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Coffee maceration and resulting side streams: Biological and chemical changes and their circular-economy implications

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ABSTRACT

Coffee processing shapes sensory quality while simultaneously transforming plant biomass and generating side streams that may be valorised. This study evaluates the biological and chemical effects of liquid maceration of coffee beans and discusses the resulting side streams within a circular-economy and environmental-engineering framework. The analysis is based on biological and chemical tests conducted within an industrial research project focused on coffee-bean maceration and processing. The investigated parameters included moisture, acidity, pH, protein, surface fat, caffeine, trigonelline, carboxylic and hydroxycinnamic acids, sugars, melanoidins, brew colour, instrumental aroma and taste, and microbiological quality. Maceration modified the physicochemical profile of the beans: caffeine and trigonelline contents decreased, organic-acid profiles changed, and the processed material remained microbiologically stable. The process should therefore be assessed together with the spent maceration medium and the coffee silverskin generated during roasting. Both streams may contain recoverable compounds or material fractions suitable for further valorisation. Linking bean modification with side-stream management supports cascade use of coffee biomass and provides a basis for further research on extraction, bio-composites and other environmental-engineering applications.

Keywords: coffee maceration, coffee silverskin, circular economy, sustainable processing, environmental engineering.

INTRODUCTION

Coffee is one of the most important plant-based raw materials used in the food industry. However, its importance is not limited to producing the beverage. From a technological perspective, coffee beans are a complex biological matrix containing alkaloids, organic acids, chlorogenic acids, proteins, lipids, sugars, and compounds formed during heat treatment, among other things (Gottstein et al., 2021). Processing methods such as fermentation, drying, roasting and maceration affect the transformation of these ingredients, thereby impacting the quality, durability and potential utility value of the raw material (Głowacka et al., 2018; Hejna, 2020).

In this study, maceration is defined as the process whereby coffee beans come into contact with a liquid medium. This results in a partial transfer of components between the solid and liquid phases, as well as a modification of the biological and chemical profile of the beans. This approach considers maceration not only as a process affecting the properties of the brew but also as a technology modifying the plant matrix. Changes in moisture, pH, acidity, caffeine, trigonelline, organic acids and hydroxycinnamic acids, as well as microbiological parameters, should be analysed together, as these factors determine product quality and process stability.

This is consistent with an approach in which the processing of plant raw materials is evaluated not only in terms of product quality but also

in terms of sustainable biomass use and waste-stream reduction (Lee et al., 2023; Bondam et al., 2022). This also applies to the coffee sector, where numerous by-products are produced alongside the main product, including husks, pulp, spent coffee grounds, technological wastewater and coffee silverskin. The coffee silverskin is a thin layer that covers the coffee bean and mainly separates during roasting. Accounting for around 4.2% of the weight of coffee beans, it has a relatively low moisture content and can therefore be stored more easily than many other coffee industry by-products (Hejna, 2020; Marzorati et al., 2023).

Coffee silverskin contains a lignocellulosic fraction, fibre, protein, and bioactive compounds, including caffeine, chlorogenic acids, and other phenolic compounds (Gottstein et al., 2021; Hejna, 2020). Consequently, coffee silverskin can be considered not only a roasting by-product but also a potential source of active ingredients and filler for bio-composites. It can also be used as a component of polymeric materials and as an additive in wood-based materials. Furthermore, it can be used as a sorbent and a substrate for thermochemical processing (Hejna, 2020; Wronka et al., 2025).

Including coffee silverskin in the broader evaluation of the maceration process is environmentally justified. The technological processes of maceration, drying and roasting generate the final product as well as by-products such as spent maceration medium, losses of soluble substances, technological deposits, and the coffee silverskin fraction formed during roasting. From a circular economy perspective, it is crucial that these fractions are not solely treated as waste, but rather as a potential source of valuable compounds or raw materials.

This approach is consistent with environmental engineering research into the management of coffee roasting by-products, including coffee silverskin. It combines the findings of the coffee maceration project by taking a broader view of how coffee biomass can be used to produce biodegradable materials and bio-composites.

Despite the growing body of literature on coffee silverskin valorisation, little information is available on whether pre-roasting liquid maceration influences the properties of silverskin subsequently generated during roasting. Therefore, the present study combines experimental observations on coffee maceration with a literature-based discussion of potential side-stream utilisation pathways and proposes directions for further research.

