occurrence of PTFE and PU in seitan is speculated to indicate probable degradation of non-stick thermal coatings or robust conveying surfaces. Furthermore, the presence of EVA in vegan cheese substitutes aligns with the possibility of particle transfer from pliable barrier films [24–26,36–38]. Comparison of these morphological and polymer characteristics among Italian, French, and Spanish samples suggests that uniform industrial processing equipment and analogous packaging forms probably act as common routes for particle introduction [17,26,36–38].

Surface Morphology (SEM) and Its Mechanistic Implications in Vegan Food Items

SEM microstructural evaluation provides pertinent information for understanding the mechanisms of plastic material transfer and fragmentation that might be taking place throughout the processing and packaging of processed plant-based foods [31]. In this scenario, we might connect the properties of MPs to the mechanical and physicochemical processes that the food may be exposed to based on the surface morphology, size, and shape of the detected particles. Thus, the rough, angular, and fractured particles identified in the vegan quinoa burger and the vegan vegetable seitan are consistent with physical abrasion processes associated with the continuous contact of the food matrix with augers, extruders, seals, and other polymeric components of the equipment. This wear could favor the detachment of particles from materials such as PTFE, PU, and PE, subsequently becoming incorporated into the food matrix [26].

Furthermore, the physicochemical interactions between the food's fat phase—which is especially rich in coconut oil—and the flexible packaging materials—such as EVA or PET films—may be responsible for the morphology of vegan “Parmesan” cheese, which is characterised by folded layers and wrinkled surfaces [32]. The mechanical forces generated during packaging, handling, and storage, along with the potential alteration or weakening of the polymer interface, may make it simpler for tiny layers to separate into the food [39]. Additionally, shearing, impact, and progressive fragmentation processes in fluid matrices may be inferred from the prevalence of fragment-MPs <50 in the vegan sauce and the vegan soy dessert. Smaller fragments could arise from the decrease in previously deteriorated plastic particles due to hydrodynamic pressures and high-speed impact events [31].

These morphological shifts are especially significant from the standpoint of food safety and human exposure due to MP's porous and rough surfaces, which may favour interaction with other substances present in food or the environment [40,41]. This surface can promote the adsorption of lipophilic pollutants and interaction with chemicals from the plastic material itself, including specific additives like phthalates and bisphenol-A, in matrices with a high lipid content, including pesto and plant-based cheese [16]. Additionally, MPs, particularly those <100 µm, may be more capable of mechanically interacting with gastrointestinal tissues if they have uneven surfaces. This might lead to inflammation of the intestinal mucosa [25]. With all factors viewed, the surface morphology observed with SEM not only enables the physical characterisation of MPs present in vegan foods but also provides hints regarding their potential mechanisms of generation, transformation, and interaction with food matrices—aspects that can be critical for comprehending their behaviour and possible toxicological relevance.

4.3. Comparative Polymer Signatures of Conventional Non-Vegan and Vegan Substitute Foods

When compared to previous studies on conventional, non-vegan food items, the analytical identification of polymer types throughout the assessed vegan matrices (Table S3) demonstrates both clear technical divergences and structural chemical similarities. Commodity thermoplastics, such as PE, PP, and PET, were widely used in all vegan product lines, reflecting the universal profile identified in processed animal-derived products including commercial sausages, chicken nuggets, and canned meats [26,29,32,33,36]. Nevertheless, an extremely complex polymer spectrum, comprising PA, PS, PTFE, PU, and SBR, was observed in ultra-processed vegan meat substitutes (plant-based burgers and seitan) (Table S3). PE, PP, and polyester (PES) fibres from agricultural bioaccumulation, slaughtering effluent, or primary film trays are the main sources of MP contamination in non-vegan processed meats [29,34]. Conversely, the identification of engineering polymers (such as PA, PU, PTFE, and SBR) in ultra-processed plant-based burgers and seitan is hypothesized to be linked to intensive thermo-mechanical operations specific to plant protein texturization, where high-shear extrusion and continuous conveying may promote localized wear of equipment coatings, seals, and heat-resistant belts. In dairy analogues, the presence of EVA is consistent with potential transfer from specialized flexible vacuum barrier films designed to encapsulate high-fat plant oil emulsions [26,30–36]. A comparison of these findings with existing literature on standard non-vegan foods indicates that traditional meat products mainly obtain commodity polymers (PE, PET, PVC) during the slaughtering and initial packaging processes, whereas ultra-processed vegan alternatives may incorporate a wider variety of engineering polymers, most likely due to intense mechanical processing and direct interaction with technical packaging materials [17,26–28,30–36,42].

