Waste Management 189 (2024) 196–210

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Research Paper

Assessing the resource potential of paper and board in lightweight packaging waste sorting plants through manual analysis and sensor-based material flow monitoring

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A R T I C L E I N F O

Keywords:
Sampling
Waste analyses
Near-infrared spectroscopy
Sensor-based material flow characterization
Plastic waste
Processing plant

A B S T R A C T

The recycling of paper and board (PB) yields economic and environmental advantages compared to primary paper production. However, PB from lightweight packaging (LWP) waste is currently not comprehensively reintegrated into the paper value stream. To develop an adapted recycling process for PB from LWP, PB quantities, qualities, and fluctuations ranges in LWP are required. Currently, no sufficient database is available. Therefore, we developed a methodical approach and conducted a case study to access the PB potential in LWP sorting plants using manual analysis and sensor-based material flow monitoring. Differences resulting from seasonal variations, materials from different settlement structures, and fluctuation ranges in LWP composition over two weeks have been investigated. PB contents in the input of 6.5 wt% (ww) and 5.9 wt% (ww) were determined for winter and summer sampling campaigns, respectively. The PB product stream amounted to 5.7 wt% (ww, winter) and 4.8 wt% (ww, summer). Around 45 wt% (ww) of PB from the PB product stream was classified as misplaced by the consumer and should have been discarded in separate paper collections. Based on the determined PB quantities and qualities, a potential of usable and in the PB product stream available PB in LWP was determined. The technically available and usable PB potential in German LWP waste amounts to 89,000 to 100,000 tons per year (average PB yield of around 65 wt% (ww)). The methodical approach can be adapted for sorting plant balances. The results can contribute to developing an adapted recycling process for PB from LWP.

1. Introduction

Paper and board recycling presents a compelling solution for paper production, providing both economic and environmental advantages. Recycled graphic paper, for instance, can yield energy and water savings of up to 68 % and 78 %, respectively, compared with primary paper production (Wellenreuther et al., 2022). Also, the recycling of other paper grades leads to environmental advantages compared to the use of primary fibers (Turner et al., 2015). In Germany, the paper and board (PB) consumption for 2021 was estimated at 18.98 million tons indicating the same amount as a resource potential for recovered paper usage (DIE PAPIERINDUSTRIE, 2022). However, in 2021 the separately collected PB for recycling amounted to only 14.47 million tons (corresponding to a recovered paper return rate of 76.2 wt%), resulting in more than 20 wt% of PB not being reintegrated into the paper value stream (DIE PAPIERINDUSTRIE, 2022). Fig. 1 shows the PB streams in Germany for 2021, including the amount of PB that is not collected separately. A part of this discarded PB ends up in mixed-waste collections, such as lightweight packaging (LWP) waste.

Abbreviations: dm, dry matter; LWP, lightweight packaging; PB, paper and board; PE, polyethylene; PET, polyethylene terephthalate; PP, polypropylene; PS, polystyrene; RQ, research question; SBS, sensor-based sorting; SBMM, sensor-based material flow monitoring; TM, target material; UK, United Kingdom; ww, wet weight.

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https://doi.org/10.1016/j.wasman.2024.07.034
Received 9 November 2023; Received in revised form 19 July 2024; Accepted 30 July 2024
Available online 2 September 2024
0956-053X/

1.1. State-of-the-art and research gap

According to Directive 94/62/EC, European member states are required to provide return, collection, and recovery systems for used packaging and/or packaging waste including LWP (European Parliament and the Council of the European Union, 1994). However, transposition into national law varies greatly depending on the country (Pires et al., 2011; European Commission, 2001). Often, separate PB collection systems are established (Pires et al., 2011; Xevgenos et al., 2015), but there are also so-called comingled systems in which PB is collected together with other materials, e.g. in the UK (Confederation of Paper Industries, 2023) or France (Expatica, 2024). However, PB can also be found in LWP of countries with separate paper collection due to misplaced PB, PB composites, or PB with substances listed as prohibited substances for separate paper collection (e.g. food) according to DIN EN 643. In Germany, LWP sorting plants are frequently sorting PB in a separate output stream (Dehoust et al., 2021; Feil et al., 2021; Grummt and Fabian, 2023).

In 2021, the material stream report for PB from LWP in Germany amounted to 109,300 tons (Grummt and Fabian, 2023). According to a report by the German environmental agency, the application of PB separation within LWP sorting plants in Germany was 95.7 % in 2021 (based on a survey of German LWP sorting plants which processed an amount of 2.872 million tons of LWP in 2021, response rate to the survey 100 %) (Grummt and Fabian, 2023). In 2022, the Delkeskamp paper mill, which previously recycled around 40 wt% of German PB from LWP (Grummt and Fabian, 2023), ceased operations (EUWID Verpackungen, 2023). It is unclear how much of this PB quantity is currently material recycled (Grummt and Fabian, 2023).

Due to the lower quality of mixed collected PB compared to separately collected PB (Faul, 2005; Grummt and Fabian, 2023; Kinsella, 2006; Miranda et al., 2013; Miranda et al., 2011) and regulatory requirements (Bundesinstitut für Risikobewertung, 2021; DIN EN 643:2014), the material recycling potential for PB from LWP and especially for PB composites (Stiftung Zentrale Stelle Verpackungsregister, 2023), is limited. In addition, the consumer protection risks expressed both in the XXXVI. Recommendation and DIN EN 643 prevent comprehensive reuse of PB from LWP including usage in the food sector (Bundesinstitut für Risikobewertung, 2021; DIN EN 643:2014). However, higher contamination and impurity rates can be countered by suitable recycling technologies (Bundesinstitut für Risikobewertung, 2021).

1.2. Research questions and objective

To adapt a suitable recycling process for PB from LWP, the available PB quantities and qualities in LWP must be determined first. Hitherto, only a few studies have determined PB quantities in LWP. Mastellone et al. (2017) sampled the input of a LWP sorting plant in southern Italy. They found 4 wt% PB in the input (Mastellone et al., 2017). A Spanish study determined the material composition of LWP which was discarded at drop-off points for different seasons and city zones (Gallardo et al., 2018). Paper contents between 2.4 wt% and 3.4 wt% and cardboard contents between 1.2 wt% and 2.8 wt% were found (Gallardo et al., 2018). Feil et al. (2016) investigated a LWP sorting plant with input material from the Netherlands. A mass share of 8 wt% was reported for the sorted PB output stream (Feil et al., 2016). Two other publications state that the PB quantity in the LWP input in Germany amounts to 8 wt % (Cimpan et al., 2016) and 5.3 wt% (Christiani, 2017) (including paper composites, excluding beverage cartons), although no method of data collection and PB quantities are specified in either case. Furthermore, the PB contained in the input cannot be regarded as a total available material potential as there is a limited sorting efficiency (Cimpan et al., 2016; Feil et al., 2016; Küppers et al., 2022; Picuno et al., 2021) and the efficiency of sorting defines the technically available material potential. To determine the LWP sorting efficiency for PB and thus link the theoretically available PB quantities in the input to the technically available PB quantities in the product stream, a mass balance for an LWP sorting plant must be conducted. [research question (RQ) 1].

When conducting a quantity estimation, fluctuation ranges should be considered due to the generally known heterogeneity of waste streams. Sensor-based material flow monitoring (SBMM) can be used for high-resolution, long-term data series that usually economically cannot be represented by manual analysis (Kroell et al., 2024; Kroell et al., 2022). Measurements over two weeks enable the classification of fluctuations e.g. caused by LWP from different collection and fee systems as well as general fluctuations occurring within the material. Other fluctuations that are often mentioned as relevant parameters in the waste analysis, and therefore were investigated in this study, are seasonal fluctuations and fluctuations caused by different settlement structures (Dahlén and Lagerkvist, 2008; European Commission, 2004; Landesamt für Umwelt, Landwirtschaft und Geologie des Freistaats Sachsen, 2014; SAEFL, 2004). [RQ2]

When combining manual analysis and SBMM, the question arises whether a comparison of data is possible. It was already shown, that

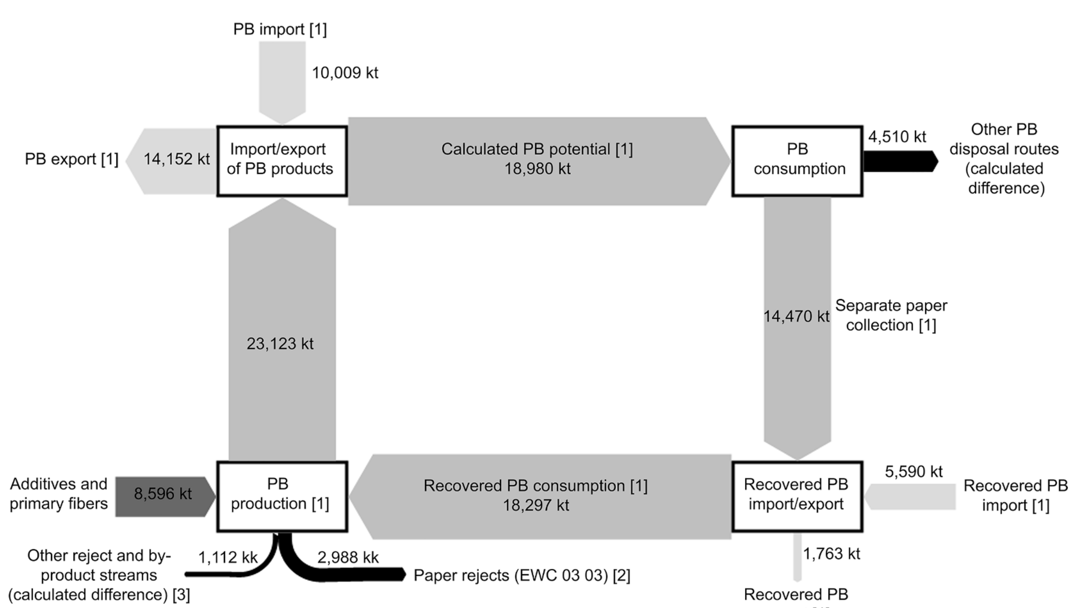

Fig. 1. PB material streams in Germany 2021 based on [1]: (DIE PAPIERINDUSTRIE, 2022) [2]: (Statistisches Bundesamt, 2021), [3]: (Weßel et al., 2021).

sensor-based quality control by near-infrared sensors can lead to reliable results within product streams (Kroell et al., 2024). However, major fluctuations are to be expected for impurities and individual material fractions, particularly in residual streams. In addition, during material sampling, only a part of the basic population is analyzed. Therefore, a comparison of manual analysis according to a defined sampling procedure and SBMM was conducted. [RQ3]

In addition to the available PB quantities in LWP, the available PB qualities are essential to develop an adapted recycling process for PB from LWP. Unlike recovered paper that is graded according to DIN EN 643, PB from LWP is not covered by specific quality parameters (DIN EN 643:2014). Moreover, in PB from mixed-waste collections higher reject contents can be expected due to higher contents of PB composites, plastics, wet-strength paper, and impurities compared to PB from separate paper collections (Faul, 2005; Grummt and Fabian, 2023; Kinsella, 2006; Miranda et al., 2013; Miranda et al., 2011). Sacia and Simmons (2006) showed that the use of 42 wt% PB from UK commingled systems leads to an increase in the amount of pulper rejects by a factor of 8 (Sacia and Simmons, 2006). As LWP and commingled collection systems are both mixed-waste collections, a similar problem can be expected for PB from LWP. Accordingly, precise knowledge of the technically available PB qualities from LWP composition, namely the PB product stream, is necessary to adjust an adapted recycling process. [RQ4] Based on the collected data including PB quantities and qualities in LWP, the total amount of technically available, well usable PB from LWP in Germany can be estimated. [RQ5]

In conclusion, assessing the resource potential of PB from LWP and developing an adapted recycling process requires data on PB quantities, qualities, and fluctuation ranges. The potential includes the PB quantity in the input and product stream as well as the technically available quantity of well usable PB. This research aims to access the PB potential in LWP using conventional sampling and manual analysis as well as sensor-based material flow monitoring (SBMM). The following RQs can be derived:

RQ1 How can a **mass balance** be conducted within a **LWP sorting plant** based on manual analysis and what are the resulting paper contents?
RQ2 How do **PB quantities** and **LWP compositions fluctuate** seasonally, over two weeks, and according to material from different settlement structures in a LWP sorting plant?
RQ3 To what extent do data from **material sampling** and **sensor-based material flow monitoring** correlate?
RQ4 What is the **PB product stream composition** in a LWP sorting plant?
RQ5 What is the estimated technically available and usable **PB potential in German LWP waste**?

