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RESEARCH ARTICLE

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Size and shape attributes of packaging remnants commonly detected in former food products

Peng Lin[a], Tom Fearn[b], Sharon Mazzoleni[a], Matteo Ottoboni[a], Alice Luciano[a], Andrea Moradei[a], Marco Tretola[c] and Luciano Pinotti[a]

[a]Dipartimento di Medicina Veterinaria e Scienze Animali (DIVAS), Università degli Studi di Milano, Lodi, Italy; [b]Department of Statistical Science, University College London, London, UK; [c]Swine Research Group, Agroscope Standort Posieux, Switzerland

ABSTRACT

Former food products (FFPs) are alternative feed ingredients used in livestock diets. Although the processes of transforming FFPs into animal feed often include mechanical unpacking and grinding, the final products may still be prone to packaging contamination. Common materials of packaging remnants found in FFPs are aluminium, cellulose, and plastic. Therefore, it is important to investigate and to provide information regarding the size and shape attributes of these materials to improve processing techniques in the feed industry. A total of 441 packaging remnants from 17 sources of FFPs were included in this study. Fourier transform infra-red spectroscopy coupled with an optical microscope was used to identify the material of the packaging remnants, which resulted in a categorisation of remnants consisting of 44 aluminium, 308 cellulose, and 89 plastic remnants. The categorised remnants were observed with a stereomicroscope and were subsequently measured by a digital camera and image analysis software. Each measurement contains 21 size attributes and 9 shape attributes, some of which were derived from calculations. The distribution of values for both size and shape attributes overlapped between the three materials though aluminium remnants were on average smaller ($p < .05$) in size and more regular ($p < .05$) in shape compared to cellulose and plastic ones. Also, aluminium remnants showed a narrower range in most of the size and shape attributes. Through the information provided by the image analysis and the measurements, it was concluded that the obtained values in size and shape attributes had broadly spread distributions that overlapped for different materials.

HIGHLIGHTS

- Former food products are slightly contaminated with packaging remnants.
- Aluminium, cellulose, and plastic are packaging materials commonly detected as remnants in former food products.
- Aluminium remnants were on average smaller and more regular in shape whereas cellulose remnants were likely to have irregular edges and stellular shapes.
- The obtained values in size and shape attributes of FFP packaging remnants had broadly spread distributions overlapping for different materials.

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Former food products; packaging remnants; feed safety; feed contamination, stereomicroscope

Introduction

Former food products (FFPs) are alternative feed sources approved by the European Commission and are regulated under the guidelines from the European Catalogue of Feed Materials (Reg. EU 2018/851; Pinotti et al. 2023a). FFPs come from food manufacturing where there are food losses generated unintentionally and unavoidably. Due to production errors or oversupply during festive occasions, FFPs have to vacate from human consumption market. However, FFPs still possess valuable nutrients such as processed starch, simple sugar, and fat suitable to be used in livestock diets (Pinotti et al. 2023b). Despite being safe from microbiological hazards (Pinotti et al. 2023b), physical hazards such as extraneous objects or foreign material contamination do exist in FFPs (Pinotti et al. 2021). The most relevant physical hazards in FFPs are residuals of packaging materials as FFPs are derived from market-rejected foodstuffs and surpluses (Lapusneanu et al. 2022). Inadvertently, these packaging remnants

CONTACT Peng Lin peng.lin@unimi.it Dipartimento di Medicina Veterinaria e Scienze Animali, via dell'Università 6, Lodi,Italy.

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may be introduced into the feed producing process (Food and Agriculture Organization of the United Nations/World Health Organisation 2015). In fact, Mazzoleni et al. (2023a) detected some packaging remnants in FFPs gathered from different FFP processing plants from various geographical areas by using Fourier transform infra-red spectroscopy paired with an optical microscope (μFT-IR).

To process considerable quantities of foodstuffs recycled from food manufacturing industry and supermarket into animal feed, several procedures and techniques are routinely practiced in feed plants (Van Raamsdonk et al. 2011). Basically, three steps are involved in removing packaging materials from FFPs: (i) pre-treatment processes including grinding, drying, dissolving, and squeezing; (ii) separation processes including sieving, wind shifting, applying magnet or electric magnetic field, and centrifugation; (iii) monitoring unpacked FFPs and, if needed, manually removing the still-remaining packaging materials. In general, packaging remnants sizing more than 1 mm can be identified visually, extracted manually, and quantified according to their weights. This procedure has evolved into a routine practice to examine the quality and safety aspects of FFPs used as animal feed ingredients (Van Raamsdonk et al. 2020; Luciano et al. 2022). Depending on the nature of the FFPs (states of matter, moisture content, solubility, particle size, density, and consistency) and packaging materials (glass, cardboard, paper, plastic, and ferrous or non-ferrous metals), combinations of the techniques mentioned above will be performed manually or/and automatically.