PROBLEM ANALYSIS

Post-harvest coffee processing is now recognised as a series of controlled biological and physicochemical transformations rather than simply a sequence of cleaning and drying operations. A review of coffee fermentation demonstrates that process conditions, water availability, oxygen exposure and microbial activity can alter the organic-acid profiles, the chemistry of precursors and sensory development. Process control is therefore essential for reproducibility and safety (Ferreira et al., 2023). Liquid maceration differs from conventional coffee fermentation because it can be designed as a direct mass-transfer operation between the bean matrix and an external medium. Nevertheless, both approaches demonstrate that pre-roast treatment can substantially influence the chemical state of green coffee prior to thermal processing.

At the same time, coffee processing generates several biomass fractions, the management of which determines the overall efficiency of the production chain. Coffee silverskin is the dry lignocellulosic layer released during roasting and has been investigated as a source of fibre, phenolic compounds and caffeine, as well as for use as a filler or feedstock in the production of bio-based materials (Nolasco et al., 2022; Bianchi et al., 2024). Case studies and life-cycle assessments indicate that valorising silverskin can enhance the environmental performance of certain applications, in the scenarios evaluated. However, the extent of the improvement depends on the reference scenario, system boundaries and processing requirements (Overturf et al., 2021; Ansanelli et al., 2023). These findings support a cascade approach, whereby valuable compounds are recovered first, and the remaining solid fraction is then used for material or energy applications.

A relevant knowledge gap remains at the interface between pre-roast bean modification and subsequent side-stream properties. Most published studies consider coffee bean processing and coffee-silverskin valorisation separately. Consequently, there is limited evidence on whether liquid maceration of green coffee beans alters the composition, surface properties or processing behaviour of the silverskin produced during roasting. This study therefore interprets the available biological and chemical results not only in terms of product quality but also as a basis for identifying side streams requiring further environmental and material characterisation.

Research aim

This study aimed to evaluate the biological and chemical effects of coffee bean maceration and to determine its potential contribution to the sustainable use of coffee raw materials and by-products.

More specifically, the objectives were to assess the effects of maceration and subsequent heat treatment on selected physicochemical parameters of coffee beans and brews; analyse changes in selected bioactive compounds, including caffeine, trigonelline and hydroxycinnamic acids; evaluate microbiological quality after processing; identify the main side streams generated during maceration and roasting; and place the results within the broader context of coffee-silverskin valorisation in environmental engineering.

Neither the spent maceration medium nor coffee silverskin were directly characterised within the analytical programme; both streams are discussed as potential research objects arising from the observed changes in coffee beans.

MATERIALS AND METHODS

The research material comprised coffee samples obtained within a project implemented by Grupa Buena Sp. z o.o. Biological and chemical analyses were performed at the Faculty of Biotechnology and Food Sciences of Lodz University of Technology as part of project POIR.01.01.01-00-1066/20. The dataset included green coffee, macerated and dried coffee, and coffee roasted after maceration (Lodz University of Technology, 2022). Additional results for green and roasted coffee obtained during the subsequent research stage were also included (Lodz University of Technology, 2023).Maceration was performed on 1000 g batches of green Guatemalan coffee beans (Santa Rosa, European Preparation), which were washed before maceration. Three maceration media were used: semi-dry white wine and semi-dry red wine from a local producer, and a dried-fruit infusion prepared by steeping dried fruit in water at 90 °C for 10 min and then cooling it. The volume ratio of beans to maceration liquid was 1:10. Each cycle comprised 30 min of heating to 50 °C, maceration at 50 °C for 2 h (or 4 h in one white-wine variant) and 30 min of cooling, with 1 min of mixing every 5 min. After maceration, the beans were rinsed, dried at 50 °C for 7 h and roasted in a ROEST S100 sample roaster (batch capacity 50–120 g). The analysed variants were coded 171221/G/WB/2H (white wine, 2 h), 231221/G/WC/2H (red wine, 2 h), 120122/G/SZ/2H (dried-fruit infusion, 2 h) and 070122/G/WB/4H (white wine, 4 h; roasted beans only). A non-macerated roasted control was not included in the 2022 analytical set; roasted macerated samples are therefore compared with green coffee.

For analytical preparation, 250 g batches of coffee beans were ground and sieved to obtain particles in the 480–680 µm range. Brews were prepared using 7 g of ground coffee and 100 mL of water at 95 °C (Lodz University of Technology, 2022; Lodz University of Technology, 2023). The analytical programme covered moisture content, acidity, pH value, protein content, surface fat content, brew colour, caffeine content, trigonelline, carboxylic and hydroxycinnamic acids, sugars, melanoidins, myo-inositol phosphates, instrumental aroma and taste, and microbiological quality.