Manual analysis was mainly used to determine the PB quantities and qualities in LWP. Data from SBMM was used for long-term measurements to show fluctuation ranges in material compositions. The results can contribute to the development of an adapted recycling process for PB from LWP.

2. Material and methods

To characterize PB from LWP, the location for the analysis must be specified. LWP can be analyzed directly from households. The sampling of waste containers has frequently been described in the literature (European Commission, 2004; Landesamt für Umwelt, Landwirtschaft und Geologie des Freistaats Sachsen, 2014; Zwisele, 1998). However, the advantages of sampling LWP sorting plants are the homogenization of the sampled material, the good accessibility of the base population by sampling out of a running stream, and the lower logistical effort (Zwisele, 2005). Moreover, SBMM can be integrated more easily when sampling a sorting plant. Therefore, a LWP sorting plant was chosen as a suitable analysis location.

The methodological approach for this study is illustrated in Fig. 2. The sampling campaigns are described in section 2.1 (cf. Fig. 2a), the SBMM in section 2.2 (cf. Fig. 2a and b), and the manual analysis in section 2.3 (cf. Fig. 2c). Unless otherwise stated, all presented results refer to the wet weights.

2.1. Sampling campaigns

During the study, two sampling campaigns were conducted. The selected LWP sorting plant is located in Erftstadt (Germany). The plant was commissioned in 2019 and has an annual LWP throughput of 120,000 tons (REMONDIS SE & Co. KG, 2023). A schematic flow chart of the sorting plant, including all output streams, and the methodical structure of the sampling campaigns, is given in Fig. 2a.

Samples were collected by hand from different input and output streams of the LWP sorting plant during the 17th and 18th of January 2022 (from here on referred to as "winter") and the 22nd to the 24th of June 2022 (from here on referred to as "summer"). Seasonal variations were thus represented. Since the input of LWP sorting plants has a high degree of heterogeneity, all output streams of the LWP sorting plant were sampled. This sampling procedure ensures the greatest possible mixing and homogeneity of individual material fractions (Feil et al., 2016).

2.1.1. Total number of samples

For the sampling campaigns, a necessary number of samples must be determined for a given degree of heterogeneity (European Commission, 2004; Feil et al., 2016; Länderarbeitsgemeinschaft Abfall, 2001; Landesamt für Umwelt, Landwirtschaft und Geologie des Freistaats Sachsen, 2014). According to Equation (1), the number of samples can be calculated based on the Student factor $t_{1\text{-}\alpha}$, the mass-related (m) coefficient of variation $CV(x_{m,i})$, and the relative maximum random deviation ϵ (European Commission, 2004; Landesamt für Umwelt, Landwirtschaft und Geologie des Freistaats Sachsen, 2014). For ϵ, 10 % can be assumed if the municipal solid waste stream is generated regularly (Landesamt für Umwelt, Landwirtschaft und Geologie des Freistaats Sachsen, 2014), which is given for LWP waste. The Student factor of a two-sided t-distribution $t_{1\text{-}\alpha}$ results in 1.96 for a number of degrees of freedom $f \to \infty$ and an error probability of 5 % (Hedderich and Sachs, 2018; Landesamt für Umwelt, Landwirtschaft und Geologie des Freistaats Sachsen, 2014; Mühl, 2017).

$$n > \frac{\left(t_{1-\alpha} * CV\left(x_{m,i}\right)\right)^2}{\epsilon^2}\ [-] \tag{1}$$

The coefficient of variation is calculated by the mean value $\bar{x}_m$ and the standard deviation s_m according to Equation (2). The mean value $\bar{x}_m$ is calculated according to Equation (3). The standard deviation s_m is defined as the square root of the sampling variance with $n\text{-}1$ degrees of freedom (cf. Equation (4)). (Fahrmeir et al., 2016)

$$CV\left(x_{m,i}\right) = \frac{s_m}{\bar{x}_m}\ [\text{wt\%, ww}] \tag{2}$$

$$\bar{x}_m = \frac{1}{n}\sum_{i=1}^{n} x_{m,i}\ [\text{g, ww}] \tag{3}$$

$$s_m = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_{m,i} - \bar{x}_m\right)^2}\ [\text{g, ww}] \tag{4}$$

An alternative approach to determining the number of samples can be found in the German guideline LAGA PN 98, where the number of samples is determined using the relative standard deviation regarding the material contents $s_{m,relative}$ according to Equation (5) (Länderarbeitsgemeinschaft Abfall, 2001). Further information on both Equations to determine the sample number can be found e.g. in (Spies et al., 2023).

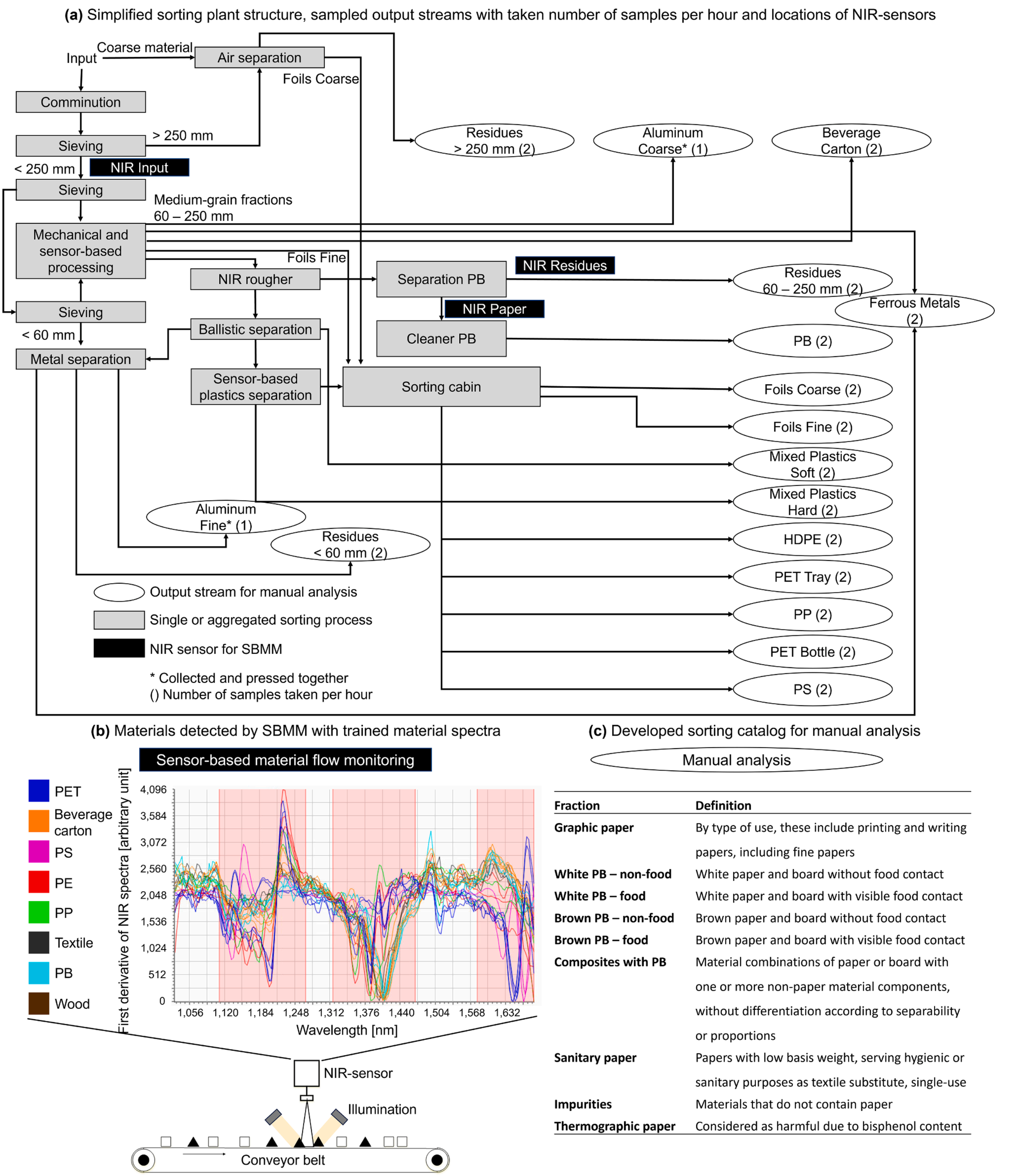

Fig. 2. Methodology to assess the PB potential in LWP by manual analysis and SBMM (the sorting catalog was developed with consideration of (DIN EN 643:2014; Naujock and Blechschmidt, 2021)).

$$n > \frac{\left(t_{1-\alpha} \bullet s_{m,\mathrm{relative}}\right)^2}{\epsilon^2} \; [-] \tag{5}$$

For the first sampling campaign, a coefficient of variation of 25 wt% (ww) was assumed based on literature values (European Commission, 2004; Zwisele, 2005, 2004). This results in a required number of 24 samples for each output stream. 25 samples were taken from the PB product stream. A slightly higher sample number was selected for the second sampling campaign, as the first sampling campaign revealed relatively high compositional variations. 30 samples were taken, resulting in a coefficient of variation of 28 wt%. From experience, a 90-liter sample volume was selected. With this volume, a sample can be taken that represents particles within the particle size ranges of an LWP sorting plant and can still be carried by one person. For the fine fraction

< 60 mm, a sample volume of 40 l was selected (Länderarbeitsgemeinschaft Abfall, 2001). The average weight per sample for the coarse output streams is provided in Supplementary material 1.