However, even with the packaging-removing treatments on FFPs and the subsequent visual inspection, small amounts of packaging residuals can still be present in the final products (Amato et al. 2017; Calvini et al. 2020; Mazzoleni et al. 2023a). Typical packaging remnants found in FFPs are paper/cardboard, plastics, and aluminium foil (Tretola et al. 2019; Mazzoleni et al. 2023a). In addition, studies have shown that cellulose or fibres from paper/cardboard are the most abundant materials of packaging remnants observed in inspected FFP samples even though the most frequently used packaging material is plastic (Van Raamsdonk et al. 2011; Tretola et al. 2019; Mazzoleni et al. 2023a). This is because grinding and dissolving are more effective at removing pieces of plastic or aluminium foil packaging from sugary FFPs such as candies. Furthermore, when the FFPs are wet products such as dairy products or beverages, dissolution of cellulose or fibres in the liquid can occur easily (Van Raamsdonk et al. 2011).

Packaging remnants, regardless of material types, are not accepted as feed ingredients (Reg. (EC) No. 767/2009, European Commission 2009, 2018). Nevertheless, implementing a zero-tolerance standard on the packaging remnants present in FFPs is not practically feasible and can be an obstacle to the exploitation of FFPs in animal nutrition (Mazzoleni et al. 2023a). Instead, since the presence of packaging remnants in FFPs is nearly unavoidable and such small quantities of remnants do not show risks for animals and humans (Van Raamsdonk et al. 2011, 2012), a maximum tolerance standard could be applied. According to Kamphues (2005), packaging material contamination levels of up to 0.15% w/w are deemed inevitable in bakery products. When several putative tolerance levels were set to test the number of FFP samples to be rejected due to higher contamination levels, tolerance levels between 0.1% w/w and 0.2% w/w did not cause major differences in the resulted numbers of rejection (Van Raamsdonk et al. 2011). Additionally, more than 90% of the tested FFP samples showed lower levels of packaging remnants than the putative tolerance levels from 0.1% w/w to 0.2% w/w. Therefore, it was concluded that a tolerance level of 0.125% w/w for packaging remnants in FFPs should not cause significant risks (Kamphues 2005) and a maximum tolerance of 0.2% w/w is acceptable (Van Raamsdonk et al. 2011). For example, assuming that 30% FFPs are included in pigs' diet (Mazzoleni et al. 2023b; Tretola et al. 2024) and that the tolerance levels are set between 0.1% w/w and 0.2% w/w, it would then lead to levels between 0.03% w/w to 0.06% w/w of packaging remnants in the final feed.

Among different packaging materials, plastics raise the highest concern (Mazzoleni et al. 2023a). Plastics can fragment into micro- and even nanoplastics which may negatively affect food security by changing soil properties and decreasing the productivity of plant and livestock (Prata and Dias-Pereira 2023). In this manner, microplastics may compromise food safety through human consumption of contaminated products. However, direct toxic effects of orally ingested microplastics occur only at extremely high doses and little is known about indirect effects of microplastic ingestion on living organisms such as particle toxicology, oxidative stress, and inflammation response (German Federal Institute for Risk Assessment [BfR] 2020). In livestock, after biliary excretion and macrophage migration, most of the microplastic particles are expected to be expelled through faeces. If some microplastics still remain in animal's body, they are predominantly found in the gastrointestinal tissue

(Prata and Dias-Pereira 2023) that is not a major food sources for human consumption.

In order to further achieve a sufficiently low-level risks in feed ingredients derived from FFPs, techniques in packaging removal and the final product monitoring require improvements. Additionally, there is no adequate reliable information on the occurrence, material type, and particle size and shape of packaging remnants in FFPs. Therefore, this work aimed at providing information about size and shape attributes of packaging remnants of three commonly detected materials in FFPs, which are aluminium, cellulose, and plastic. Accordingly, with such information, FFPs and respective feed processors could further improve production techniques and perform different combinations of packaging removal treatments. In this way, minimising the amount of packaging remnants in FFPs and enhancing feed safety are possible. This will then help to take a step forward in promoting the use of FFPs in livestock farming industry.