Moisture content was determined using the gravimetric oven-drying method. The total acidity of the brews was determined by potentiometric titration to pH 8.2, and the pH was measured using a pH meter. Protein content was determined using the Kjeldahl method. Caffeine and trigonelline were analysed using ultra-high-performance liquid chromatography coupled with electrospray ionisation mass spectrometry (UHPLC-ESI-MS). Brew colour was measured in the CIE L*a*b* colour space, where L* represents lightness and a* and b* axes represent the green–red and blue–yellow dimensions, respectively (Lodz University of Technology, 2022; Lodz University of Technology, 2023).

Hydroxycinnamic acids, carboxylic acids (acetic, lactic, malic and citric) and myo-inositol hexaphosphate were determined by UHPLC-ESI-MS. Sugars (fructose, glucose and sucrose) were determined by HPLC with refractive-index detection using a Rezex RPM-Monosaccharide Pb^{2+} column. Maillard reaction products were assessed as acrylamide and 5-hydroxymethylfurfural (UHPLC-ESI-MS) and as brew absorbance at 420 nm. Surface fat was determined extraction-gravimetrically (Soxhlet extraction with hexane) as the fat residue collected from the grinder after grinding 10 g of beans. Aroma was analysed with a HERACLES electronic nose (Alpha MOS, Toulouse, France) and taste with an ASTREE electronic tongue (Alpha MOS), with taste intensity expressed on a 0–12 scale.

Microbiological analyses comprised the total mesophilic bacterial count (PN-EN ISO 4833-1), Escherichia coli (PN-ISO 16649-2), yeasts and moulds (PN-ISO 21527-1), coagulase-positive staphylococci (PN-EN ISO 6888-2) and sulphite-reducing bacteria (PN-ISO 15213), with samples prepared according to PN-EN ISO 6887 (Lodz University of Technology, 2022; Lodz University of Technology, 2023).

All determinations were performed in triplicate, and the results are expressed as mean ± standard deviation. Inferential statistical tests were not performed; differences between samples are therefore discussed descriptively.

For the purposes of this article, the analytical framework was extended to identify process side streams. The main streams considered were the spent maceration medium, which may contain compounds transferred from the beans to the liquid phase, and coffee silverskin produced during roasting. Their potential valorisation requires further chemical, material and environmental assessment.

The analytical scope and its relationship to the identified process side streams are summarised in Table 1.

RESULTS AND DISCUSSION

The available results demonstrate that coffee maceration affects several biological and chemical parameters. The following subsections discuss changes and their implications for process control, resource efficiency and side-stream management.

Moisture as a technological and environmental parameter

The moisture content of coffee beans is a key parameter governing the stability, storage and microbiological safety of the raw material, as well as the energy demand of subsequent processing. Green coffee had a moisture content of 10.67 ± 0.92 g/100 g. After maceration and drying, moisture ranged from 6.90 to 9.91 g/100 g, whereas coffee roasted after maceration contained 4.20–5.54 g/100 g (Lodz University of Technology, 2022).

From a sustainable processing perspective, optimising the post-maceration drying stage is important because this stage is energy intensive. Therefore, the target moisture content should reflect the intended downstream handling of the beans. Material intended for immediate roasting may not require the same degree of drying as material intended for longer storage, as excessive drying can increase energy use without providing a proportional technological benefit; this energy trade-off remains to be tested. In the context of waste streams, the moisture content of coffee silverskin is also important. The coffee silverskin formed during roasting has a relatively low moisture content. Compared to waste from wet coffee processing, this reduces the risk of rapid spoilage and the need for energy-intensive drying prior to further use (Hejna, 2020; Marzorati et al., 2023). If the coffee has been macerated beforehand, it would be sensible to check whether this affects the silverskin moisture content, composition, and susceptibility to further processing. The moisture results for green, macerated and roasted coffee samples are summarised in Table 2.

Table 1. The scope of biological and chemical analyses and the connection with the assessment of process side streams (Lodz University of Technology, 2022; Lodz University of Technology, 2023)

Parameters	Example parameters	Importance for process evaluation	Related side stream
Physicochemical parameters	Moisture content, pH, acidity, colour CIE L*a*b*	Stability of the raw material, process flow, batch repeatability	Spent maceration medium; silverskin after roasting
Chemical composition	Protein, surface fat, sugars, melanoidins	Evaluation of transformations occurring during maceration, drying and roasting	Sediments, surface fat, fractions separated during roasting
Bioactive compounds	Caffeine, trigonelline, carboxylic and hydroxycinnamic acids	Assessment of the bio-chemical profile of the coffee matrix	Potential value of spent maceration medium and silverskin as sources of extracts
Instrumental assessment	Aroma and taste by instrumental methods	Identification of technological effects in the final product	Reduction of defective batches and raw material losses
Microbiology	Total bacterial count, fungi, *E. coli*, staphylococci, sulfate-reducing bacteria	Process safety and reduction of production losses	Reduced risk of disposing of rejected or contaminated fractions

Note: own study based on (Lodz University of Technology, 2022; Lodz University of Technology, 2023).