2.1.2. Number of samples per hour

The number of samples per hour was determined based on the German guideline LAGA PN 98 (Länderarbeitsgemeinschaft Abfall, 2001). Since the samples were taken out of running streams, the number of samples could not be calculated based on the volume of a waste heap as suggested in LAGA PN 98 (Länderarbeitsgemeinschaft Abfall, 2001). Therefore, the sample number per hour was determined based on the volume flow rate. According to Equation (6), the volume flow rate per output stream was calculated using the average plant mass throughput per hour $\dot{m}$, the average mass share of each output stream j regarding the input $c_{\mathrm{m,j}}$ (equivalent to the average mass recovery per output stream of the plant based on long-term values) and the bulk density of each output stream ρ_{j}. A long-term average value of 25 tons per hour was used as the mass throughput of the plant. The respective bulk densities were determined from empirical data. To obtain a sufficiently large number of samples per hour, the maximum average mass share rates based on long-term values from the sorting plant were used. With the calculated volume flow rates, the number of required samples per hour was determined following LAGA PN 98 (Länderarbeitsgemeinschaft Abfall, 2001).

$$\dot{V}_j = \frac{\dot{m}^* c_{m,j}}{\rho_j} \left[\frac{m^3}{h}, ww\right] \tag{6}$$

The sample numbers taken per hour and output stream are given in Fig. 2a. For better orientation, all material streams are written in capital letters. For the output streams, Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyethylene Terephthalate (PET) Bottle, PET Tray, Mixed Plastics Hard, Beverage Carton, Ferrous Metals, PB and Aluminum, 2 samples per hour were calculated and taken, respectively (Länderarbeitsgemeinschaft Abfall, 2001). The sorting process divides the aluminum fraction into Aluminum > 60 mm and Aluminum < 60 mm, collected in one material hopper. To achieve the necessary 2 samples per hour, a sample from each fraction was taken.

For the Residues and the Foils (sometimes also referred to as films), the volume flow rate results in 4 necessary samples per hour for each material stream. The sorting plant divides the Foils into Foils Coarse and Foils Fine, from each of which two samples were taken. For the Residues, two samples per hour were taken from the grain size ranges 60 – 250 mm and > 250 mm. In addition, 40 l per hour were taken from the Residues < 60 mm.

For the Mixed Plastics Soft 5 necessary samples per hour were calculated (Länderarbeitsgemeinschaft Abfall, 2001). The number of samples was reduced from 5 to 2 samples per hour since preliminary investigations had shown only a small PB content in this material stream. Moreover, the number of samples was set to 2 samples per hour for all output streams, which reduces the probability of systematic errors and limits the effort to a presentable and economic level. The number of samples taken per hour and output stream are shown in Fig. 2a.

The samples of the Residues < 60 mm and the Aluminum < 60 mm were taken once per hour and subjected to a visual inspection regarding the PB content. Subsequent processing of these fine fractions is often not economically affordable. Due to the small PB content and the organic contamination concentrated in these grain size classes, all samples from these two output streams were combined. For Residues < 60 mm and Aluminum < 60 mm, one 35-liter, and 20-liter mixed sample were taken for further analyses, respectively.

2.1.3. Conducted sampling campaign

The material streams PE, PP, PET Bottle, PET Tray, PS, and both Foil streams were sampled from the running conveyor belts in the sorting cabin. Sampling thus took place before the manual sorting. In the sorting cabin, a sample was taken from the belt every half hour. Samples were taken from all material streams at the same time as far as possible. The actual sampling took place within a few minutes. The samples were taken with a 90-liter container directly from the belt (cf. Supplementary material 2). Care was taken to sample the entire cross-section of the conveyor belts.

The material streams PB, Beverage Cartons, Aluminum, Residues > 250 mm, Mixed Plastics Soft and Mixed Plastics Hard were taken from the material hoppers once per hour. Sampling was conducted within the same time intervals per hour and at the same time as the sorting cabin sampling. However, due to sorting plant operation (material hoppers had to be emptied a few times to prevent the plant from stopping), an exact time interval during the sampling of the material hoppers could not always be precisely maintained. For each material stream, one sample was taken from the free-falling stream and one from the lying bulk material heap. The samples were taken with a 90-liter container at minimal six points of the bulk material heap (cf. Supplementary material 2).

The output streams Residues 60 – 250 mm and Ferrous Metals were sampled at two discharge points outside the plant (cf. Supplementary material 2). These two streams were sampled at the same time as the sampling of the material hoppers. To avoid the segregation of lighter particles, the samples were taken directly from the falling stream at the belt discharge. An overview of the sampling characteristics of all coarse output streams is given in Supplementary material 1.

2.1.4. Determination of PB and PB composite content

During the sampling campaign, for all samples except the Fine Fractions and the PB product stream, the PB and PB composite contents were determined (cf. Supplementary material 2). Detailed photos of different PB fractions from LWP are given in Supplementary material 3. PB composites were defined as all particles consisting of paper and another material compound. A categorization of PB composites in LWP is provided in Supplementary material 4. For the output stream Beverage Carton, all particles were counted as PB composites except the correctly sorted beverage cartons. Paper with thin plastic layers, also known as barrier paper, presented a challenge during the sorting procedure. Tear-off tests were conducted to identify a detachable bond. If a plastic layer was found, the particle was classified as PB composite.

2.1.5. Parameters to evaluate the sorting plant

To validate the sorting process, different process parameters can be used. The output per material stream j can be described via the mass recovery $R_{\mathrm{m,j}}$ (cf. Equation (7)) using the mass per output stream m_{j} and the mass of the input m_{Input} (Feil et al., 2016).

$$R_{\mathrm{m,j}} = \frac{m_{\mathrm{j}}}{m_{\mathrm{Input}}} \ [\mathrm{wt\%, ww}] \tag{7}$$

The mass-based contents of target materials TM (in this study PB, PB composites, or specific PB fractions) per material stream $c_{\mathrm{m,TM,j}}$ are calculated with the target material masses per sample $m_{\mathrm{TM,i,j}}$, the total mass per sample $m_{\mathrm{Sample,i,j}}$ and the number of samples n according to Equation (8).

$$c_{\mathrm{m,TM,j}} = \frac{1}{n}\sum_{i=1}^{n}\frac{m_{\mathrm{TM,i,j}}}{m_{\mathrm{Sample,i,j}}} \ [\mathrm{wt\%,\ ww}] \tag{8}$$

The product of the average target material content $c_{\mathrm{m,T_M,j}}$ and the mass recovery $R_{\mathrm{m,j}}$ per output stream results in the target material content per output stream regarding the LWP input $c_{\mathrm{m,T_M,Input,j}}$ (cf. Equation (9)). The target material content in the LWP input $c_{\mathrm{m,TM,Input}}$ is determined by the sum of the target material contents regarding the LWP input over all output streams J (in this case 16 output streams) according to Equation (10).

$$c_{\mathrm{m,TM,Input,j}} = c_{\mathrm{m,TM,j}} {}^* R_{\mathrm{m,j}} \ [\mathrm{wt\%,\ ww}] \tag{9}$$

$$c_{\mathrm{m,\,TM,Input}} = \sum_{j=1}^{J} c_{\mathrm{m,TM,Input,j}} \ [\mathrm{wt\%,\ ww}] \quad (10)$$

Using the target material content in the LWP input $c_{\mathrm{m,TM,Input}}$ and the target material content in the target material product stream regarding the input $c_{\mathrm{m,TM\text{-}Product\_stream,Input}}$, the yield $Y_{\mathrm{m,TM,Input/Product\_stream}}$ can be calculated according to Equation (11). Within the target material PB, graphic, white, brown, sanitary, and thermographic PB are counted as PB. For the fines in the PB product stream the same PB content was assumed as for the other fractions.

$$Y_{\mathrm{m,\,TM,Input/Product\_stream}} = \frac{c_{\mathrm{m,TM-Product\_stream,Input}} {}^{*} m_{\mathrm{Input}}}{c_{\mathrm{m,TM,Input}} {}^{*} m_{\mathrm{Input}}} \ [\mathrm{wt\%,\ ww}] \quad (11)$$

2.2. Sensor-based material flow monitoring

In addition to the sampling campaigns, a SBMM of the LWP plant was conducted from the 22$^{\mathrm{nd}}$ of June to the 7$^{\mathrm{th}}$ of July 2022 (parallel to the summer sampling campaign).

2.2.1. Sensor specifications

Three inline near-infrared (NIR) sensors were positioned at different points in the sorting plant (cf. Fig. 2a). The used NIR sensors were EVK HELIOS EQ32 hyperspectral imaging sensors from EVK Kerschhaggl GmbH (Raaba, Austria) with a spectral resolution of 3.1 nm/channel. The first sensor further on called *NIR Input* was mounted behind coarse screening over the material stream < 250 mm. The second sensor further on called *NIR Paper* was placed above the acceleration belt in front of the post-cleaning of the PB product stream. The third sensor further on called *NIR Residues* was installed in front of the belt discharge of the Residues 60 – 250 mm. A wavelength range of 1,029 nm to 1,683 nm, 1,042 nm to 1,677 nm, and 1,029 nm to 1,683 nm were used and the operations were performed at a framerate of 450 Hz, 300 Hz, and 446 Hz for the NIR-sensors Input, Paper and Residues, respectively. Photos of the three sensors installed in the LWP sorting plant are given in Supplementary material 5–7.

2.2.2. Sensor-based material classification

A separate classification model had to be developed for each sensor, as the background (conveyor belt), the lighting conditions, and general installation and operation parameters differed between the positions of the sensors. The detected NIR spectra were classified into eight material classes based on the CLASS 32 on-chip classification from EVK (cf. Fig. 2b). For every classification model, a threshold for the mean intensity was defined to differentiate between the material and the background. Since the focus was on determining the PB content, spectral data similar to the PB spectrum was trained particularly. Material with similar spectral data to PB includes organic materials like wood, textiles, and beverage cartons made of paper and a thin PE layer. Moreover, the spectral data of PE, PET, PP, and PS were included to provide a more comprehensive understanding of the composition and fluctuation ranges of different materials in LWP. For each material class, representative partial areas were extracted from exemplary particles to obtain the different material spectra. Characteristic multi-material spectra were trained to ensure the correct classification of the total material stream including labels, sleeves, contaminations, and multilayers. Material particles to train the classification model are shown in Supplementary material 8. To improve the classification performance, wavelength ranges were defined in which the selected material spectra differ significantly (cf. Fig. 2b). To classify the material, the spectra were preprocessed (first derivation, normalization, and smoothing) and recorded spectra were compared with trained spectra.

2.2.3. Determination of fluctuations caused by material from different settlement structures

To investigate fluctuation ranges in LWP composition resulting from different settlement structures, LWP material from urban and rural areas was collected and stored separately. The urban material came from three large cities with more than 150,000 inhabitants each (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2022). The rural material came from two small middle-sized cities with less than 32,000 inhabitants each (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2022). For both settlement structures, 40 to 50 tons of LWP from four trucks each were stored separately. A photo of the collected material is given in Supplementary material 9. The aim was not to assign waste-relevant parameters to region-specific LWP waste but to estimate the extent to which fluctuations caused by settlement structure can be detected. Therefore, during the sampling campaign on the 23$^{\mathrm{rd}}$ of June 2022, separate collected LWP from urban and rural settlement structures were sorted over two hours each in the sorting plant. The material was detected by the NIR Input sensor.