Material and methods

Former food product sample acquisition

This work was a continuation of Mazzoleni et al. (2023a). Hence, the packaging remnants of FFPs used in the present study were found and extracted by Mazzoleni et al. (2023a). Briefly, 17 FFP samples collected from FFP processors geographically located in or outside of Europe, including 5 countries and several different processing plants, were analysed. The foreign objects in FFP samples (3 technical replicates with 20 g of feed per replicate) were identified by visual sorting under a stereomicroscope (OLYMPUS SZX9) and by using tweezers, which highly depended on the expertise of the trained laboratory staff (Van Raamsdonk et al. 2023). The extracted foreign objects were defatted with 50 mL of detergent (Triton X-100, 1:4 dilution v/v) in a beaker and rinsed with ultrapure water several times (Bessa et al. 2019). Implementing these washing steps ensured that the instrument accurately characterised the chemical nature of foreign objects, preventing potential interference from organic substances such as sugar and fat from FFPs that may cover the surface of the object. Afterwards, the chemical composition of extracted foreign objects was analysed with the μFT-IR (Spotlight 200i equipped with a Spectrum Two microscope by Perkin Elmer). Eventually, the extracted foreign objects were then classified as packaging remnants made of aluminium, cellulose, or plastic materials (Mazzoleni et al. 2023a).

Microscopy and image analysis

In total, over 17 FFP samples, there were 441 packaging remnants detected, of which 44 were aluminium, 308 were cellulose, and 89 were plastics. Each remnant was observed using a stereomicroscope (OLYMPUS SZX9) at a range of magnifications from 6.3x to 20x depending on their sizes. Then, by using a digital camera (CoolSNAP-Pro colour camera) and image analysis software (Image-Pro Plus 7.0; Media Cybernetics Inc., Rockville, MD, USA), a total of 441 images, one from each remnant, were acquired according to Pinotti et al. (2016). After acquisition, according to Pinotti (2009) a monochrome mask was applied on each image corresponding to a packaging remnant (Figure 1). Subsequently, measurements and calculations including 30 geometric variables were conducted on each image. According to Pinotti et al. (2016), the 30 geometric variables can be classified into two groups, being 21 size attributes and 9 derived shape attributes. The size attributes, also named as dimension (primary) attributes, indicate direct measurements on the packaging remnants. The derived shape attributes are obtained after combining various size attributes into calculations. Hereby, the dimension units are eliminated in derived shape attributes which are all dimensionless ratios (Neal and Russ 2012). Table 1 lists the size and shape attributes and their corresponding definitions and units, if applicable.

Statistical analysis

The results were analysed using R software (v 4.3.0). Shapiro-Wilk method was performed to test normality of the data before statistical analysis. Due to non-normal distribution of the data, a non-parametric Kruskal-Wallis test was applied to compare the median values of each size and shape attributes of remnants from the three packaging materials (aluminium, cellulose, and plastic). For pairwise comparisons, the pairwise Wilcoxon test with Benjamini-Hochberg method to control the false discovery rate was performed. Statistical mean, median, maximum, and minimum were calculated with the "by ()" function. Differences with p values $< .05$ were considered significant. Data of each size and shape attribute of packaging remnants from the three materials are presented as mean, median, maximum, and minimum.

Results

In general, it can be stated that in the present sample sets, cellulose > plastic > aluminium remnants for the

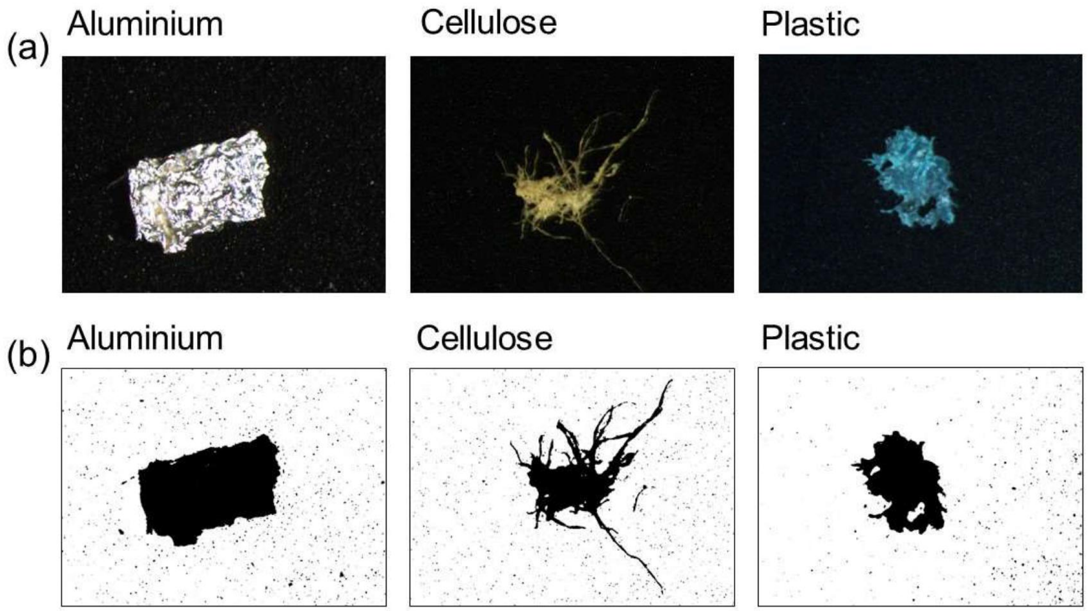

Figure 1. (a) Examples of packaging remnants (aluminium, cellulose, and plastic) detected in former food products under a stereomicroscope. (b) Images of packaging remnants found in former food products after the application of a monochrome mask.