4.4. Exploratory Scenario-Based Dietary Exposure Assessment

Using the obtained MP concentrations and predetermined consumption assumptions, a scenario-based Estimated Daily Intake (EDI) was determined to provide an exploratory illustration of potential dietary exposure. The average intake of vegans or exposure at the population level is not meant to be represented by this estimate. The EDI was determined using the standardised equation (Equation (1)):

$$EDI = \frac{C_{MP} \times \text{Serving size (g)}}{BW} \quad (1)$$

where C_{MP} represents the microplastic concentration in the food matrix (MPs/g), serving size (FIRs, g) and assuming an average adult body weight (BW) of 70 kg.

When baseline C_{MP} values expressed in MPs/g are integrated into exposure equations (Equation (1)), significant differences in serving burdens and individual EDIs emerge across the product categories. Plant-based quinoa burgers exhibited the highest contamination level ($C_{MP} = 0.84$ MPs/g on average, ranging from 0.67 to 0.93 MPs/g across markets), delivering an estimated 84.0 MPs/serving (100 g portion) and an EDI of 1.20 MPs/kg_{bw}/day. Seitan with vegetables yielded $C_{MP} = 0.65$ MPs/g (0.53–0.73 MPs/g), corresponding to 78.0 MPs/serving (120 g portion) and an EDI of 1.11 MPs/kg_{bw}/day. Among dairy analogues and semi-solid formulations, lower mass-normalized burdens were observed. Vegan ‘Parmesan’-style cheese ($C_{MP} = 0.51$ MPs/g, 0.47–0.53 MPs/g) contributed 15.3 MPs/serving (30 g portion) and an EDI of 0.22 MPs/kg_{bw}/day. Vegan pesto sauce ($C_{MP} = 0.34$ MPs/g, 0.17–0.47 MPs/g) provided 8.5 MPs/serving (25 g portion) and an EDI of 0.12 MPs/kg_{bw}/day. Finally, soy-based desserts ($C_{MP} = 0.21$ MPs/g, 0.03–0.33 MPs/g) yielded 26.25 MPs/serving (125 g portion), representing an EDI of 0.38 MPs/kg_{bw}/day.

The mechanical abrasion of dried grains during industrial milling, along with HMTE and automated moulding equipment shedding PE and PP fragments from processing

belts and packaging films, are the causes of this increased particle load in quinoa burgers. These processes cause physical micro-abrasion of the intestinal mucosa and encourage the sorptive carrying of lipophilic environmental contaminants. The rigorous mechanical isolation of essential wheat gluten, high-shear mixing, and multi-stage dough handling that introduce substantial fractions of PU and EVA synthetic fibres and rubberised fragments from conveyors and sealing gaskets are the main causes of seitan's high MP concentration. These particles are susceptible to chemical degradation under acid-enzymatic gastric conditions, potentially leaching reactive isocyanate monomers, vinyl acetate residues, and toxic plasticiser additives, resulting in oxidative stress.