2.3. Manual analysis of PB product stream samples

The PB product stream samples were analyzed in the technical lab of the Department of Anthropogenic Material Cycles at RWTH Aachen University. All samples were sieved at 40 mm with a drum screen. The separation of the fine fraction reduced the manual analysis effort and supported the sortability of the samples. The fraction < 40 mm was not analyzed, since the PB product stream < 40 mm has limited use for potential recycling with an upstream sorting process. In cooperation with PROPAKMA GmbH, a sorting catalog was developed for the sorting analysis. PROPAKMA GmbH is an engineering office that has been involved in standardization processes including paper and board quality definitions regarding the paper industry. The sorting catalog is given in Fig. 2c. Detail photos of the paper fraction are provided in Supplementary material 3. The differentiation of paper with food contact ("food") and without food contact ("non-food") during the use phase was made to assess the PB content that could have been discarded in separate paper collection. This PB was classified as misplaced by the consumer. The assumption that food contact is an exclusion criterion for separate paper collection was made since food is listed as prohibited material in DIN EN 643 and food residues cannot be excluded with certainty in case of contact with food during the use phase. PB composites were not counted as a misplaced fraction because there is no precise classification if they belong to the separate paper collection or not (detailed photos of contained PB composites can be found in Supplementary material 4). The consumers also misplace sanitary and thermographic papers since these papers should properly have been discarded in residual waste (also referred to as mixed municipal solid waste) (WEPA Hygieneprodukte GmbH, 2020). However, these paper grades do not represent a potential for separate paper collection. Impurities are caused by incorrect sorting within the sorting process of the plant or by composites that got loosened after the sorting process.

After the sorting analysis, all sorted fractions from the PB product stream were dried till weight constancy according to DIN EN 12880 (DIN EN 12880:2000). During the summer sampling campaign, three samples were dried before sorting to verify the determined water content after the sorting analysis. Using Equation (12), the water content w can be calculated by the sample mass m_{ww} regarding the wet weight (ww) and the sample mass m_{dm} regarding the dry matter (dm). The samples from Residues < 60 mm and Aluminum < 60 mm were dried till weight constancy and sorted afterward to determine the PB and PB composite content.

$$w = \frac{m_{ww} - m_{dm}}{m_{ww}} \ [\mathrm{wt\%,\ ww}] \quad (12)$$

2.4. Estimation of technically available and usable PB quantity in LWP

With the obtained data an estimation of technically available and usable PB quantities in German LWP can be conducted. The technically available PB potential is defined as the PB quantities in the PB product stream. The usable PB content in the PB product stream was calculated according to Equation (13). As usable PB fractions in the PB product stream graphic paper, white and brown PB were classified. Sanitary paper, thermographic paper, and impurities were excluded from the usable PB content as they are classified as unusable fractions according to DIN EN 643. In a conservative estimation, it was assumed that 50 wt% (ww) of PB composites and fines < 40 mm consist of usable PB. Dissolution tests in the laboratory tended to show lower reject contents of 20 wt% to 25 wt% for both fractions (PROPAKMA GmbH, 2022). However, higher fiber losses can be expected in production processes. Therefore, this assumption is permissible.

$$c_{m,usable\_PB,PB\_product\_stream} = c_{m,Graphic\_paper,PB\_product\_stream} + c_{m,White\_PB,PB\_product\_stream} + c_{m,Brown\_PB,PB\_product\_stream} + 0.5\cdot(c_{m,PB\_composites,PB\_product\_stream} + c_{m,<40\ mm,PB\_product\_stream})\ [wt\%,\ ww] \quad (13)$$

To relate the usable and technically available PB content $c_{m,usable\_PB,PB\_product\_stream}$ to the LWP input Equation (9) with the mass recovery of the PB product stream is used.

To extrapolate the usable and technically available PB content in the

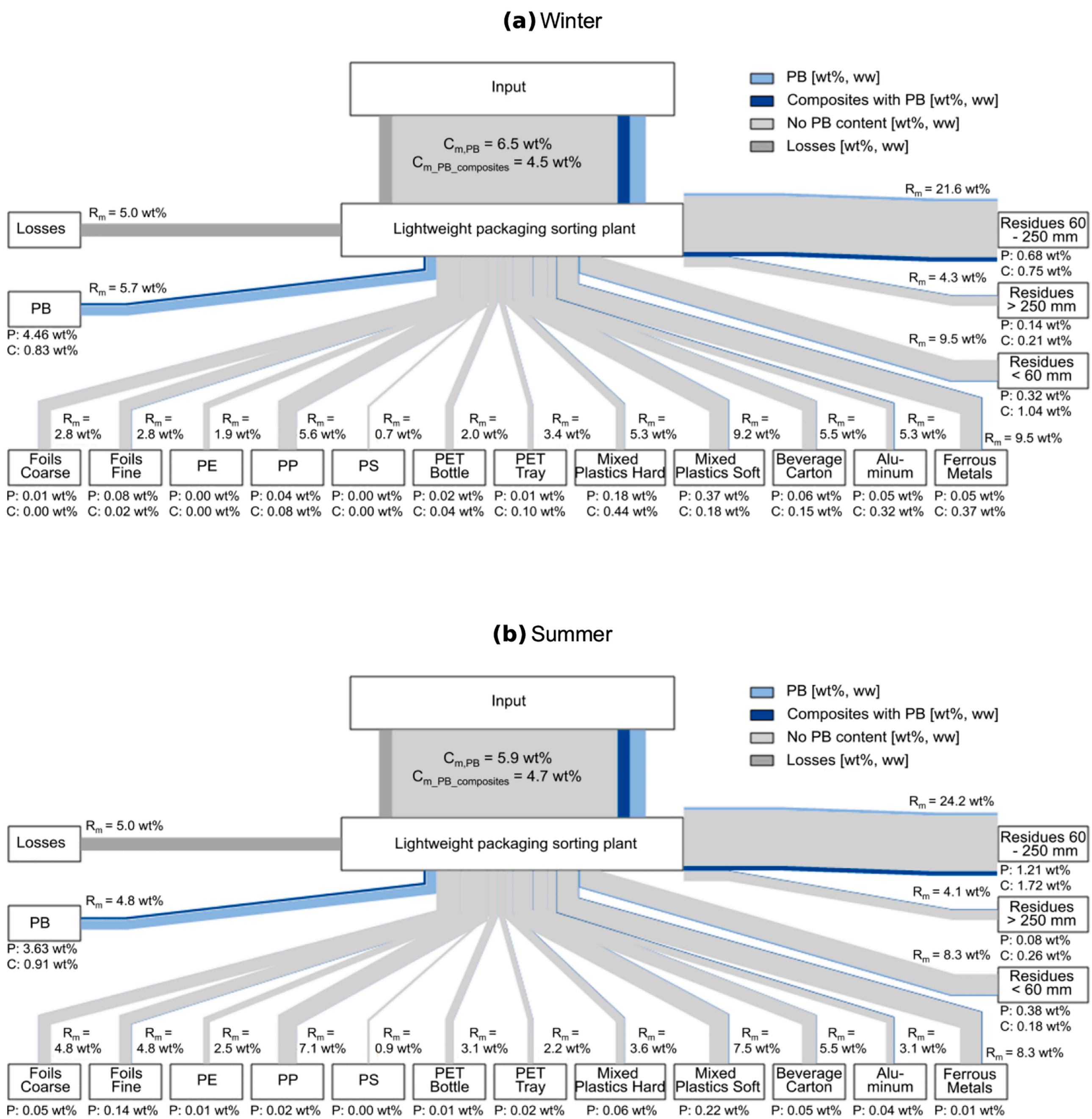

Fig. 3. Mass balance of the LWP sorting plant with average mass-based PB (P) and PB composite (C) contents regarding the input (cf. Equation (9)), and mass recoveries $R_{m,j}$ for all output streams (cf. Equation (7)) determined for winter and summer periods, all mass contents refer to the wet weight.

LWP input to Germany, the content can be related to the total LWP quantity in Germany m_{LWP} according to Equation (14).

$$m_{\mathrm{m,TM,LWP}} = c_{\mathrm{m,TM,Input}} * m_{\mathrm{LWP}} \left[\frac{\mathrm{t}}{\mathrm{a}}, \mathrm{ww}\right] \tag{14}$$

3. Results and discussion

The results of the conducted manual analysis and sensor-based material flow monitoring are given below.

3.1. LWP sorting plant balance to determine PB contents (RQ1)

For the LWP sorting plant balance, all output streams were sampled, and the total masses of the output streams produced during the sampling campaigns were determined. Except for the streams Fe, Residues < 60 mm, and Residues 60–250 mm, all quantities were determined by weighing the bales. The masses of both Aluminum and both Foil streams were reported together. For the Foils, it was assumed that the output was evenly composed of Foils Coarse and Foils Fine. For the Aluminum streams, it was assumed that the output consisted of one-third Aluminum < 60 mm and two-thirds Aluminum > 60 mm. These assumptions were confirmed by visual inspections of mass flows within the LWP sorting plant and the experience reports of the plant operators. Belt scales reported the masses of the input and Residues 60 – 250 mm. Due to logistical reasons (storage with other material streams and no allocation of weighing data and time stamp possible), the Residues < 60 mm mass and the Ferrous Metal mass could not be determined during sampling campaigns. Therefore, the difference between the input and all available output masses was calculated. 5 wt% (ww) losses regarding the input due to evaporation or littered material within the sorting process were assumed. The remaining mass was equally distributed into Residues < 60 mm and Ferrous Metals. All assumptions and the resulting output stream mass balance were evaluated with long-term values of the sorting plant. Fig. 3 shows the resulting mass balance of the sorting plant for the winter (Fig. 3a) and the summer (Fig. 3b) sampling campaign. The thickness of the lines represents the mass per material stream. The PB content per output stream was calculated according to Equation (8). In Fig. 3 the mass recovery $R_{m,j}$ per output stream (cf. Equation (7)) and the mass-based contents to the input (cf. Equation (9)) of PB (P) and PB composites (C) are given. The sum of all PB/PB composite output stream contents results in the PB/PB composite input contents (cf. Equation (10)).

The standard deviations and coefficients of variation for the PB content per output stream over both sampling campaigns as well as the resulting relative maximum random deviation ∊ and number of samples *n* calculated by Equations (1) and (5) are given in Supplementary material 10. The fine fractions are excluded since only one sample per sampling campaign was analyzed. The results for the PB product stream are discussed in section 3.4. For most sampled output streams, the relative maximum random deviation ∊ of 20 wt% (ww) (European Commission, 2004) for the PB and PB composite contents calculated by Equation (1) could not be maintained. Since the coefficient of variation is calculated by the standard deviation divided by the mean value of the target parameter, low PB and PB composite contents lead to a high coefficient of variation and therefore also to high necessary numbers of samples. This problem can be observed especially for output streams where over 90 % of samples have PB contents below 1 wt% (ww) (e.g., PE and PS). For the PB content in the PE output stream, a coefficient of variation of 411 wt% (ww) was determined resulting in 6,504 necessary samples according to Equation (1), while the standard deviation was only 0.57 wt% or 19 g (ww). At this point, the question arises whether a certain accuracy is necessary and economically justifiable for the desired result. If the number of samples is calculated based on the standard deviation according to Equation (5), the number of necessary samples reduces to round up one sample for all output streams. Due to the general heterogeneity of the output streams, this number of samples cannot be considered appropriate either. In future work, other statistical models to determine the necessary sample number for low target material contents should be investigated. However, the calculated PB and PB composite contents in the presented results should be seen with limitations.