Acidity and pH as indicators of chemical change

The pH and acidity of coffee brews are useful indicators of the transformations that occur in coffee beans and of the quality of the final product. In a 2023 study, the pH was found to be 6.48 ± 0.39 for green-coffee brews and 5.08 ± 0.24 for roasted-coffee brews (Lodz University of Technology, 2023). The total acidity was found to be 7.48 ± 0.30 mL of 1 mol L^{-1} NaOH per 100 g for green coffee, compared to 15.18 ± 0.44 mL of 1 mol L^{-1} NaOH per 100 g for roasted coffee. This increase after roasting is consistent with the formation and transformation of acidic compounds during thermal processing (Lodz University of Technology, 2023). In the 2022 dataset, brew pH ranged from 5.40 to 6.51; green coffee had the highest pH, while maceration reduced it to 5.52–6.20 (Lodz University of Technology, 2022).

From an environmental perspective, pH and acidity levels are key indicators of the production process's effectiveness. A stable maceration and roasting process reduces the number of batches that do not meet quality requirements and consequently reduces losses of raw materials, energy and packaging materials. At the same time, the change in acidity means that some compounds can pass into the maceration medium. This medium should therefore be considered a potential secondary stream rather than merely process wastewater. The acidity of coffee silverskin and the presence of phenolic compounds may be relevant for downstream material applications, as these constituents can influence antioxidant activity and interactions with polymer matrices (Głowacka et al., 2018; Hejna, 2020).

Table 2. Moisture content of green, macerated and roasted coffee beans (Lodz University of Technology, 2022)

Sample	Sample type	Moisture content [g/100 g]
1	Green coffee	10.67 ± 0.92
2	Macerated coffee	9.20 ± 0.80
3	Coffee roasted after maceration	4.20 ± 0.31
4	Macerated coffee	9.91 ± 0.25
5	Coffee roasted after maceration	5.54 ± 0.27
6	Macerated coffee	6.90 ± 0.17
7	Coffee roasted after maceration	4.42 ± 0.48
8	Coffee roasted after maceration	4.59 ± 0.33

Note: own study based on (Lodz University of Technology, 2022).

Changes in caffeine and trigonelline

Caffeine and trigonelline are two characteristic coffee constituents contributing to its biological, sensory and technological properties. In the 2022 study, green coffee contained 4.22 ± 0.13 g/100 g dry matter (d.m.) caffeine. After maceration, the caffeine content was 3.94–3.98 g/100 g d.m., i.e. approximately 5.7–6.6% lower than in green coffee (Lodz University of Technology, 2022). Trigonelline also decreased during processing. Green coffee contained 0.96 ± 0.02 g/100 g d.m. and after maceration, the values ranged from 0.71 to 0.79 g/100 g d.m. A further decrease was observed in some roasted samples (Lodz University of Technology, 2022). In the 2023 study, caffeine decreased from 3.44 ± 0.01 to 3.12 ± 0.01 g/100 g, while trigonelline decreased from 0.83 ± 0.01 to 0.31 ± 0.01 g/100 g after roasting (Lodz University of Technology, 2023). From a sustainable technology perspective, it is important that the maceration process did not completely degrade the key coffee compounds but rather modified them partially. At the same time, the observed changes suggest that some components may have been transferred to the maceration medium, although direct chemical analysis of the liquid phase was not available in the present dataset. The liquid remaining after maceration may contain caffeine, trigonelline and phenolic compounds. In a circular economy model, this liquid should therefore be considered a potential source of extracts or a substrate for further processes rather than being dismissed as waste. A similar approach applies to coffee silverskin. The literature indicates that contains caffeine, chlorogenic acids, caffeic acid, ferulic acid, gallic acid and other antioxidant-active compounds (Głowacka et al., 2018; Hejna, 2020). They can therefore act as a solid carrier for active ingredients associated with the chemical profile of the coffee bean.