High C_{MP} in vegan pesto is triggered by the mechanical grinding of hard botanical ingredients in high-shear rotary blenders, which contaminates the matrix mainly with PET and PS, whose pre-adsorbed endocrine-disrupting additives (such as phthalates and bisphenol-A) are easily desorbed in the gut due to the sauce's lipid-rich solvent phase. Whereas aged dairy cow cheese usually exhibits decreased MP burdens ($C_{MP} \approx 1.5\text{--}2.8$ MPs/g; $EDI \approx 0.64\text{--}1.20$ MPs/kg_{bw}/day). Intestinal tight-junction proteins are disrupted by PE and PET micro-fragments introduced by the industrial agitation of modified starches and coconut oils followed by thermoformed plastic packing, increasing permeability ("leaky gut"). Finally, among the assessed vegan items, soy-based desserts indicated the lowest exposure tier, bringing them closer to conventional cow's milk yoghurt ($C_{MP} \approx 0.3\text{--}0.6$ MPs/g; $EDI \approx 0.54\text{--}1.07$ MPs/kg_{bw}/day), including small amounts of PP and PE micro-fragments from liquid UHT pumping and filling lines. To illustrate the potential magnitude of dietary exposure under a defined consumption scenario, we considered a hypothetical daily combination of selected products included in the present datasets (i.e., one plant-based burger together with a small portion of pesto or a cheese analogue and one soy-based dessert). To illustrate potential cumulative exposure under defined dietary assumptions, a scenario combining one plant-based burger, one portion of cheese or pesto analogue, and one soy dessert daily yields an estimated aggregate daily exposure of 1.70–1.79 MPs/kg_{bw}/day. Extended over 365 days, this corresponds to approximately 43,000–46,000 MPs/year. These intake estimates are scenario-dependent and reflect specific product categories analysed in this exploratory pilot study rather than population-wide vegan dietary surveys.

Rather than being estimates of real yearly MP consumption among vegan consumers, these data points should be carefully considered as scenario-dependent estimates. Benchmarked against a conventional omnivorous diet—where fresh meat and milk yield low EDIs (0.5–2.5 MPs/kg_{bw}/day), and seafood provides moderate exposure (2.0–5.0 MPs/kg_{bw}/day)—it becomes evident that multi-stage industrial transformation acts as a far more potent vector for MP contamination than biological or environmental bioaccumulation [29–36]. From a human health perspective, the potential biological effects of ingested microplastics remain an active area of investigation in the toxicological literature. While the literature reports potential toxicological mechanisms for microplastics (e.g., oxidative stress, mucosal irritation, potential epithelial translocation, and intestinal barrier alteration), these biological outcomes were not evaluated in the present study and remain illustrative context based on published literature. The size of physical particles (<100 µm) and the polymer characteristics observed in these commercial matrices are delineated in current research as significant factors for exposure models. Nonetheless, further empirical multidisciplinary studies directly assessing bioavailability, cellular absorption, and prolonged biological impacts are required in order to provide conclusive toxicological assessments regarding the intake of plant-based foods. Crucially, individual dietary habits, food frequency, portion-size variability, brand-to-brand variability, batch-to-batch variability, packaging differences, and intake of other plant-based and non-plant-based foods are

all ignored in this scenario. All data, exposure values, polymer profiles, and toxicological mechanisms described above are summarized in Table 2.

Table 2. Illustrative scenario-based dietary exposure calculations for the selected vegan food items (based on [16]).

Food Item	Mean C _{MP} (MP/g) *	Serving Size (g)	Serving Burden (MPs/Serving)	Individual EDI (MPs/kg _{bw} /Day)	Main MPs	Hypothesised Mechanisms (from Literature)
Quinoa/ tomato burger	0.84	100	84.0	1.20	PE, PP, PS	Associated in literature with localized mechanical irritation and potential sorptive carrying of lipophilic environmental xenobiotics
Seitan with vegetables	0.65	120	78.0	1.11	EVA, PTFE, PU	Reported in published studies to involve physical interaction with mucosal surfaces and additive leaching under acidic gastric conditions
Vegan Pesto sauce	0.34	25	8.5	0.12	PA, PET, PS	Hypothesised in external literature to interact with the lipid phase, potentially facilitating chemical desorption
Vegan “Parmesan” cheese	0.51	30	15.3	0.22	EVA, PE, PET	Described in general toxicological models as a potential carrier for pre-adsorbed lipophilic compounds
Soy-based dessert	0.21	125	26.25	0.38	PE, PP	Represent low-dose background physical particle exposure
Hypothetical Cumulative Scenario ** (Convenience daily diet)			118.8–125.5	1.70–1.79	EVA, PE, PET, PP, PS, PU	Illustrative scenario-based daily estimate: corresponds to 43,000–46,000 MPs/year. Biological endpoints and systemic translocation remain non-evaluated hypotheses based on published literature