The PB composite quantity in the input is at a similar level of about 4.5 wt% (ww) to 4.7 wt% (ww). Beverage cartons that have been sorted correctly into the respective output stream are excluded from this content as they are already used for material recycling. It should be noted that not all remaining composites can be counted as theoretical potential since composites in which another material component has a significantly higher mass share are also included (cf. Supplementary material 4). This share can be estimated by the amount of PB composites that are actually sorted into the PB product stream. The PB composite content in the PB product streams results in 0.8 wt% (ww) and 0.9 wt% (ww), which is for both sampling campaigns 3.7 wt% (ww) to 3.8 wt (ww) lower than the PB composite potential in the input.

PB contents in the input of 6.5 wt% (ww) in winter and 5.9 wt% (ww) in summer were determined. The calculated PB contents are in a similar range to comparable literature values (Christiani, 2017; Cimpan et al., 2016; Feil et al., 2016; Gallardo et al., 2018; Mastellone et al., 2017). A PB yield of 69 wt% (ww) and 61 wt% (ww) regarding the input (cf. Equation (11)) were sorted into the PB product stream during the winter and the summer period, respectively. Relatively high PB contents can be found in Residues 60 – 250 mm, Residues < 60 mm, and Mixed Plastic streams. A theoretical optimization potential was identified for around one-third of PB from the input for both sampling campaigns. However, the theoretical potential does not represent the technically accessible potential. Since each unit and each sorting step has limited efficiency, sorting all PB contained in the input into the PB product stream is not feasible.

3.2. Fluctuation ranges of LWP composition and PB contents (RQ2)

Since the material to be characterized represents a waste stream, an estimation of potential should always show fluctuation ranges. The parameters presented in this study are seasonal variations, variations depending on the settlement structure and fluctuation ranges over two weeks. Fig. 4a shows the manually determined PB contents (wt%) in the output streams for which the largest seasonal differences were identified. The PB contents for the other output streams are often at a similar range for winter and summer sampling campaigns and can be taken from Supplementary material 11. The average PB content in both Mixed Plastics streams was higher during winter. In contrast during summer, PB contents were higher in Residues 60 – 250 mm and Foils Fine. These streams and Residues > 250 mm are the output streams with the highest misdirected PB contents. Overall, it can be stated that the absolute mean deviation of PB content based on seasonal fluctuations does not exceed 2 wt% (ww) in any coarse output stream.

Fig. 4b shows the composition (a%) detected by the NIR Input sensor for LWP material from urban and rural areas. There is a general high degree of variation in the composition of the material. It can be assumed that wood and textiles represent materials that are misplaced in LWP by the consumer. The area contents for both materials were slightly higher for LWP from urban areas. In LWP material from urban areas, a slightly lower average PB content was detected. This corresponds to the results which were calculated based on manual analysis results and the average output stream masses during the sampling campaign in summer. The manual analysis results show that PB input contents amounted to 6.8 wt % (ww) and 7.6 wt% (ww) for material from urban and rural areas, respectively. However, further analyses should be conducted due to the rather low amounts of LWP analyzed and the small differences detected.

Fig. 5 shows the material composition registered by NIR at the three different positions in the LWP sorting plant over two weeks. Points, where the stacked area graphs decrease sharply for a longer period,

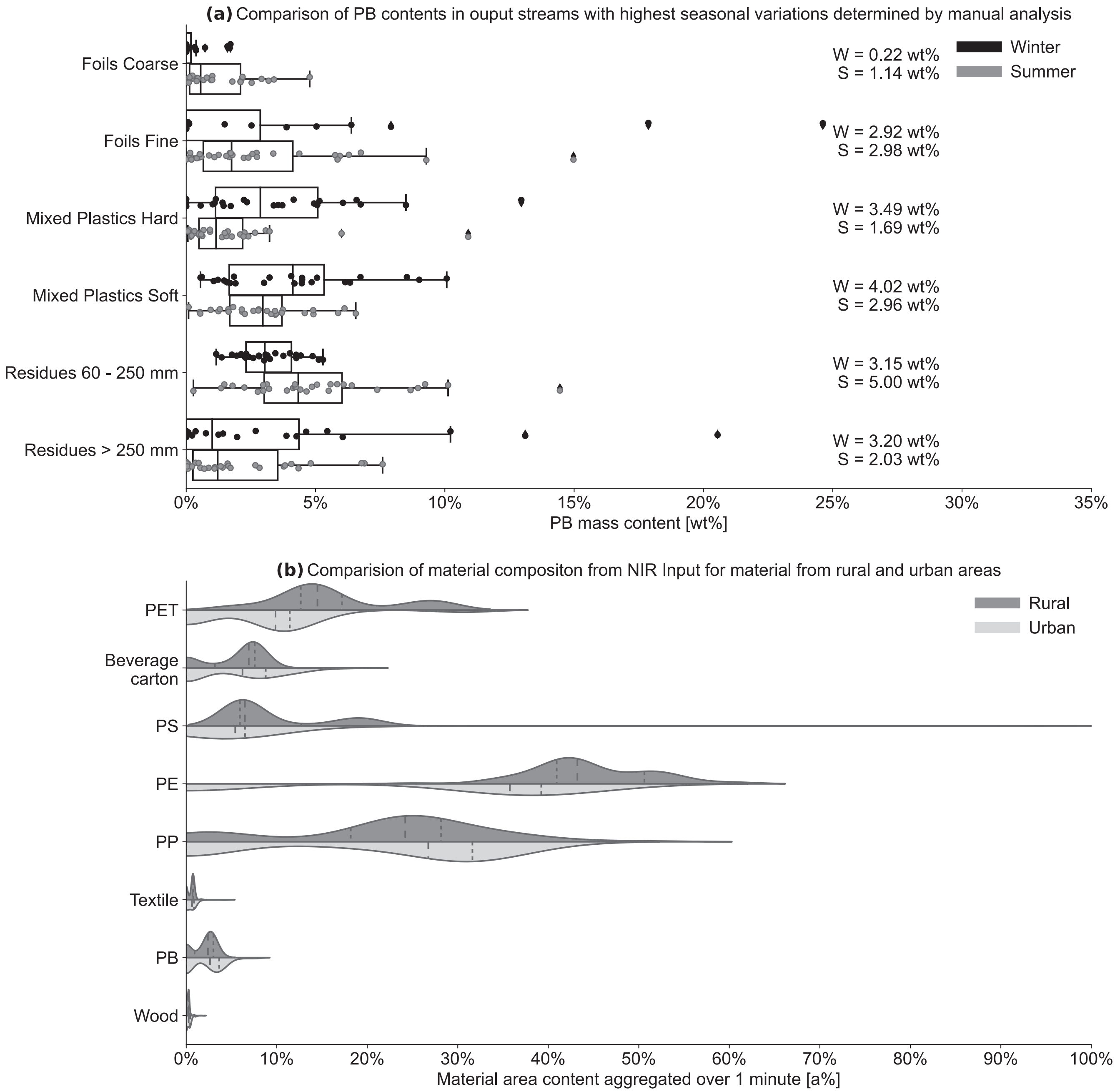

Fig. 4. Fluctuation in LWP material composition depending on seasonal variations and material from different settlement structures (a) PB mass contents determined by manual analysis, all mass contents refer to the wet weight (boxplot with boxes from the lower to the upper quartile and whiskers with a maximum of 1.5 times the interquartile range) (b) area contents determined by SBMM (data aggregated over 1 min, violin plot with entire data range and lines at the quantiles).

represent plant downtimes for cleaning and maintenance intervals. Since the material at the input belt after coarse screening at 250 mm formed a bulk, the NIR Input sensor detected only the top layer (compare also Supplementary material 5). Previous research has shown that material bulks have influences on the detected material composition due to segregation effects (Kroell et al., 2023). Therefore, the detected composition by NIR Input should be interpreted with limitations. The average PB area flows were 85 m^2/h, 1,454 m^2/h, and 160 m^2/h for NIR Input, NIR Paper, and NIR Residues, respectively. For the NIR Paper sensor, the largest interfering material detected represents Textile with 432 m^2/h. The highest area flows in Residues 60 – 250 mm, and therefore high material losses were observed for PP (459 m^2/h) and PS (175 m^2/h). Comparing the area flows of different sensors shows that different shares of the total area flows are detected depending on the material flow presentation (Kroell et al., 2023). Accordingly, a direct comparison between the different area flows without correction factors is not possible but compositions can be compared within the data from one sensor. For the NIR Input sensor, area flow variations with similar magnitudes were observed for all materials except for the small contents of textile and wood. Using standard deviations and mean values of the area flows, the coefficients of variation for the material classes (following Equation (2)) lie between 37.6 a% and 42.6 a%. The coefficient of variation for PET, Beverage carton, PS, PP, and PB detected by NIR Input even only is between 42.0 a% and 42.6 a%. Based on these data, a data aggregation of one hour compensates large fluctuation ranges even within the < 250 mm LWP material composition (cf. also Fig. 4b). The results suggest that variations in LWP input do exist, but for most materials < 250 mm they are within defined limits.

