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Recyclability Assessment of Pressure-Sensitive Labels Made from Agro-Industrial By-Products

ABSTRACT

The growing demand for sustainable packaging materials has increased the use of agro-industrial by-products as alternative fibre sources in packaging production. However, the recyclability of such materials remains an important factor for their successful integration into circular economy systems. This study investigates the recyclability of pressure-sensitive labels (PSLs) containing citrus, barley, and grape agro-industrial fibres. All label materials were printed under identical conditions using conventional offset printing ink. Recycling was performed according to the INGEDE Method 11 under laboratory conditions. For each label type, laboratory sheets were produced from pulp obtained before and after the deinking flotation process. Recycling efficiency was evaluated through measurements of optical properties, including ISO brightness, CIE Lab colour coordinates and opacity. Citrus fibre-based labels exhibited the highest recycling efficiency, showing the greatest increase in brightness and the most effective removal of ink particles. Barley fibre-based labels showed moderate improvements, whereas grape fibre-based labels exhibited the lowest deinking efficiency, with a larger amount of residual ink remaining after flotation. The findings confirm that pressure-sensitive labels manufactured from agro-industrial by-products can be successfully recycled using conventional deinking technology. Nevertheless, the recycling performance is strongly influenced by the type of agro-industrial fibres incorporated into the paper structure, highlighting the importance of considering recyclability during the design of sustainable label materials.*

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KEY WORDS
Pressure-sensitive labels, agro-industrial by-products, recycling, circular economy

1. Introduction

The transition from a linear to a circular economy has become one of the key strategies for achieving sustainable development and reducing the environmental impacts associated with industrial production. Unlike the traditional linear model of "take–make–dispose", the circular economy aims to maintain the value of materials and products through reuse, repair, remanufacturing and recycling while minimizing waste generation and the consumption of virgin resources (Meherishi et al., 2019) . Within this framework, packaging plays a crucial role because of its short service life and the large quantities of waste generated after use. Consequently, packaging materials are increasingly being designed according to eco-design principles, taking into account not only their functionality but also their recyclability and compatibility with existing waste management systems (Liu et al., 2023; Meherishi et al., 2019). Paper-based packaging is considered one of the most sustainable packaging materials due to its renewable origin, high recycling rates and well-established collection infrastructure. Approximately 40% of all packaging materials are paper or paperboard, and paper packaging exhibits one of the highest recycling rates among packaging materials.

Nevertheless, successful recycling depends on numerous factors, including fibre composition, printing inks, coatings, adhesives and multilayer structures that may reduce fibre recovery efficiency and deteriorate the quality of recycled pulp (Runte et al., 2015). Therefore, recyclability has become an essential criterion during the design phase of paper-based packaging products. The growing demand for renewable raw materials has stimulated considerable interest in the utilization of agro-industrial by-products as alternative lignocellulosic fibre sources for paper production (Abd El-Sayed et al., 2020). Every year, the agricultural and food industries generate enormous quantities of residues, including grape, banana, coconut, corn, citrus peels and other lignocellulosic wastes that are often disposed of by landfilling or incineration, creating additional environmental burdens. Since these residues contain significant amounts of cellulose and hemicellulose, they represent valuable secondary raw materials that can replace a portion of virgin wood fibres in paper production while simultaneously contributing to waste valorisation and resource efficiency (Alzate Acevedo et al., 2021; Jeetah & Jaffur, 2021; Vallejo et al., 2021). The incorporation of agro-industrial fibres into paper products therefore supports circular economy principles by extending the value chain of agricultural biomass and reducing dependence on forest resources.

Among paper-based packaging products, pressure-sensitive labels (PSLs) represent an important application because they are extensively used in the food, beverage, pharmaceutical and logistics sectors. A pressure-sensitive label typically consists of three functional layers: a facestock, an adhesive layer and a release liner (Kirwan, 2011; Marošević Dolovski, 2016). Although these multilayer structures provide excellent functionality during product use, they also complicate recycling processes (Runte et al., 2015). Adhesives, printing inks and other non-fibrous components may interfere with repulping and deinking, reduce pulp quality and generate contaminants that adversely affect recycled paper production. Consequently, newly developed sustainable label materials should be evaluated not only regarding their functional performance but also with respect to their recyclability.

Recent studies have demonstrated that pressure-sensitive labels manufactured from agro-industrial by-products exhibit promising optical and functional properties while contributing to a reduced environmental footprint. Furthermore, paper products containing agricultural residues have shown potential as sustainable alternatives to conventional wood-based materials (Karlovits et al., 2020; Pogačar & Gregor-Svetec, 2025). However, despite increasing interest in alternative fibre sources, relatively few studies have investigated how these materials behave during recycling processes (Pogačar et al., 2023; Vukoje et al., 2021). Since recyclability is one of the fundamental requirements of circular packaging systems, comprehensive evaluation of recycling performance is necessary before these materials can be widely adopted by industry.