* Scenario-based calculation using predefined consumption assumptions for selected products included in this study. Values represent cross-country arithmetic of MP concentrations (CMP in MP/g) calculated across the sampled items in Spain, France, and Italy (N = 15 total commercial products). ** The cumulative scenario (1.70–1.79 MP/kgbw/day; ~43,000–46,000 MPs/year) represents a hypothetical, illustrative daily diet combining specific sampled products (1 burger, 1 portion of cheese/pesto analogue, 1 soy dessert for a 70 kg adult). It serves as an illustrative model rather than a population-wide dietary exposure estimate for vegan consumers.

Particle size and polymer identity determine systemic effects on health from a human toxicological perspective. MPs of coarse size (>150 µm) mainly cause superficial mechanical abrasion of the mucosal epithelium and are not absorbed throughout the intestinal lumen (>99% ejected fecally) [16,26,27]. Conversely, small MPs (<150 µm, especially <20 µm), including the PE, PET, PU, and PS fractions identified in these ultra-processed matrices, easily pass through the intestinal barrier via paracellular passage or transcellular endocytosis (M cells of Peyer’s patches), entering the blood and lymphatic circulation (Table 2, Figure 3) [16,26,27]. Once systemically distributed, small MPs accumulate in secondary target organs (liver, kidneys, vascular endothelium), where polymers like PS and PU generate excessive reactive oxygen species (ROS), triggering chronic inflammation and endothelial dysfunction [37–39].