Table 1. Size and shape attributes and their corresponding definitions and units.

Geometric variables	Definition	Unit[1]
Size attribute		
Area	Area of the object including area of the holes if "Fill Holes" option is turned on.	μm^2
Axis major	Length of major axis of ellipse.	μm
Axis minor	Length of minor axis of ellipse.	μm
Diameter max	Length of the longest line joining two points of the object's outline and passing through the centroid.	μm
Diameter min	Length of the shortest line joining two points of the object's outline and passing through the centroid.	μm
Diameter mean	Average length of diameters measured at 2◦ intervals and passing through the object's centroid.	μm
Radius max	Maximum distance between object's centroid and outline.	μm
Radius min	Minimum distance between object's centroid and outline.	μm
Perimeter	Length of the object's outline (more accurate than Perimeter 2).	μm
Perimeter 2	Chain code length of the outline including any outlines of holes. Faster to measure but less accurate than Perimeter.	μm
Perimeter (convex)	Perimeter of the convex outline of the object.	μm
Perimeter (ellipse)	Perimeter of the equivalent ellipse of the object.	μm
Size (length)	Feret diameter (e.g. calliper length) along major axis of the object.	μm
Size (width)	Feret diameter (e.g. calliper length) along minor axis of the object.	μm
Polygon area	Area included in the polygon defining the object's outline. The same polygon as that used for Perimeter.	μm^2
Box height	Height of the object's bounding box.	μm
Box width	Width of the object's bounding box.	μm
Feret max	The longest calliper (feret) length.	μm
Feret min	The smallest calliper (feret) length.	μm
Feret mean	Average calliper (feret) length.	μm
Convex area	Area of a polygon which has major and minor axes for sides.	μm^2
Shape attribute		
Aspect	Ratio between major axis and minor axis of the ellipse equivalent to the object.	–
Area/Box	Ratio between area of the object and area of its bounding box.	–
Box X/Y	Ratio between width and height of the object's bounding box.	–
Radius ratio	Ratio between maximum radius and minimum radius.	–
Roundness	$(Perimeter^2)/(4\pi Area)$. The software uses Perimeter 2 and Area by default. Select Perimeter and Area for deriving more accurate Roundness.	–
Roundness 2	$4Area/\pi Axis\ major^2$	–
Form factor	$4\pi Area/Perimeter^2$	–
Perimeter ratio	Ratio of convex perimeter to perimeter.	–
Solidity	Area/Convex area	–

[1]Since shape attributes are derived after combining various size attributes into calculations, the dimension units are then cancelled. Namely, the derived shape attributes are all dimensionless ratios.

overall mean size, whereas when Roundness (shape) was considered, a different pattern, i.e. aluminium remnants are rounder than plastic and then cellulose remnants, was observed. However, both size and shape distribution of values overlapped between the three materials, even though aluminium showed a narrower range. As an example, Figure 2 shows the distribution of the size attribute, Area. In Tables 2 and 3, the results of FFP packaging remnants' size and shape attributes are presented. Only one size attribute (Radius min) did not show any significant differences ($p > .05$) among the three packaging materials. When comparing the median values in Axis minor and Diameter min of aluminium and cellulose remnants, there was no observable difference ($p > .05$). However, different median values in these two size attributes did exist between aluminium and plastic as well as between cellulose and plastic remnants ($p < .001$ for Axis minor and $p < .01$ for Diameter min). The rest of the size attributes all displayed different ($p < .05$) median values when pairwise comparisons between the three materials were considered. In particular, the median values in each size attribute of plastic remnants were the largest, those of cellulose remnants were in the middle, and those of aluminium remnants were the smallest. However, the minimum and maximum values in these size attributes did not follow this pattern of ranking. The maximum values of plastic remnants were not always the largest. Likewise, the minimum values of aluminium remnants were not always the smallest. That is, cellulose remnants can have minimum values smaller than aluminium and/but bigger maximum values than plastic remnants.