The quality of recycled paper is commonly assessed through laboratory deinking procedures, with flotation representing the most widely applied industrial method for removing hydrophobic ink particles from waste paper (Vukoje & Rožić, 2018). The efficiency of flotation is generally evaluated using optical properties such as ISO brightness, colour coordinates (CIE L*a*b*), opacity and Effective Residual Ink Concentration (ERIC), together with image analysis of residual ink particles. These parameters provide valuable information regarding ink removal efficiency, fibre cleanliness and the overall quality of recycled pulp.

Therefore, the aim of this study was to evaluate the recyclability of pressure-sensitive labels containing agro-industrial by-products originating from citrus grape, and barley residues. Recycling was performed according to the INGEDE Method 11, and the influence of flotation deinking on recycling efficiency was assessed through optical characterization and image analysis of recycled laboratory sheets. The results provide new insights into the suitability of agro-industrial fibre-based pressure-sensitive labels for integration into existing paper recycling systems and contribute to the development of more sustainable packaging materials.

2. Materials and methods

2.1. Pressure-sensitive label materials

Three commercially available paper-based pressure-sensitive labels (PSLs) containing agro-industrial by-products were used in this study. The investigated facestock materials were produced from citrus (C), grape (G) and barley (B) residues. According to the manufacturer's specifications, the facestock consisted of 15% agro-industrial by-products, 40% post-consumer recycled fibres and 45% virgin wood pulp. The citrus fibres originated from residues remaining after juice production, grape fibres from wine production residues, and barley fibres from brewing industry by-products. All label materials were supplied with a glassine release liner (70 g m^{-2}; 61 µm) certified by the Forest Stewardship Council (FSC). The citrus and barley labels were coated with a permanent acrylic emulsion adhesive (S2030), while the grape labels contained a permanent rubber-based hot-melt adhesive (S2047N) (Avery Dennison, Europe). Each label was applied to a cardboard substrate to simulate real packaging conditions, as labels typically enter the recycling stream attached to paper or paperboard packaging.

2.2. Printing procedure

Test samples were printed using a commercial dry-offset printing press designed for pressure-sensitive label production under industrial conditions. A UV-curable warm red offset ink was printed as a full-tone solid on all three label materials. Printing conditions, substrate preparation and curing parameters were maintained constant throughout the experiment to eliminate process-related variability.

2.3. Laboratory recycling

Laboratory recycling was performed according to ISO 21993:2020 standard procedure intended for evaluating the deinkability of printed paper products (ISO, 2020). For each label material, printed samples were manually shredded into small pieces and disintegrated in for 20 min using laboratory disintegrator Enrico Toniolo. Following disintegration, the pulp suspension was homogenized, after which two sets of laboratory sheets were prepared. The first set was produced directly from the pulp suspension without flotation (BF), while the second set was prepared after flotation deinking (F). Flotation was performed in a laboratory flotation cell by introducing air into the suspension, allowing hydrophobic ink particles to attach to air bubbles and be removed as froth. Following flotation, the pulp was homogenized again before sheet formation. Laboratory handsheets with a target grammage of 45 g m^{-2} were prepared using a standard Rapid-Köthen sheet former (ISO 5269- 2, 2004).

2.4. Optical characterization

The recycling efficiency was evaluated by measuring the optical properties of the laboratory sheets obtained from pulp before and after flotation. Measurements were performed using a Technidyne Colour Touch 2 spectrophotometer. ISO brightness (R457) was determined according to ISO 2470 (ISO, 2016), while CIE L*ab** colour coordinates, CIE whiteness were determined according to ISO 11475 and Effective Residual Ink Concentration (ERIC) were determined according to (ISO, 2008) Ten measurements were performed for each sample and the results are reported as the mean value ± standard deviation.

3. Results and discussion

Figure 1 presents representative laboratory handsheets prepared from undeinked (UP) and deinked pulp (DP). Visual examination revealed distinct differences in the morphology of the recycled handsheets. The Citrus samples exhibited uniformly distributed coloured fibres originating from the citrus agro-industrial residues incorporated into the facestock material (Figures 1a and 1b). In contrast, the Barley (Figures 1c and 1d) and Grape samples (Figures 1e and 1f) contained numerous coloured agglomerates that are most likely associated with adhesive-related stickies formed during repulping and insufficiently removed during flotation. These agglomerates were particularly pronounced in the Grape samples, which contained a rubber-based hot-melt adhesive, whereas the Citrus samples showed no comparable adhesive deposits. The observed differences are consistent with the adhesive systems used in the investigated labels. While Citrus and Barley employed the same acrylic emulsion adhesive, Grape contained a rubber-based hot-melt adhesive, which is generally more prone to the formation of larger hydrophobic agglomerates during recycling.