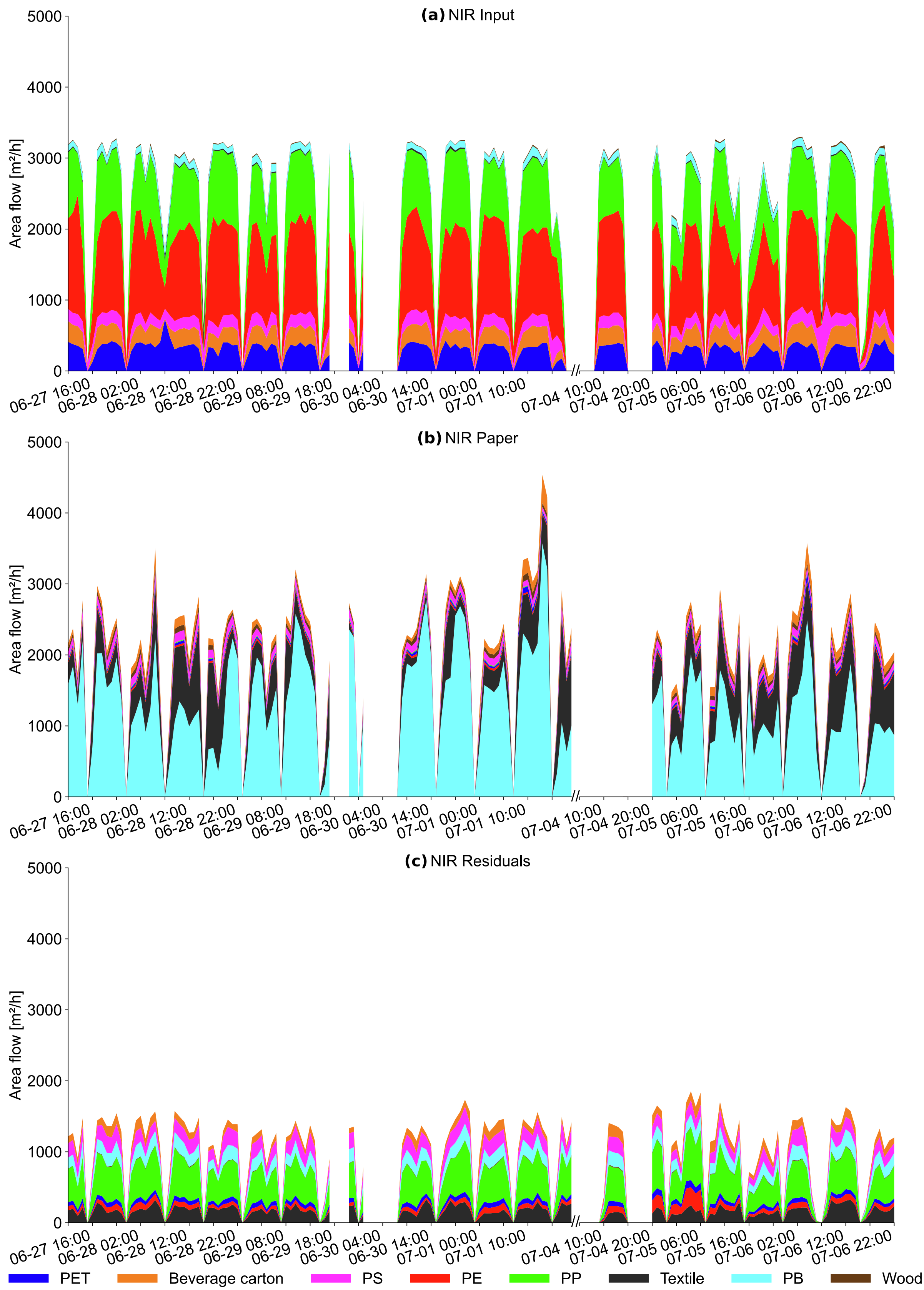

Fig. 5. LWP composition at different point of the LWP sorting plant Erftstadt over two weeks determined by SBMM (data aggregated over 1 h).

3.3. Correlation of manual and sensor-based data (RQ3)

For Residues 60 – 250 mm, PB contents from both manual analysis and SBMM were detected during the summer sampling campaign over 11 h (cf. Fig. 6). For mass-based PB contents, the mean values from both samples per hour are combined. For area-based PB contents, the values obtained over one hour are aggregated.

Fig. 6a provides the PB content in Residues 60 – 250 mm determined by manual analysis and SBMM over the sampling time. The concentration trends of both data sets have a comparable course. However, the PB area contents are consistently higher than the mass contents which can mainly be explained by the following two factors: (1) The sensor-based data includes every PB pixel occurring on the surface (difference between article-based and material-based purity definition, cf. (Kroell et al., 2024)). This also includes paper composites and paper labels. A comparison with manually determined PB composites is not permissible, due to the PB composite definition (cf. section 2.3). (2) PB consists of a lower grammage compared to other LWP materials (Kroell et al., 2021). In addition, materials that are commonly found in Residues 60 – 250 mm like textiles or organics potentially have a higher particle mass than PB due to their high water content.

Fig. 6b shows the linear regression for PB area contents plotted over PB mass contents in Residues 60 – 250 mm. The linear regression is not significant. Several factors can be used as an explanation. First, the analyzed waste stream differs because the sensor-based analysis considers the entire basic population, while the gravimetric analysis considers only a portion of the population. Moreover, only the PB content is subjected to the comparison of mass- and sensor-based data. Since the stream Residues 60 – 250 mm is analyzed, only PB that was not sorted into the PB product stream is included (cf. also Fig. 2a). The sensor-based sorting (SBS) of the PB product stream is conducted by compressed air. Particularly light PB such as sanitary paper is challenging because it often moves relative to the belt. The particularly heavy paper also poses a challenge, as it is sometimes not discharged by the compressed air. This results in a high variance of PB grammages, which leads to a high difference between PB mass and area contents. In summary, a comparable concentration trend for PB from LWP can be expected for manual- and sensor-based data. A direct comparison of mass and area contents is not possible, based on the presented data. For the determination of residual stream compositions in particular to identify small material contents, further investigations should be conducted for both analysis methods.

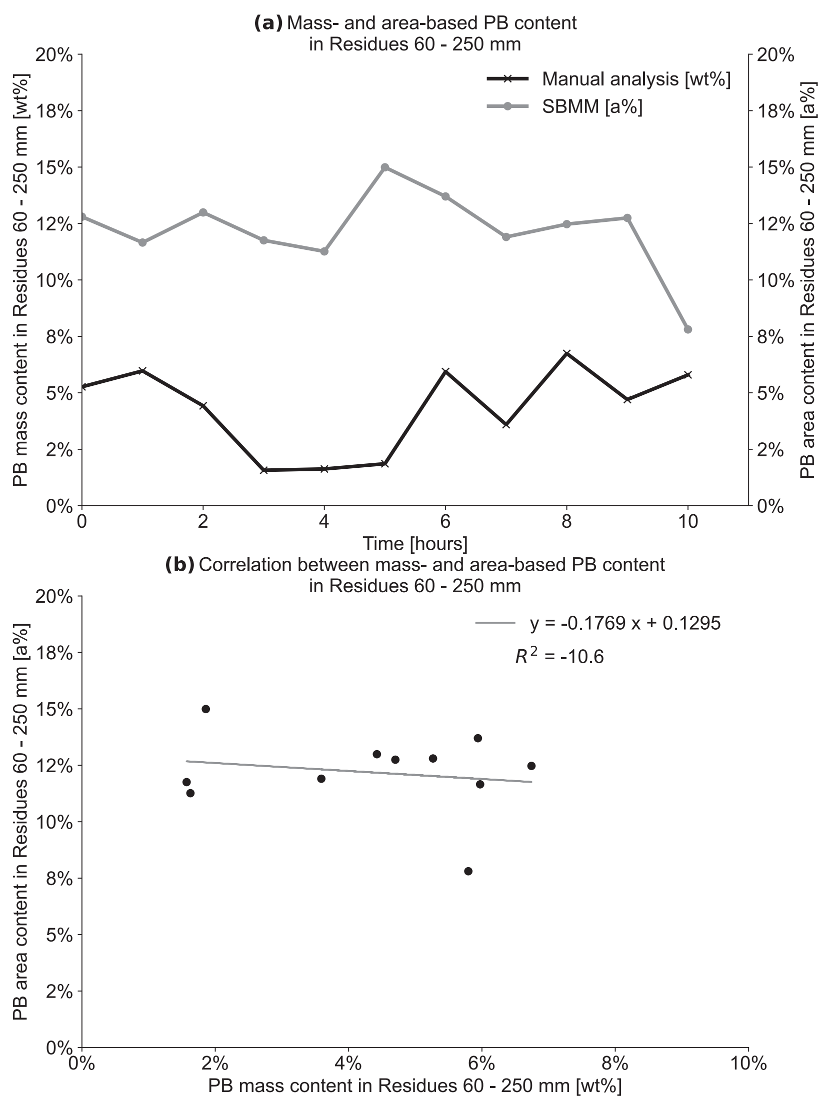

Fig. 6. Comparison of PB contents determined by manual and sensor-based analyses for Residues 60 – 250 mm, all mass contents refer to the wet weight.

3.4. PB product stream composition from a LWP sorting plant (RQ4)

The PB product stream represents the technically available potential of PB from LWP. Therefore, a more detailed analysis was conducted. Three samples from the summer sampling campaign were directly dried and not manually analyzed to confirm the water content determined after the sorting analysis. The screening results show a mean < 40 mm content of 5.6 wt% (ww) for the winter period and 4.7 wt% (ww) for the summer period. Since the < 40 mm content would be separated in subsequent sorting processes, the fraction was not analyzed in more detail. The relative standard deviation for the < 40 mm content was 1.1 wt% (ww) for both sampling campaigns. The results show that fine-grain classes can be found in the PB product despite prior screening during the LWP sorting process.

The subsequent manual analysis was conducted according to the sorting catalog given in Fig. 2c. Pictures of the sorted fractions are provided in Fig. 7a and Fig. 7b for samples from the winter and summer period, respectively. The samples are ordered from the highest paper quality (left) to the lowest (right). The volume of the sanitary paper and the PB composites remain approximately the same for both sampling campaigns. However, it should be noted that two more samples were analyzed during the summer. Nevertheless, the volume ratios show that more brown and fewer white fibers were contained in the PB product stream during summer. A larger volume of impurities in the winter period consisted mainly of foils that had been incorrectly sorted by the PB cleaner due to their ability to fly, tapes that had become entangled, and other structurally similar organic materials such as wood and cotton textiles, which have similar NIR spectra to PB.

The distribution and the average mass contents of the paper fractions contained in the samples from the PB product stream are given in Fig. 8. The mass fractions show that more graphic paper and white PB, and therefore, more white fibers were contained in the samples from the winter period. This remains in a higher content of good usable fibers during winter. However, the content of sanitary paper and impurities were also higher during the same sampling campaign. The average PB composite contents were higher during summer. This corresponds to a predicted increase of PB composites in LWP due to the substitution of plastic packaging for paper packaging often with plastic layers (Gesellschaft für Verpackungsmarktforschung, 2019). The average water content was 37.8 wt% for the samples from the winter and 25.6 wt % for the samples from the summer period.

For the composition of paper fractions from the PB product stream determined by samples taken during both sampling campaigns, relative maximum random deviations ∊ between 11 % and 13 % were obtained. Only for thermographic paper with a small content of 0.3 wt%, ∊ amounted to 25 %. Thus, for the average composition of the PB product

Fig. 7. Photos of sorted paper fractions from the PB product stream during winter (n = 25) and summer (n = 27) sampling campaign.

stream, good accuracy can be assumed.

As discussed in section 2.3, graphic paper, white PB non-food, and brown PB non-food were assumed to be a misplaced fraction by the consumer. Therefore, misplaced fraction rates of 44.2 wt% (ww) and 44.6 wt% (ww) were calculated for the paper product stream during the winter and summer period, respectively. This results in a potential of almost 45 wt% (ww) of well-recyclable fibers in the PB product stream from LWP.

3.5. Technically available and usable PB quantity in German LWP (RQ5)

With the determined PB quantities (cf. section 3.1) and qualities (cf. section 3.4), an estimation of the technically available, well usable PB quantity in LWP for Germany can be conducted (cf. section 2.4). The extrapolated results should be seen with limitations, as inaccuracies related to the quantities of the output streams have to be assumed and only one LWP sorting plant was sampled. However, the LWP material processed in the LWP sorting plant (Erftstadt) in 2022 came from cities and districts with a weighted specific LWP quantity of 34 kg per inhabitant and year (Bundesinstitut für Bau-, Stadt- und Raumforschung, 2022; REMONDIS GmbH & Co. KG., 2024). This specific LWP quantity is close to the German average of 33 kg per inhabitant and year (Grummt and Fabian, 2023; Statistisches Bundesamt, 2024). Therefore, the LWP quantity generated within the depicted area is comparable to the German average. Moreover, the PB content in the input is at a similar level as the few given literature values regarding PB in German LWP input material (Christiani, 2017; Cimpan et al., 2016).