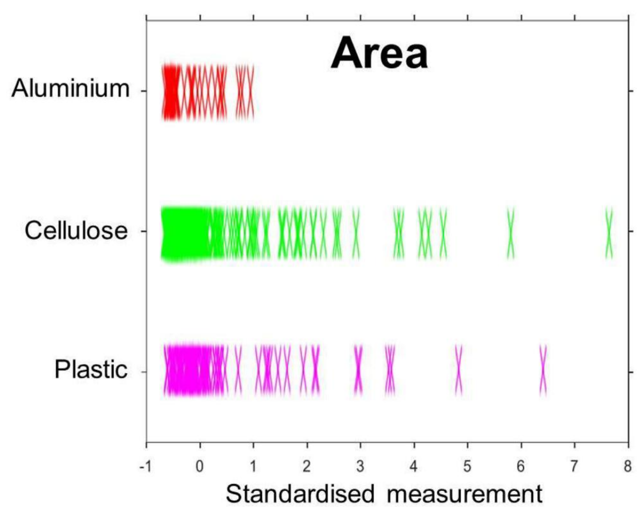

Figure 2. Plots of size attribute, area, measured in aluminium, cellulose, and plastic packaging remnants found in former food products. The values were standardised before plotting so that the mean and standard deviation over all particles are 0 and 1, respectively.

Regarding shape attributes, only one, Box X/Y, did not show any significant differences ($p > .05$) among the three packaging materials. When comparing cellulose and plastic remnants, their median values in Aspect, Area/Box, Box X/Y, Radius ratio, and Roundness 2 attributes were similar ($p > .05$). The rest of the shape attributes all showed significantly different ($p < .05$) median values when pairwise comparisons between the three materials were considered, except that the median values in Perimeter ratio of aluminium remnants tended ($p \leq .10$) to be larger than those of plastics.

Discussion

Although most of the median values in size and shape attributes of aluminium, cellulose, and plastic remnants significantly differed from each other, these attributes were of limited use for separating remnants in FFPs by the three packaging materials. For example, the distribution of Area (Figure 2) within each type of packaging material demonstrates a strong positive skew. There are overlapping distributions among the three materials, but the aluminium remnants show a narrower range than cellulose and plastic remnants. In addition, the other 20 size attributes exhibited similar behaviours mentioned above. Therefore, it was suggested that the values in the 21 size attributes obtained from FFP packaging remnants were strongly inter-correlated and that aluminium remnants possessed higher consistency in terms of size and shape compared to the other two materials.

Regarding shape attributes, aluminium remnants had the highest median value of 0.56 in Roundness 2, which means they were closer to a "circle like" shape as a value of 1.00 indicates an ideal circle. The smaller the values in Roundness 2, the greater the measured object departs from a circular shape (Neal and Russ 2012). Additionally, aluminium remnants had the highest median value of 0.49 in Form factor. Form factor is derived by calculating measurements of Area and Perimeter. To elucidate, assuming objects that have the same values of Area, when the apparent irregularity of boundary, depth of indentations, and the length of perimeter increases, Form factor of such object decreases. Namely, the higher the value is in Form factor, the more regular-shaped an object is characterised. On the other hand, the smaller the value obtained in Form factor, the more likely the object seems to be star-shaped (Pinotti et al. 2016). In this context, cellulose and plastic remnants had less circular and less regular shape than aluminium ones.

Table 2. Measurements of size attributes of aluminium, cellulose, and plastic packaging remnants found in former food products.