(a)



(b)

» **Figure 1 (part 1):** *Representative handsheets prepared from undeinked and deinked pulps obtained from pressure-sensitive label materials: (a) Citrus – UP; (b) Citrus –DP; (c) Barley – UP; (d) Barley – DP; (e) Grape – UP; (f) Grape – DP*



(c)



(f)



(d)



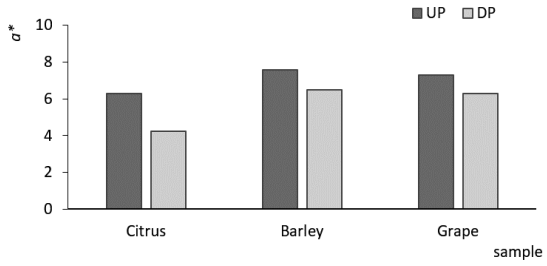
(e)

» **Figure 1 (part 2):** *Representative handsheets prepared from undeinked and deinked pulps obtained from pressure-sensitive label materials: (a) Citrus – UP; (b) Citrus –DP; (c) Barley – UP; (d) Barley – DP; (e) Grape – UP; (f) Grape – DP*

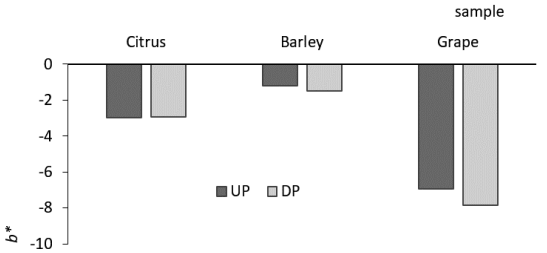
The *a** colorimetric parameter values of the samples produced from undeinked pulp (UP) and deinked pulp (DP) are presented in Figure 2. The positive a values obtained for all samples indicate the presence of a red colour component in the recycled handsheets. Following flotation, the a values decreased for all investigated materials, with the largest reduction observed for citrus. Because the printing ink used in this study was water-based, the decrease in a* should not be interpreted exclusively as the removal of discrete ink particles. During repulping, soluble or finely dispersed colourants may migrate into the fibre network, resulting in partial staining of the cellulose fibres. Consequently, the remaining positive *a** values reflect both residual colourants associated with the fibres and visible coloured contaminants (Vukoje et al., 2021b).

The negative *b** values (Figure 3) indicate a shift toward the blue region of the CIELAB color space. Since the investigated samples were printed with red printing ink and visual assessment confirmed that the papers exhibited a reddish appearance, the observed blue component cannot be attributed to either the printing ink or the inherent color of the paper. Instead, it is most likely associated with the presence of optical brightening agents (OBAs) incorporated into the paper. This interpretation is consistent with our previous study, which demonstrated that the Grape base PSL contained the highest amount of OBAs, followed by Citrus and Barley (Vukoje et al., 2021a). Accordingly, the Grape samples exhibited the most negative *b** values, whereas the Barley samples showed values closest to zero. The agree-

ment between the present and previous findings further supports the contribution of OBAs to the *b** colorimetric parameter and is consistent with the persistence of OBAs in the recycled paper after the deinking process. *The negligible changes in b* after flotation indicate that the optical brightening agents remained associated with the fibre network throughout recycling, as expected for compounds incorporated within the paper structure.

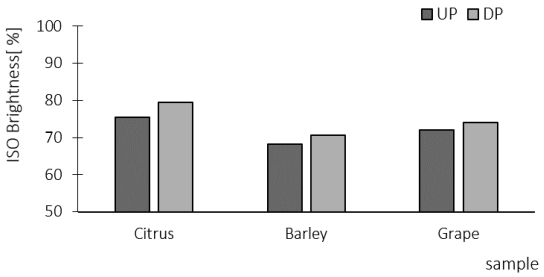


» **Figure 2:** *a* colorimetric parameter of samples obtained from undeinked (UP) and deinked (DP) pulp*