The PB product stream can be classified as the technically available PB potential and accounts for 4.8 wt% (ww) of the input during the summer and 5.7 wt% (ww) during the winter period (cf. Equation (7)). The respective PB yield amounts to 61 wt% (ww) and 69 wt% (ww) for summer and winter, respectively (cf. Equation (11)). With a total amount of 2.7 million tons of LWP generated in 2021 in Germany (Grummt and Fabian, 2023), masses for the PB product stream can be calculated according to Equation (14). The calculation results in 130,000 tons to 154,000 tons per year for summer and winter sampling campaigns, respectively.

To control the plausibility of this calculation, a cross-check is carried out using available literature data. The material stream report of recovered PB from LWP in 2021 amounted to 109,300 tons (Grummt and Fabian, 2023). Since 95.7 % of all LWP sorting plants in Germany sorted PB from LWP in 2021 (Grummt and Fabian, 2023), the total amount of separated PB from LWP amounts to 114,200 tons per year if all LWP plants would sort PB from LWP. The lower quantity of recovered PB from LWP based on the material stream report compared to the calculated quantities based on the presented results seems plausible, as the LWP sorting plant Erftstadt, a comparatively new sorting plant from 2019, was sampled. The PB yield in older plants can be assumed to be lower. In addition, sampling was conducted in 2022. Higher values of PB product stream quantities compared to 2021 are to be expected, primarily due to the increase of PB composites (Gesellschaft für Verpackungsmarktforschung, 2019). In conclusion, the PB product stream quantities can be considered reasonable to estimate the technically available PB potential with the current state of the art LWP sorting plant (average PB yield of around 65 wt%).

According to Equation (13), the amount of usable PB in the PB product stream was calculated to be 67.6 wt% (ww) and 64.4 wt% (ww) for summer and winter, respectively. By this estimation, different impurity contents in the PB product stream are eliminated. This results in 3.3 wt% (ww) to 3.7 wt% (ww) of usable and in the PB product stream technically available PB regarding the LWP input (cf. Equation (9)). With Equation (14) a technical available and usable PB quantity of 89,000 tons per year (summer) to 100,000 tons per year (winter) for Germany (PB yield of around 65 wt% (ww)) is determined.

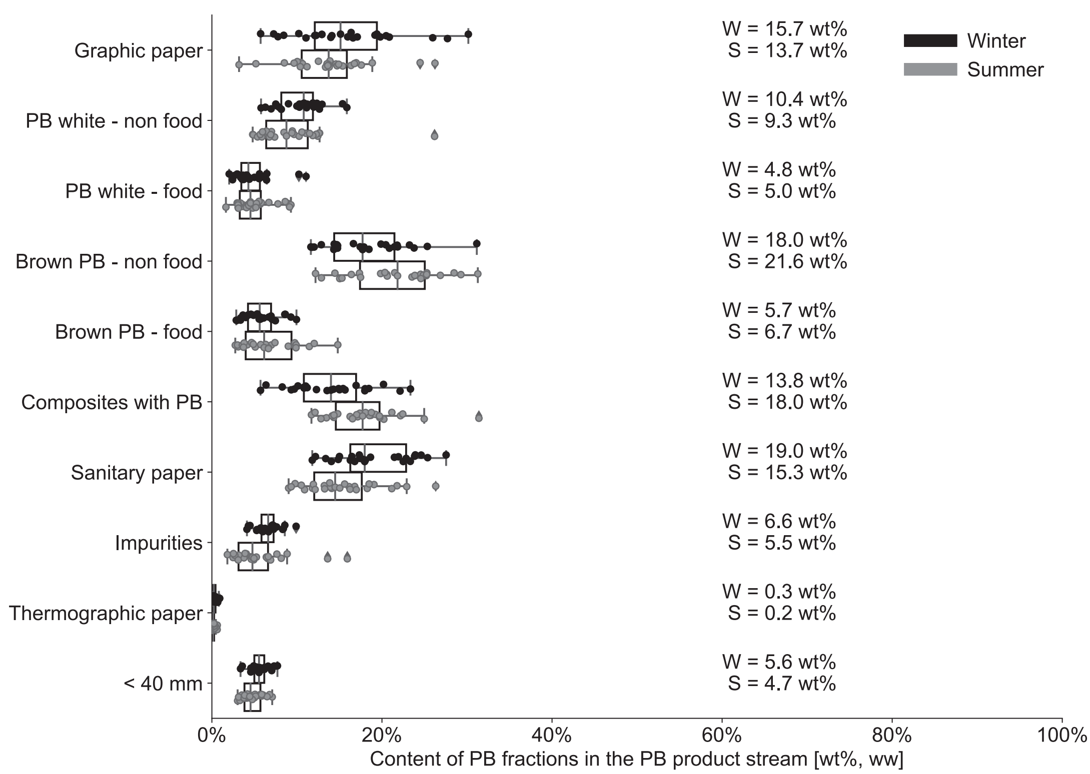

Fig. 8. Composition of PB product streams determined by manual analysis during winter (W, n = 25) and summer (S, n = 27) sampling campaign, all mass contents refer to the wet weight (boxplot with boxes from the lower to the upper quartile and whiskers with a maximum of 1.5 times the interquartile range).

4. Conclusion

Paper recycling offers environmental and economic advantages compared to primary paper production. At the moment, however, PB discarded in LWP waste is not extensively used for material recycling. To assess the resource potential of PB from LWP and to contribute to the development of an adapted recycling process, this study presented a methodical approach and determined PB quantities, qualities and fluctuation ranges in a LWP sorting plant using conventional manual analysis and sensor-based material flow monitoring (SBMM).

Observed fluctuation ranges showed similar PB mass contents in most of the output streams during winter and summer. Material from urban areas had a slightly higher PB content according to manual and sensor-based obtained data. Notable, after two weeks of SBMM, comparable variations between material classes were observed for varying material compositions of LWP after coarse screening at 250 mm. The results suggest that variations in LWP input over longer periods are within defined limits. [cf. RQ2].

The conducted sorting plant balance showed average PB contents in the LWP input between 6.5 wt% (ww, winter) and 5.9 wt% (ww, summer). The technically available PB product stream was 5.7 wt% (ww) in winter and 4.8 wt% (ww) in summer including impurities and paper composites. The sorting efficiency, expressed by the PB yield, was on average 65 wt% (ww). [cf. RQ1] For both sampling campaigns, around 45 wt% (ww) of the PB from the PB product stream was misplaced and could have been discarded in separate paper collections. This PB has a particularly good potential for paper recycling. [cf. RQ4] Using the determined PB quantities and qualities, the technically available and well usable PB potential in the PB product stream in German LWP was calculated to be 89,000 to 100,000 tons per year (average PB yield of around 65 wt% (ww)). [cf. RQ5].

In summary, the results show a significant resource potential for material recycling of PB from LWP. The obtained results can help in designing subsequent dry and wet mechanical sorting processes. Due to variability in material composition and reasonable amounts of impurities, in future research, we will investigate the subsequent sorting of the PB product stream. Moreover, possible adjustments to the process control in the wet mechanical recycling process should be investigated.

Due to the technical sorting efficiency, PB quantity and quality enriched within PB product streams of packaging sorting plants represent the technically available PB potential. For this reason, PB separated through a sorting process should be evaluated in particular to analyze the PB potential for material recycling contained in other European packaging collection systems. The presented methodical approach developed for sampling LWP sorting plants can be adapted to enable analyses of other packaging sorting plants and to assess the PB resource potential in different packaging waste collection systems.

Funding

The research project on which the presented article is based is funded by the Federal Ministry for Economic Affairs and Climate Action under grant number 03EN2073B. Responsibility for the content lies with the authors. As the research project with grant number 03EN2073B only had a 95 % funding rate, the remaining 5 % funding was provided by REMONDIS GmbH & Co. KG in the form of third-party funds to the Department of Anthropogenic Material Cycles.

CRediT authorship contribution statement

Alena Maria Spies: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Funding acquisition, Supervision. **Nils Kroell:** Writing – review & editing, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization, Software. **Annika Ludes:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Conceptualization. **Bastian Küppers:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization, Funding acquisition, Project administration. **Karoline Raulf:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization, Project administration. **Kathrin Greiff:** Writing – review & editing, Supervision.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgement

The authors would like to thank REMONDIS GmbH & Co. KG and, in particular, David Schumacher and Michelle Bongartz for providing access to the LWP sorting plant as well as supporting us with comprehensive technical and logistical data on the process, the material streams, and their origin and for their great support during the sampling campaigns.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.07.034.

References

Statistisches Bundesamt, 2021. Genesis Online Data Base - Statistic, Code 32111-0002: Quantity of Waste Group 03 03 as Input in Waste Processing Plants (after EWC (European Waste Catalog)). https://www-genesis.destatis.de/genesis/online?sequenz=statistikTabellen&selectionname=32111*#abreadcrumb (accessed 22 July 2023).
Bundesinstitut für Bau-, Stadt- und Raumforschung, 2022. Referenztabellen zu Raumgliederungen des BBSR. https://www.bbsr.bund.de/BBSR/DE/forschung/raumbeobachtung/downloads/download-referenzen.html;jsessionid=83CECB1DE9F7FD465AC11368E4934576.live21302 (accessed 9 March 2024).
Bundesinstitut für Risikobewertung, 2021. XXXVI. Papiere, Kartons und Pappen für den Lebensmittelkontakt. https://bfr.ble.de/kse/faces/resources/pdf/360.pdf (accessed 6 December 2021).
Christiani, J., 2017. Recycling und Recyclingfähigkeit bei Verpackungen - Das neue VerpackG in der Praxis: Stand der Technik und Herausforderungen für einzelne Verpackungsmaterialen. HTP Ingenieurgesellschaft, 2017, Berlin.
Cimpan, C., Maul, A., Wenzel, H., Pretz, T., 2016. Techno-economic assessment of central sorting at material recovery facilities – the case of lightweight packaging waste. J. Clean. Prod. 112, 4387–4397. https://doi.org/10.1016/j.jclepro.2015.09.011.
Confederation of Paper Industries, 2023. The UK's Paper-based Industries stress that End of Waste for paper and board occurs at the point of actual recycling. https://paper.org.uk/CPI/CPI/Content/News/Press-Releases/2023/End-of-Waste-for-paper-and-board.aspx (accessed 14 March 2024).
Dahlén, L., Lagerkvist, A., 2008. Methods for household waste composition studies. Waste Management 28, 1100–1112. https://doi.org/10.1016/j.wasman.2007.08.014.
Dehoust, G., Hermann, A., Christiani, J., Bartnik, S., Beckamp, S., Bünemann, A., 2021. Ermittlung der Praxis der Sortierung und Verwertung von Verpackungen im Sinne des § 21 VerpackG. Texte 11/2021, Dessau-Roßlau. https://www.umweltbundesamt.de/publikationen (accessed 13 January 2022).
DIE PAPIERINDUSTRIE, 2022. Leistungsbericht PAPIER 2022: Statistiken zum Leistungsbericht.
DIN Normenausschuss Wasserwesen (NAW). DIN EN 12880:2000: Characterization of sludges – Determination of dry residue and water content.
DIN-Normenausschuss Papier, Pappe und Faserstoff, DIN-Normenausschuss Verpackungswesen. DIN EN 643:2014: European list of standard grades of paper and board for recycling.
European Commission, 2001. European Packaging Waste Management Systems: Final Report 2001. https://ec.europa.eu/environment/pdf/waste/studies/packaging/epwms.pdf (accessed 14 March 2024).
European Commission, 2004. Methodology for the Analysis of Solid Waste (SWA-Tool) User Version: SWA-Tool, Development of a Methodological Tool to Enhance the

Precision & Comparability of Solid Waste Analysis Data, 57 pp. https://www.wien.gv.at/meu/fdb/pdf/swa-tool-759-ma48.pdf (accessed 5 August 2022).