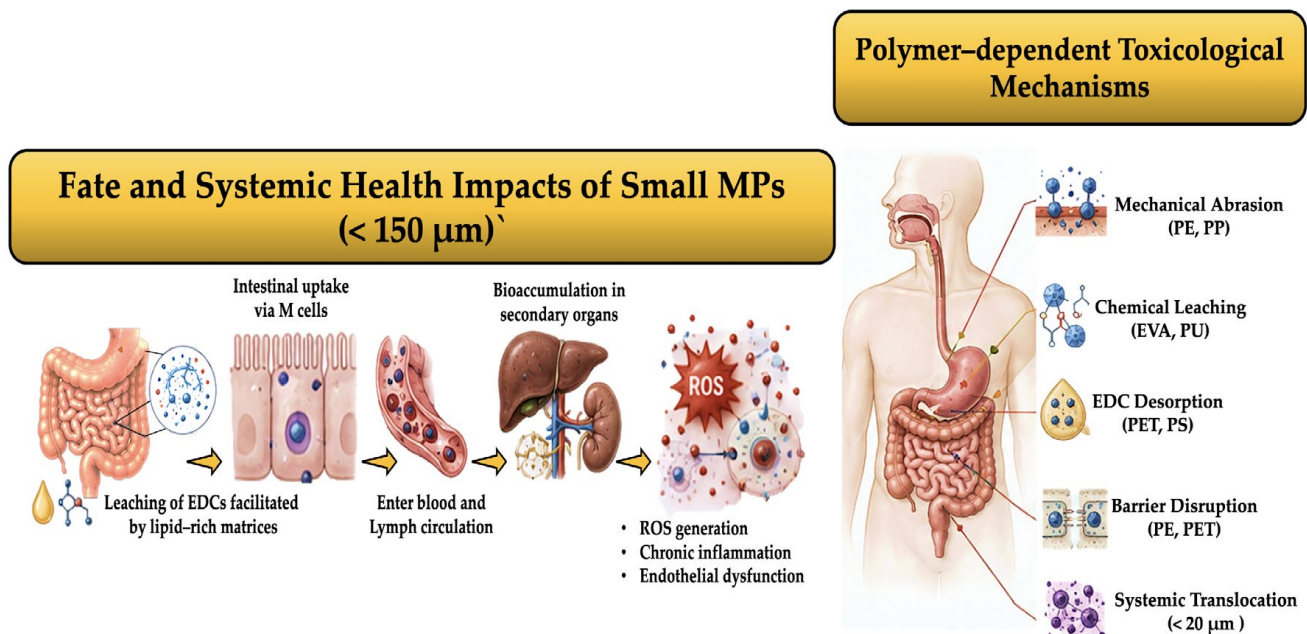


Figure 3. Hypothesized biological fate and potential exposure pathways of ingested small MPs (<150 µm) based on current literature models. Note: Specific biological mechanisms (i.e., barrier disruption, ROS generation, organ bioaccumulation) were not directly investigated in this study and serve as general contextual background (This image was generated by Nano Banana 2; gemini-3.1-flash-image. Prompt: “An educational scientific vector infographic and anatomical cross-section diagram illustrating the biological fate and exposure pathways of ingested small microplastics (<150 µm) in the human digestive system. The layout features clear descriptive labels, flow arrows, and medical illustration elements. Left side shows ingestion, gastrointestinal tract, intestinal uptake via M cells, blood and lymphatic circulation, and bioaccumulation in secondary organs (liver, kidneys). Right side details polymer-dependent toxicological mechanisms: mechanical abrasion (PE, PP), chemical leaching (EVA, PU), EDC desorption (PET, PS), barrier disruption, and systemic translocation (<20 µm). Clean professional medical journal style, high resolution, detailed vector graphics with text callouts.”).

Concurrently, the intestinal leaching of embedded endocrine-disrupting chemicals (EDCs), such as phthalates and bisphenol A, is facilitated by the lipid-rich matrices of plant-based sauces and cheeses, resulting in a dual physical-chemical toxicity burden [16,17,31,32]. The importance for public health strategies to prioritise fresh, minimally processed whole plant foods over industrially transformed convenience formulations is highlighted by the reality that, although a plant-based diet eliminates marine and animal bioaccumulation pathways, a heavy reliance on ultra-processed, plastic-packaged vegan analogues presents serious MP hazards (Figure 3).

4.5. Limitations of the Study

When evaluating the current findings, a number of limitations should be taken into consideration. First, only 15 commercial items—five from each nation—were included in the study; each product was represented by a single production batch. Technical triplicates were carried out; however, the number of independent commercial items is not increased by these repetitions. As a result, the study’s statistical power is limited, and it is unable to produce reliable estimates of variability between brands, batches, seasons, or markets. Second, the variety of foods consumed within vegan dietary patterns cannot be represented by the five vegan food categories that were studied. Third, the exposure calculations should not be considered as estimates of real dietary exposure in vegan communities since they were scenario-based and depended on predetermined serving sizes and consumption

assumptions. Fourth, market share, customer purchase frequency, packaging variety, and regional variability within each nation were not taken into consideration in the study. Furthermore, direct comparisons of MP concentrations observed in the present study with those in existing literature should be approached with caution, as discrepancies in digestion methodologies, sieve mesh dimensions, spectroscopic thresholds, and possible operator-induced visual sorting biases may affect the reported data. To conclusively ascertain if ultra-processed plant-based foods possess greater MP burdens than traditional animal products, forthcoming study designs must examine comparable plant and animal matrices concurrently utilising uniform analytical methodologies, automated particle enumeration, and double-blind operator protocols.