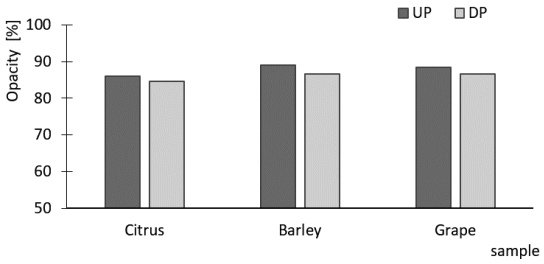
» **Figure 3:** *b* colorimetric parameter of samples obtained from undeinked (UP) and deinked (DP) pulp*

The ISO brightness values (Figure 4) increased for all samples after the deinking process, indicating an improvement in the optical properties of the recycled papers. The increase in ISO brightness is attributed to the removal of the red printing ink during flotation, resulting in higher reflectance at 457 nm. The largest increase was observed for the Citrus sample, which is consistent with the greatest reduction in the **a*** value, suggesting the most effective removal of the red color component. Smaller increases were observed for the Barley and Grape samples, indicating a lower degree of improvement in brightness after deinking. Although ISO brightness increased for all samples after flotation, this increase does not necessarily indicate complete removal of the printing ink. Since water-based colourants may partially stain the fibres, the increase in brightness should rather be interpreted as an overall improvement in optical cleanliness resulting from the removal of coloured contaminants and a reduction in the red colour component.



» **Figure 4:** *ISO Brightness of samples obtained from undeinked (UP) and deinked (DP) pulp*

The opacity values of the papers before and after deinking are presented in Figure 5. A slight decrease in opacity was observed for all samples following the deinking process. The reduction was relatively small, ranging from approximately 1 to 2 percentage points. The decrease in opacity is most likely associated with the loss of mineral fillers during the flotation process. Since fillers contribute significantly to light scattering within the paper structure, their partial removal reduces the opacity of the recycled sheets. Among the investigated samples, Barley exhibited the highest opacity values both before and after deinking, whereas Citrus showed the lowest opacity. The relatively small decrease in opacity indicates that flotation removed only a limited fraction of mineral fillers while preserving the integrity of the fibre network.



» **Figure 5:** *Opacity of samples obtained from undeinked (UP) and deinked (DP) pulp*

To complement the optical measurements, flotation yield was calculated to estimate the amount of material removed during flotation. The flotation yield values are presented in Table 1. The flotation yield was calculated based on the mass of the sample used in the recycling process and the mass of the foam collected as a filter cake on a Büchner funnel. The flotation yield of the samples was calculated using Equation (1):

$$\text{Flotation yield} = \left(1 - \frac{m_p}{m_u}\right) * 100 \qquad (1)$$

Where:

- m_p = mass of the foam, i.e., the filter cake
- m_u = mass of the sample introduced into the recycling process

Table 1
Flotation yield

	C	B	G
m_u, g	100	100	100
m_p, g	25.16	34.20	22.47
Flotation yield, %	74.84	65.80	77.53

Barley exhibited the lowest flotation yield, indicating that the largest amount of material was transferred into the froth fraction. Nevertheless, this was not accompanied by the largest decrease in either the a parameter or ERIC. This suggests that the removed material consisted predominantly of adhesive-derived contaminants, fillers and fines rather than colour-forming components originating from the water-based printing ink. Conversely, Grape exhibited the highest flotation yield but retained the largest number of visible adhesive agglomerates after flotation, indicating that flotation yield alone cannot be used as an indicator of deinking efficiency.

The combined results demonstrate that the recycling behaviour of the investigated labels was governed not only by the printing ink but also by the structural characteristics of the facestock and the adhesive system. The Citrus based PSL material differed fundamentally from the Barley based and Grape based PSL material because the coloured features observed in the recycled handsheets originated predominantly from naturally coloured citrus fibres rather than adhesive-derived contaminants. In contrast, the Barley and Grape based PSL samples contained numerous adhesive-related agglomerates (stickies), indicating that adhesive behaviour during repulping had a greater influence on the visual quality of the recycled sheets than the printing ink itself. These findings demonstrate that visual assessment alone cannot be interpreted as an indicator of residual ink content, since the observed coloured structures originate from different components depending on the investigated label material. Therefore, a comprehensive assessment of recyclability requires the combined interpretation of optical properties, flotation yield and visual examination.

4. Conclusions

The investigated pressure-sensitive labels containing agro-industrial by-products proved compatible with conventional paper recycling by flotation. However, the results demonstrated that the visual appearance of the recycled handsheets was governed by different mechanisms depending on the label material. In Citrus-based labels, the visible coloured structures originated primarily from naturally coloured citrus fibres incorporated into the facestock, whereas the Barley and Grape materials exhibited adhesive-related agglomerates (stickies) remaining after flotation. Furthermore, the water-based printing ink partially coloured the fibre network during repulping, indicating that colourimetric changes cannot be attributed solely to the removal of discrete ink particles. Consequently, the recyclability of agro-industrial pressure-sensitive labels should be evaluated using a combination of optical measurements, flotation yield and visual assessment, while considering the individual contributions of fibres, adhesives and printing ink to the final appearance of the recycled paper.