European Parliament and the Council of the European Union, 1994. Directive 94/62/EC of 20 December 1994 on packaging and packaging waste.

Expatica, 2024. Trash and recycling in France. https://www.expatica.com/fr/living/household/trash-and-recycling-in-france-536594/#paper (accessed 14 March 2024).

Fahrmeir, L., Heumann, C., Künstler, R., Pigeot, I., Tutz, G., 2016. Statistik: Der Weg zur Datenanalyse, 8th ed. Springer Spektrum, Berlin, Heidelberg, 581 pp.

Faul, A., 2005. Quality aspects of recovered paper for deinking. Prog. Pap. Recycl. 15 (1), 6–10.

Feil, A., van Thoden Velzen, E.U., Jansen, M., Vitz, P., Go, N., Pretz, T., 2016. Technical assessment of processing plants as exemplified by the sorting of beverage cartons from lightweight packaging wastes. Waste Management 48, 95–105. https://doi.org/10.1016/j.wasman.2015.10.023.

Feil, A., Kroell, N., Pretz, P., Greiff, K., 2021. Anforderungen an eine effiziente technologische Behandlung von Post-Consumer Verpackungsmaterialien in Sortieranlagen: Möglichkeiten und Grenzen. Müll und Abfall 362–370.

Gallardo, A., Carlos, M., Colomer, F.J., Edo-Alcón, N., 2018. Analysis of the waste selective collection at drop-off systems: Case study including the income level and the seasonal variation. Waste Management and Research. https://doi.org/10.1177/0734242X17733539.

Gesellschaft für Verpackungsmarktforschung, 2019. Potenzial der Substitution von Kunststoffverpackungen durch Verpackungslösungen aus Wellpappe: Kurzversion des Endberichts. https://www.klingele.com/fileadmin/user_upload/Ergebnisbericht_GVM-Studie_2019.pdf (accessed 7 December 2021).

Grummt, S., Fabian, M., 2023. VerpackGPraxis der Sortierung und Verwertung von Verpackungen im Sinne des § 21 VerpackG 2021/2022: Teilbericht 2 des ReFoPlan-Vorhabens "Ermittlung der Praxis der Sortierung und Verwertung von Verpackungen im Sinne des § 21 VerpackG für den Zeitraum 2021 bis 2024, Empfehlungen zur Fortentwicklung des Mindeststandards zur Ermittlung der Recyclingfähigkeit und Entwicklung von Guidelines für umweltfreundliche Verpackungsgestaltung". Texte 120/2023. https://www.umweltbundesamt.de/publikationen (accessed 25 February 2024).

Hedderich, J., Sachs, L., 2018. Angewandte Statistik: Methodensammlung mit R, 16th ed. Springer Berlin Heidelberg, Berlin, Heidelberg, 1025 pp.

Kinsella, S., 2006. Single-stream: Closing the loop. Resource Recycling.

Kroell, N., Chen, X., Maghmoumi, A., Koenig, M., Feil, A., Greiff, K., 2021. Sensor-based particle mass prediction of lightweight packaging waste using machine learning algorithms. Waste Management 136, 253–265. https://doi.org/10.1016/j.wasman.2021.10.017.

Kroell, N., Chen, X., Greiff, K., Feil, A., 2022. Optical sensors and machine learning algorithms in sensor-based material flow characterization for mechanical recycling processes: A systematic literature review. Waste Management 149, 259–290. https://doi.org/10.1016/j.wasman.2022.05.015.

Kroell, N., Chen, X., Küppers, B., Lorenzo, J., Maghmoumi, A., Schlaak, M., Thor, E., Nordmann, C., Greiff, K., 2023. Near-infrared-based determination of mass-based material flow compositions in mechanical recycling of post-consumer plastics: Technical feasibility enables novel applications. Resources, Conservation and Recycling 191. https://doi.org/10.1016/j.resconrec.2023.106873.

Kroell, N., Chen, X., Küppers, B., Schlögl, S., Feil, A., Greiff, K., 2024. Near-infrared-based quality control of plastic pre-concentrates in lightweight-packaging waste sorting plants. Resources, Conservation and Recycling 201. https://doi.org/10.1016/j.resconrec.2023.107256.

Küppers, B., Schlögl, S., Kroell, N., Radkohl, V. Relevance and challenges of plant control in the pre-processing stage for enhanced sorting performance, in: Sensor-Based Sorting & Control 2022, vol. 9, pp. 17–33.

Landesamt für Umwelt, Landwirtschaft und Geologie des Freistaats Sachsen, 2014. Richtlinie zur einheitlichen Abfallanalytik in Sachsen. https://publikationen.sachsen.de/bdb/artikel/23865 (accessed 17 July 2022).

Länderarbeitsgemeinschaft Abfall, 2001. LAGA PN 98: Richtlinie für das Vorgehen bei physikalischen, chemischen und biologischen Untersuchungen im Zusammenhang mit der Verwertung/Beseitigung von Abfällen.

Mastellone, M.L., Cremiato, R., Zaccariello, L., Lotito, R., 2017. Evaluation of performance indicators applied to a material recovery facility fed by mixed packaging waste. Waste Management. https://doi.org/10.1016/j.wasman.2017.02.030.

Miranda, R., Monte, M., Blanco, A., 2011. Impact of increased collection rates and the use of commingled collection systems on the quality of recovered paper. Part 1: increased collection rates. Waste Management 31, 2208–2216. https://doi.org/10.1016/j.wasman.2011.06.006.

Miranda, R., Monte, M.C., Blanco, A., 2013. Analysis of the quality of the recovered paper from commingled collection systems. Resources, Conservation and Recycling 72, 60–66. https://doi.org/10.1016/j.resconrec.2012.12.007.

Mühl, T., 2017. Elektrische Messtechnik: Grundlagen, Messverfahren, Anwendungen, 5th ed. Springer Vieweg, Wiesbaden, Heidelberg, p. 306.

Naujock, H.-J., Blechschmidt, J., 2021. Taschenbuch der Papiertechnik, 3rd ed. Hanser, Munich, p. 746.

Picuno, C., Alassali, A., Chong, Z.K., Kuchta, K., 2021. Flows of post-consumer plastic packaging in Germany: An MFA-aided case study. Resources, Conservation and Recycling 169. https://doi.org/10.1016/j.resconrec.2021.105515.

Pires, A., Martinho, G., Chang, N.-B., 2011. Solid waste management in European countries: a review of systems analysis techniques. Journal of Environmental Management 92, 1033–1050. https://doi.org/10.1016/j.jenvman.2010.11.024.

PROPAKMA GmbH. Laboratory dissolution test of paper and board samples from lightweight packaging waste. Email from 02 Januar 2022.

REMONDIS SE & Co. KG, 2023. Anlagenverbund: Anlagenbeispiele aus den sechs REMONDIS-Regionen. https://www.remondis-entsorgung.de/anlagenverbund/ (accessed 20 July 2023).

REMONDIS GmbH & Co. KG, 2024. 2022 Mengen LVP. E-Mail from 13 March 2024.

Sacia, W.K., Simmons, J., 2006. The effects of changing ONP quality on a newsprint mill. TAPPI J.

SAEFL, 2004. A survey of the composition of household waste 2001/02. Environmental Series 356, Bern.

Spies, A.M., Geldmacher, J., García López, C., Pretz, T., Raulf, K., 2023. Methodology to quantify single-use plastic products in municipal solid waste - Part 1: Development of a sampling methodology. Waste Management and Research. https://doi.org/10.1177/0734242X231190803.

Statistisches Bundesamt, 2024. Pressemitteilung Nr. 035 vom 25. Januar 2024.

Turner, D.A., Williams, I.D., Kemp, S., 2015. Greenhouse gas emission factors for recycling of source-segregated waste materials. Resources, Conservation and Recycling 105, 186–197. https://doi.org/10.1016/j.resconrec.2015.10.026.

EUWID Verpackungen, 2023. Delkeskamp: Die Papierfabrik in Nortrup wurde geschlossen und die Maschine bereits verkauft. https://www.euwid-verpackung.de/news/unternehmen/delkeskamp-die-papierfabrik-in-nortrup-wurde-geschlossen-und-die-maschine-bereits-verkauft-270123/ (accessed 6 March 2024).

Stiftung Zentrale Stelle Verpackungsregister, 2023. Mindeststandard für die Bemessung der Recyclingfähigkeit von systembeteiligungspflichtigen Verpackungen gemäß § 21 Abs. 3 VerpackG, Osnabrück. https://www.verpackungsregister.org/fileadmin/files/Mindeststandard/Mindeststandard_VerpackG_Ausgabe_2023.pdf (accessed 15 March 2024).

Wellenreuther, F., Detzel, A., Krüger, M., Busch, M., 2022. Updated life-cycle assessment of graphic and tissue paper: Spotlight report. https://www.umweltbundesamt.de/publikationen (accessed 15 March 2024).

WEPA Hygieneprodukte GmbH, 2020. What belongs in the waste paper? https://www.wepa.eu/en/blog/article/was-gehoert-ins-altpapier/#:~:text=These%20do%20not%20belong%20in%20the%20waste%20paper%3A&text=Baking%20and%20sandwich%20paper%20and,are%20often%20treated%20with%20chemicals. (accessed 21 February 2023).

Weßel, C., Brabender, K., Öller, H.-J., Persin, C., 2021. Wasser- und Rückstandsumfrage der deutschen Zellstoff- und Papierindustrie 2021: Optimierter Ressourceneinsatz für nachhaltig produzierte, hochwertige Produkte. https://www.papierindustrie.de/fileadmin/0002-PAPIERINDUSTRIE/07_Dateien/6_Positionen/WRU_2021_Veroeffentlichung.pdf (accessed 18 April 2023).

Xevgenos, D., Papadaskalopoulou, C., Panaretou, V., Moustakas, K., Malamis, D., 2015. Success stories for recycling of MSW at municipal level: a review. Waste and Biomass Valorization 6, 657–684. https://doi.org/10.1007/s12649-015-9389-9.

Zwisele, B., 1998. Statistische Gesichtspunkte bei der Auswahl von Stichprobeneinheiten für Hausmülluntersuchungen. Müllhandbuch.

Zwisele, B., 2005. Probenahmemethoden für die Bestimmung von Menge und Zusammensetzung fester Abfälle. Müllhandbuch.

Zwisele, B., 2004. Entwicklung einer neuen Probenahmemethode für heterogene Abfälle geringer Schüttdichte. Dissertation. Berlin.