Finally, unless directly verified by source-tracing studies, the mechanical attribution of individual MPs to particular processing machinery or packaging materials remains inferential. Therefore, in order to confirm and generalise the current results, larger research involving numerous brands, production batches, sampling dates, packaging types, and consumer-relevant consumption statistics is necessary.

Techniques such as micro-Raman spectroscopy (μ Raman) or high-resolution Raman spectroscopy, known as atomic force microscopy-Raman (AFM-Raman) may be capable of detecting MPs $< 1 \mu\text{m}$ and providing more accurate characterisation in future studies.

5. Future Perspectives

From a risk management and food safety perspective, understanding the pathways governing microplastic contamination in processed food supply chains is essential for developing targeted mitigation strategies. Future research should prioritize two main avenues.

First, analytical capabilities must be expanded by incorporating higher-resolution spectroscopic and microscopic techniques, such as μ Raman spectroscopy (μ Raman) or Atomic Force μ Raman (AFM-Raman), to reliably isolate, quantify, and characterize MPs $< 20 \mu\text{m}$ and NPs ($< 1 \mu\text{m}$) in complex food matrices. Secondly, mechanisms for translation that focus on minimising human dietary exposure need to be investigated. This requires investigating food-grade biopolymer matrices (such as chitosans sourced from fungi or crustaceans) as prospective luminal binding agents to enhance intestinal movement and faecal elimination of consumed MPs/NPs, alongside refining industrial machinery parts (such as non-shedding elastomers and non-stick coatings) to reduce particle dispersion during high-shear food processing. Comprehensive longitudinal studies including wider product batches and varied food matrices would be essential to authenticate these preventative and technological measures.

Severe health risks, including oxidative stress, mitochondrial dysfunction, pro-inflammatory cytokine release, and potential endocrine disruption, have been associated with long-term exposure to MPs [40]. Oral administration of *Procambarus clarkii*-derived chitosan (PCC) prior to MP intake has been reported to enhance faecal excretion by at least 45% [40]. Mechanistically, MP entrapment and integration into mixed lipid micelles—a crucial requirement to facilitate uptake via endocytosis and transcytosis—are prevented by a high-viscosity hydrogel matrix in the stomach lumen. Additionally, PCC hydrogels have been demonstrated in vitro to effectively sequester polystyrene nanoplastics (NPs) in simulated gastric fluid (SGF, pH 3.0), suggesting that biopolymer therapy may be able to remove both MPs and NPs from the human body [41]. Furthermore, chitosan attenuates epithelial translocation while reducing MP-induced inflammatory cascades, including Toll-like receptor (TLR)-mediated signalling and NLRP3 inflammasome activation [42].

An ongoing in vitro study is currently assessing the comparative effectiveness of vegan chitosan fungal extract from *Aspergillus niger* versus PCC, building on these encouraging biological findings while harmonising with plant-based and cruelty-free paradigms. The

relative binding affinities and entrapment capabilities of the biopolymers for MPs in SGF (pH 3.0) are analysed in this study. With its unique degree of deacetylation (DDA) and molecular weight (MW) distribution, fungal chitosan may provide similar or better MP sequestration capability in acidic luminal settings without depending on animal sources generated from crustaceans, according to preliminary mechanistic findings.

Biopolymer-based treatments are a very promising therapeutic strategy from a translational perspective for human health applications. Cattle are frequently impacted by long-term exposure to MP through interior surroundings, synthetic feeding equipment, and processed dietary habits. In scenarios of long-term low-dose food exposure, future prospective studies should concentrate on improving biopolymer matrices to avoid intestinal barrier hyperpermeability, systemic bioaccumulation, and organ toxicity.