	Packaging material[b]							Pairwise comparison[d]		
	Aluminium		Cellulose		Plastic					
Size attributes[a] (μm)	Mean	Median (min–max)	Mean	Median (min–max)	Mean	Median (min–max)	*p*-values[c]	Aluminium vs. Cellulose	Aluminium vs. Plastic	Cellulose vs. Plastic
Area (μm^2)	2.32	1.20 (0.21–9.69)	3.83	1.96 (0.001–49.72)	5.77	3.31 (0.22–42.30)	<.001	<.01	<.001	<.001
Axis major	2.19	1.73 (0.58–6.54)	3.11	2.54 (0.06–13.64)	3.86	3.31 (0.80–15.57)	<.001	<.001	<.001	<.001
Axis minor	1.12	0.89 (0.46–2.46)	1.36	1.13 (0.03–6.25)	1.74	1.50 (0.35–5.43)	<.001	.12	<.001	<.001
Diameter max	2.25	1.74 (0.61–6.74)	3.34	2.86 (0.06–15.00)	4.22	3.56 (0.84–15.46)	<.001	<.001	<.001	<.001
Diameter min	0.94	0.77 (0.29–2.23)	1.09	0.88 (0.03–5.22)	1.37	1.17 (0.17–4.62)	<.01	.33	<.01	<.01
Diameter mean	1.43	1.12 (0.51–3.17)	1.78	1.51 (0.04–7.27)	2.28	1.90 (0.5–17.02)	<.001	<.01	<.001	<.001
Radius max	1.22	0.98 (0.33–4.18)	1.89	1.64 (0.03–7.86)	2.47	2.17 (0.47–8.81)	<.001	<.001	<.001	<.001
Radius min	0.39	0.33 (0.04–1.03)	0.44	0.35 (0.01–2.40)	0.54	0.44 (0.02–2.11)	.10	.66	.14	.14
Perimeter	6.79	5.17 (2.05–17.71)	12.27	10.30 (0.12–51.87)	13.59	12.36 (2.99–50.01)	<.001	<.001	<.001	<.05
Perimeter 2	7.21	5.51 (2.15–18.72)	13.12	11.23 (0.12–55.62)	14.42	13.12 (3.17–52.13)	<.001	<.001	<.001	<.05
Perimeter (convex)	5.79	4.49 (1.80–16.74)	8.58	7.70 (0.12–35.30)	10.89	9.73 (2.21–35.79)	<.001	<.001	<.001	<.001
Perimeter (ellipse)	5.36	4.22 (1.67–14.40)	7.38	6.22 (0.15–30.93)	9.17	8.05 (1.94–32.63)	<.001	<.001	<.001	<.001
Size (length)	2.29	1.81 (0.64–7.58)	3.40	2.90 (0.05–14.99)	4.37	3.79 (0.85–15.71)	<.001	<.001	<.001	<.001
Size (width)	1.29	0.99 (0.50–2.72)	1.70	1.42 (0.02–7.40)	2.22	1.95 (0.51–6.82)	<.001	<.05	<.001	<.001
Polygon area (μm^2)	2.30	1.19 (0.21–9.63)	3.79	1.93 (0.0006–49.51)	5.72	3.26 (0.21–42.15)	<.001	<.01	<.001	<.001
Box height	1.83	1.59 (0.61–4.58)	2.46	2.12 (0.06–8.79)	3.24	2.81 (0.63–9.83)	<.001	<.01	<.001	<.001
Box width	1.88	1.32 (0.55–6.81)	2.87	2.29 (0.02–14.37)	3.57	3.01 (0.74–13.35)	<.001	<.001	<.001	<.001
Feret max	2.31	1.82 (0.63–7.66)	3.46	2.96 (0.05–15.08)	4.44	3.81 (0.85–15.73)	<.001	<.001	<.001	<.001
Feret min	1.26	0.98 (0.50–2.71)	1.63	1.38 (0.02–6.57)	2.13	1.85 (0.48–6.40)	<.001	<.05	<.001	<.001
Feret mean	1.84	1.43 (0.57–5.33)	2.68	2.38 (0.04–11.24)	3.43	3.03 (0.70–11.40)	<.001	<.001	<.001	<.001
Convex area (μm^2)	3.09	1.57 (0.28–13.24)	5.28	2.92 (0.002–68.80)	8.36	4.99 (0.32–55.73)	<.001	<.01	<.001	<.001

[a]The unit of size attributes is μm unless otherwise indicated.
[b]Data are presented as mean and as median (minimum-maximum) due to non-normal distribution of the data.
[c]Non-parametric Kruskal-Wallis test was applied to compare the median values of each size attribute of remnants from the three packaging materials (aluminium, cellulose, and plastic).
[d]Pairwise Wilcoxon test with Benjamini-Hochberg adjustment method was applied to control the false discovery rate for pairwise comparisons between each pair of packaging materials.

Table 3. Measurements in shape attributes of aluminium, cellulose, and plastic packaging remnants found in former food products.

	Packaging material[a]							Pairwise comparison[c]		
	Aluminium		Cellulose		Plastic					
Shape attributes	Mean	Median (min–max)	Mean	Median (min–max)	Mean	Median (min–max)	p-values[b]	Aluminium vs. Cellulose	Aluminium vs. Plastic	Cellulose vs. Plastic
Aspect	1.96	1.72 (1.11–3.89)	2.91	2.11 (1.06–15.02)	2.33	2.20 (1.09–5.14)	<.05	<.05	<.05	.98
Area/Box	0.56	0.56 (0.38–0.75)	0.45	0.47 (0.08–0.95)	0.44	0.44 (0.05–0.79)	<.001	<.001	<.001	.36
Box X/Y	1.05	1.00 (0.42–2.02)	1.31	1.06 (0.12–8.40)	1.24	1.10 (0.32–3.33)	.41	.42	.42	.62
Radius ratio	4.27	2.84 (1.48–32.54)	8.22	4.27 (1.45–107.40)	9.81	4.36 (1.77–89.79)	<.001	<.001	<.001	.33
Roundness	2.22	1.85 (1.36–9.11)	5.41	3.80 (1.31–35.83)	4.47	3.24 (1.36–25.70)	<.001	<.001	<.001	<.05
Roundness 2	0.54	0.56 (0.25–0.87)	0.44	0.42 (0.06–0.90)	0.42	0.42 (0.09–0.78)	<.01	<.01	<.01	.54
Form factor	0.46	0.49 (0.10–0.68)	0.27	0.24 (0.03–1.06)	0.31	0.28 (0.04–0.65)	<.001	<.001	<.001	<.05
Perimeter ratio	0.86	0.88 (0.50–0.97)	0.74	0.75 (0.39–1.00)	0.80	0.83 (0.51–0.99)	<.001	<.001	.06	<.001
Solidity	0.75	0.76 (0.67–0.78)	0.71	0.74 (0.24–0.80)	0.68	0.74 (0.23–0.78)	<.001	<.001	<.001	<.01