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6. References

Abd El-Sayed, E. S., El-Sakhawy, M. and El-Sakhawy, M. A. M. (2020) 'Non-wood fibers as raw material for pulp and paper industry', *Nordic Pulp & Paper Research Journal*, 35, pp. 215–230. DOI: 10.1515/npprj-2019-0064

Alzate Acevedo, S., Díaz Carrillo, Á. J., Flórez-López, E. and Grande-Tovar, C. D. (2021) 'Recovery of Banana Waste-Loss from Production and Processing: A Contribution to a Circular Economy', *Molecules*, 26, 5282. DOI: 10.3390/molecules26175282

ISO (2020) *ISO 21993:2020 Paper and pulp — Deinkability test for printed paper products*. Geneva: International Organization for Standardization.

Jeetah, P. and Jaffur, N. (2021) 'Coconut Husk, a Lignocellulosic Biomass, as a Promising Engineering Material for Non-wood Paper Production', *Journal of Natural Fibers*, 00, pp. 1–15. DOI: 10.1080/15440478.2021.1889428

Karlovits, I., Kavčič, U., Lavrič, G., Šinkovec, A. and Zorić, V. (2020) 'Digital printability of papers made from invasive plants and agro-industrial residues', *Cellulose Chemistry and Technology*, 54, pp. 523–529. DOI: 10.35812/CelluloseChemTechnol.2020.54.53

Kirwan, M. J. (2011) 'Paper and Paperboard Packaging'. In: *Food and Beverage Packaging Technology: Second Edition*. pp. 213–250. DOI: 10.1002/9781444392180.ch8

Liu, W., Zhu, Z. and Ye, S. (2023) 'A Framework Towards Design for Circular Packaging (DfCP): Design Knowledge, Challenges and Opportunities', *Circular Economy and Sustainability*. DOI: 10.1007/s43615-023-00264-3

Marošević Dolovski, A. (2016) 'Etikete i etiketiranje', *Print Magazin*, 4.
Meherishi, L., Narayana, S. A. and Ranjani, K. S. (2019) 'Sustainable packaging for supply chain management in the circular economy: A review', *Journal of Cleaner Production*, 237, 117582. DOI: 10.1016/j.jclepro.2019.07.057
Pogačar, A., Bolanča-Mirković, I. and Gregor-Svetec, D. (2023) 'Print Durability and Recyclability of Label Paper Equipped with Printed RFID Antenna', *Sustainability*, 16, 129. DOI: 10.3390/su16010129
Pogačar, A. and Gregor-Svetec, D. (2025) 'Eco-Friendly Design for Sustainable Gift Packaging', *Applied Sciences*, 15. DOI: 10.3390/app15062973
Runte, S., Putz, H.-J., Bussini, D., Limongi, L. and Elegir, G. (2015) 'Recyclability criteria for paper based packaging products', *Cellulose Chemistry and Technology*, 49, pp. 667–676.
Vallejo, M., Cordeiro, R., Dias, P. A. N., Moura, C., Henriques, M., Seabra, I. J., Malça, C. M. and Morouço, P. (2021) 'Recovery and evaluation of cellulose from agroindustrial residues of corn, grape, pomegranate, strawberry-tree fruit and fava', *Bioresources and Bioprocessing*, 8. DOI: 10.1186/s40643-021-00377-3
Vukoje, M., Bolanča Mirković, I., Babić, A. and Majnarić, I. (2021a) 'The influence of labels on paper recycling'. In: Ćorić, D., Šolić, S. and Ivušić, F. (eds.) *Matrib 2021 - Materials, Tribology and Recycling*. Zagreb: Hrvatsko društvo za materijale i tribologiju (HDMT), pp. 487–498.
Vukoje, M., Itrić Ivanda, K., Kulčar, R. and Marošević Dolovski, A. (2021b) 'Spectroscopic Stability Studies of Pressure Sensitive Labels Facestock Made from Recycled Post-Consumer Waste and Agro-Industrial By-Products', *Forests*, 12(12), 1703. DOI: 10.3390/f12121703
Vukoje, M. and Rožić, M. (2018) 'Various valorisation routes of paper intended for recycling – A Review', *Cellulose Chemistry and Technology*, 52, pp. 515–541.



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