6. Conclusions

This exploratory pilot study provides preliminary baseline information regarding MP contamination across 5 commercially available vegan food categories sampled in Spain, France, and Italy (N = 15). MPs were detected across all evaluated product categories, with solid ultra-processed meat substitutes (quinoa burgers and seitan) exhibiting higher mean particle burdens (5.3–9.3 MPs/10 g, or 0.53–0.93 MPs/g) than liquid and semi-solid formulations (0.3–4.7 MPs/10 g, or 0.03–0.47 MPs/g). The structural predominance of small MPs (<100 µm) and the detection of both commodity thermoplastics and engineering polymers imply that contamination is mainly caused by human processing techniques—such as mechanical high-shear manipulation, thermo-mechanical extrusion, and contact with flexible packaging—rather than the natural plant origin of the raw components [17].

Due to the single-batch pilot design and limited sample size of the present study, the identified cross-country and inter-category variances reflect descriptive patterns among the analysed items rather than definitive market-wide insights. In a comparable approach, scenario-driven intake computations yield demonstrative approximations based on specified consumption premises rather than estimations of exposure at the population level. Future multi-batch, multi-brand studies that include larger sample data sets, market-share statistics, and enhanced analytical precision are essential for improving exposure models and bolstering evidence-based quality assurance benchmarks in the growing plant-based food industry.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/microplastics5040211/s1>, Table S1: Information on ingredients, nutrients, and/or primary protein sources in all vegan food samples analyzed; Table S2: Comparing MPs in all vegan food samples (analysed in triplicate) in each Country; Table S3: Main characteristics of MPs recovered in all vegan food samples in France, Spain and Italy (analysed in triplicate).

Author Contributions: C.C.: Conceptualization, Methodology, Formal Analysis, Supervision, Statistical Analysis, Visualization, Validation, Writing—Original Draft, Writing—Review and Editing; R.L.: Visualization, Funding, Methodology, Writing—Review and Editing; K.A.S.-L.: Visualization, Methodology; and U.C.: Conceptualization, Methodology, Formal Analysis, Visualization, Validation, Writing—Original Draft, Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the RUDN University Scientific Projects Grant System, grant number: 021411-0-000.

Data Availability Statement: The datasets used and analyzed during this study are available from the corresponding author on reasonable request.

Acknowledgments: The authors are grateful to the Photonic Microscopy and Imaging Processing Unit of the Scientific-Technical Services of the University of Oviedo (Confocal UniOvi ImageJ), for assistance in the MPs analysis and to the Molecular Spectroscopy Unit of the Autonomous University of Madrid (UAM) for assistance in FTIR analysis. R.L. acknowledged the support from the RUDN University Scientific Projects Grant System, grant number: 021411-0-000. During the preparation of this study, the authors used Nano Banana 2 (gemini-3.1-flash-image) for the purposes of Figure 3. The authors have reviewed and edited the output and take full responsibility for the content of this publication. This article is dedicated to Alexander Santiago Casella Flores.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AFM–Raman	Atomic Force Microscopy–Raman
BW	Body Weight
CIs	Confidence Intervals
C _{MP}	Cross-Country Arithmetic Means of Microplastic Concentrations
DDA	Degree of Deacetylation
EDCs	Endocrine-Disrupting Chemicals
EDI	Estimated Daily Intake
EVA	Ethylene-Vinyl Acetate
FIRs	Food Ingestion Rates
GHGE	Global Greenhouse Gas Emissions
GLPs	Good Field and Laboratory Practices
HMTE	High-Moisture Thermal Extrusion
KBr	Potassium Bromide
MPs	Microplastics
MW	Molecular Weight
NCDs	Non-Communicable Diseases
NPs	Nanoplastics
PA	Polyamide
PCC	Procambarus Clarkii Chitosan
PE	Polyethylene
PES	Polyester
PET	Polyethylene Terephthalate
PP	Polypropylene
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PU	Polyurethane
ROS	Reactive Oxygen Species
SBR	Styrene-Butadiene Rubber
SEM	Scanning Electron Microscopy
SGF	Simulated Gastric Fluid
UAM	Autonomous University of Madrid
μFTIR	Micro–Fourier Transform Infrared Spectrometry
μRaman	Micro–Raman Spectroscopy

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