[a]Data are presented as mean and as median (minimum–maximum) due to non-normal distribution of the data.
[b]Non-parametric Kruskal-Wallis test was applied to compare the median values of each shape attribute of remnants from the three packaging materials (aluminium, cellulose, and plastic).
[c]Pairwise Wilcoxon test with Benjamini-Hochberg adjustment method was applied to control the false discovery rate for pairwise comparisons between each pair of packaging materials.

These findings could be associated with: (i) the pre-treatment methods adopted during the processing of FFPs; (ii) the intrinsic features of the three packaging materials; (iii) the types of initial former food material used; (iv) the considerable variability in size and shape attributes of extracted packaging remnants in the current study. Common pre-treatment methods operated to remove FFP packaging materials include mechanical unpacking, grinding, and squeezing (Luciano et al. 2022; Van Raamsdonk et al. 2023). Subsequently, sieving, air blowing, magnet field, and/or eddy current are applied to separate the remaining packaging materials and former food. Then, treated FFPs may be further ground to increase the homogeneity of the final product (Van Raamsdonk et al. 2023). This step of extra-fine grinding can lead to higher fragmentation of packaging remnants that affects their quantity, size, and shape in the sample (Mazzoleni et al. 2023a). Our results agreed with this statement as small remnants were more abundant than larger ones (Figure 2). Considering the highly malleable and formable property of aluminium, it can be easily converted to sheets with varying thickness from 4 to 150 microns and rolled or folded (Deshwal and Panjagari 2020; Sarkar and Aparna 2020). At the same time, the ductility and friability of aluminium allow aluminium foil to be easily crumpled, torn, or punctured (Kerry 2012). Therefore, it is not surprising that after intensive mechanical processing, aluminium remnants could be further folded and become more compact, which contributes to their smaller sizes and greater regularity in shapes.

In this work, cellulose remnants included paper, paperboard, and natural fibres such as cotton (Chandramohan and Marimuthu 2011; Mazzoleni et al. 2023a). Most of the papers used for food packaging are crafted from cellulose fibre derived from wood (Sarkar and Aparna 2020), whose main feature is the presence of long, straight, and parallel fibres, designating its fibre-forming property (Deshwal et al. 2019). As a consequence, after undergoing the mechanical packaging removing protocols run in the FFP processing plant, cellulose can be ripped and ragged. This could explain why cellulose remnants had the lowest median value in Form factor. Their irregular boundaries, deep indentations, and elongated perimeter may result from the torn fibres.

Above these aspects, another source of variability comes from the types of starting food material used. The production of energy-dense foods, especially snacks and sweet beverage, in a multi-pack with single-serving packages has become popular and has been increased (Steenhuis et al. 2010). This trend of introducing smaller packages can stem from the promotion of self-control and energy intake regulation (Steenhuis et al. 2010) as well as increased prevalence of snacking behaviour (Almoraie et al. 2021). Smaller portions of food in a multi-pack require smaller but more packages, eventually leading to increased wasted space on a pallet during product shipment. Therefore, the balance between single-serving and bulk packaging and the packaging materials used can vary based on the types of initial food processed in the former food plant (Mazzoleni et al. 2023a). For example, the target foods made into multi-pack with single-serving packages are predominantly snacks packed with plastic and aluminium instead of pasta packed with cardboard and plastic. Hence, the prevalence and types of packaging remnants found in FFPs are different, which can subsequently affect the size and shape of packaging remnants according to various machinery and packaging removal and separation methods in use by the FFP processors.

For the large variability in size and shape attributes of packaging remnants found in FFPs, several possible explanations can be speculated. Since FFP samples were collected from different FFP processors in various countries, the types of FFPs and unpacking methods practiced in the processing plant were not the same. Depending on the original product type of FFPs, different packaging materials are chosen to ensure optimsed preserving conditions for specific products during handling, transportation, and storage (Ibrahim et al. 2022). For instance, aluminium foil is often used to wrap chocolate and sweets that contain volatile compounds contributing to flavours (Kerry 2012). Paperboard is usually used as secondary packaging for pasta, biscuits, and breakfast cereals (Sarkar and Aparna 2020; Mazzoleni et al. 2023a). Plastics are used as wrapper or laminate for oily foods like cookies and candy bars as well as for foods like bread that needs to avoid moisture (Sarkar and Aparna 2020). Different countries may have different types of FFPs recycled and different packaging materials in use due to seasonality and consumer preferences (Otto et al. 2021; Mazzoleni et al. 2023a). Besides, the pre-treatment to grind and squeeze FFPs, the method to separate treated packaging materials and FFPs, and the efficiency of the facilities in FFP processing plants are not standardised. Taking everything into consideration, it is not surprising that a great variability in size and shape attributes was observed in the FFP samples analysed.

A particle's primary properties such as size and shape attributes can be used to predict its secondary properties such as settling velocity, flowability, compaction, etc (Ulusoy 2023). Hence, it is relevant to characterise these properties of packaging remnants for process control and quality management of feed derived from FFPs. Common pre-treatments to unpack FFPs include milling and grinding. Although the packaging material and FFPs inside the package are also factors that should be considered, the type of equipment and mechanism of particle breakdown can have major effects on the size and shape of the particle generated (Ulusoy 2023). For example, massive fracture usually creates non-spherical particles with sharp edges, whereas attrition chips the edges or abrades the surface, leading to relatively rounder particles. Again, the procedure and machinery adopted to produce feed from FFPs are not standardised and can vary a lot depending on different FFP processors.

Taken together, general recommendations to minimise packaging remnants in FFPs could be pre-sorting the starting former foods with similar packaging materials. In this way, the size and shape of the milled packaging and former food may be more consistent, which helps the FFP processors design the following separation of packaging and former food. For instance, flatter and smaller particles can be separated more easily by using mechanical and electrical forces in a plate-type separator (Ulusoy 2023) even though their density also plays a role. In addition, a particle's shape affects its motion such as rolling and sliding and electrical conductivity. For instance, flat particles are less likely to roll; decreased Aspect ratio of aluminium flake particles results in increased electrical conductivity (Pinto and Jiménez-Martín 2001); and irregular particles affect the efficiency of gravity separation (Ulusoy and Atagun 2023). Afterwards, a second post-treating packaging remnant inspection could be employed after the final product has been stored for a while as larger packaging remnants may tend to rise to the top due to Brazil-nut effect, namely granular convection (Gajjar et al. 2021). Thus, it can be suggested that the particle size, shape, and nature of packaging remnants may affect remnant segregation and distribution in different feed fractions (Van Raamsdonk et al. 2012), potentially impacting the efficacy, precision, and specificity of sampling and detection methods. Lastly and importantly, FFPs are feed ingredients, instead of a complete diet, to be integrated with other feedstuffs in livestock diets. For example, as suggested by recent studies (Mazzoleni et al. 2023b; Pinotti et al. 2023b; Tretola et al. 2024), the inclusion level of FFPs in pig's diet is usually up to 30%. Therefore, there is also dilution effects on packaging remnants that can be detected in the final diet, moderating the associated risk of using FFPs in animal nutrition.

Conclusions

The present study aimed at providing information about size and shape attributes of aluminium, cellulose, or plastic packaging remnants detected in FFPs. Such information is important for improving packaging removal techniques in FFP processing industry as well as quality monitoring and inspection in the final feed products. With this, the safety aspect of FFPs intended as feed ingredients can be further strengthened. Combining the results of size and shape attributes obtained by microscopy and image analysis, it can be concluded that aluminium remnants were generally smaller in size as well as rounder and more regular in shape compared to cellulose and plastic remnants. Furthermore, the obtained values of aluminium remnants seemed to be more consistent owing to its pliable and dead-fold characteristics. However, there was not enough separation in either size or shape attributes to give a concrete sort of classification rules in remnants made from these three materials. Hence, further studies are required to better understand the chemical and physical properties of packaging remnants in FFPs and their association to the processing methods running in the feed plants. Accordingly, while reusing FFPs in livestock nutrition to boost circular economy, feed safety and quality can be guaranteed.

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ORCID

Peng Lin http://orcid.org/0000-0001-5351-2817
Tom Fearn http://orcid.org/0000-0003-2222-6601
Sharon Mazzoleni http://orcid.org/0000-0002-8141-3442
Matteo Ottoboni http://orcid.org/0000-0003-0123-3888
Alice Luciano http://orcid.org/0000-0003-0600-9498
Andrea Moradei http://orcid.org/0009-0000-5139-1986
Marco Tretola http://orcid.org/0000-0003-3317-4384
Luciano Pinotti http://orcid.org/0000-0003-0337-9426

Data availability statement

Data used for this study are available from corresponding author upon reasonable request.

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