Organic and hydroxycinnamic acids

Organic and hydroxycinnamic acids are important compounds that influence the biological and chemical profile of coffee. A 2022 study found that the maceration process increased the content of acetic and lactic acids in green coffee

beans, and that this was linked to the presence of these organic acids in the maceration media. The green coffee beans contained practically no acetic or lactic acid. Roasting macerated coffee beans decreased the acetic acid content in all maceration variants, while increasing the lactic acid content compared with the corresponding macerated coffee beans before roasting, particularly in macerated beans in a dried fruit infusion (Lodz University of Technology, 2022).

The 2023 study found that green coffee had a high total chlorogenic acid content of 15.24 ± 0.15 g/100 g, whereas roasted coffee contained 8.74 ± 0.05 g/100 g. This reduction was explained by the partial thermal degradation of polyphenols during roasting (Lodz University of Technology, 2023). These results are important for assessing coffee quality and for developing a broader understanding of coffee biomass as a source of bioactive compounds.

Phenolic compounds are also present in coffee silverskin, with their content varying depending on the coffee species, processing method and roasting temperature (Gottstein et al., 2021; Hejna, 2020). Marzorati et al. demonstrate the possibility of the targeted valorisation of the polar fraction of coffee silverskin using supercritical CO_2 with ethanol as a co-solvent, thereby reducing the need for traditional organic solvents (Marzorati et al., 2023).

Taken together, these findings support the concept of cascade processing: first, the coffee bean is modified and characterized; second, compounds that may have been transferred to the spent maceration medium could potentially be recovered for further utilisation; however, direct verification requires chemical characterisation of the liquid phase.

Brew colour as an indicator of technological change

The colour of the infusion is the result of various transformations that occur during coffee processing. These include the Maillard reaction, the oxidation of phenolic compounds, and the formation of browning products. In the results of the 2022 study, the L* parameter, which determines brightness, took values ranging from 34.37 to 81.36. The lowest value, i.e. the darkest colour, was recorded for coffee infusions roasted after maceration in red wine, while the highest value was recorded for green coffee macerated in white wine. Brews prepared from all macerated beans were lighter than the brew prepared from green coffee (L* = 71.65) (Lodz University of Technology, 2022).

The observed colour changes suggest that transformations of chromophoric compounds occurred during maceration and subsequent processing. These changes may reflect transformations of coloured compounds; the underlying reactions were not determined in the reported analyses (Lodz University of Technology, 2022). From a technological perspective, colour can be considered a rapid indicator of the transformations occurring in the bean. From an environmental perspective, a stable and predictable process minimises defective batches and reduces the risk of losses relating to raw materials, energy and labour.

The colour and products of the browning reaction are also important for side streams. For example, coffee silverskin, which separates during roasting, can contain thermal reaction products and phenolic compounds. These components may affect the antioxidant properties and colour of bio-composites, as well as their interactions with polymeric or lignocellulosic matrices (Hejna, 2020; Wronka et al., 2025).

Maceration also changed the sugar profile of the beans. Green coffee contained 6.47 ± 0.54 g/100 g of total sugars, mainly sucrose (6.09 ± 0.57 g/100 g). After maceration and drying, total sugars increased to 8.65–10.10 g/100 g, mainly because of higher fructose (1.18–2.48 g/100 g) and glucose (1.53–3.40 g/100 g) contents taken up from the maceration media, whereas after roasting they ranged from 5.52 to 6.38 g/100 g. Acrylamide and 5-hydroxymethylfurfural were not detected in green coffee; roasted samples contained 2.95–6.84 µg/100 g of acrylamide and 0.07–0.24 mg/100 g of 5-hydroxymethylfurfural, with the lowest 5-hydroxymethylfurfural content after maceration in red wine. The content of myo-inositol hexaphosphate increased from 46.03 ± 0.45 mg/100 g in green coffee to 94.44–105.35 mg/100 g after maceration in wine, but remained similar after maceration in the dried-fruit infusion (48.21 ± 8.75 mg/100 g) (Lodz University of Technology, 2022).

Instrumental analyses showed that maceration also modified the aroma and taste of the brews. In the volatile profile determined with the electronic nose, ethanol accounted for 15% of the volatile fraction in green coffee, 87–88% after maceration in wine and 55–60% after subsequent roasting. Roasting increased the share of furfuryl alcohol, and 1-methylpyrrole was detected only in roasted

samples. In the electronic-tongue analysis, the green-coffee brew was dominated by saltiness (10.0 on the 0–12 scale), whereas roasted macerated samples showed sourness of 6.8–8.5, umami of 7.4–7.7, bitterness of 6.3–8.6 and sweetness of 6.2–8.6 (Lodz University of Technology, 2022).

Protein, surface fat and process stability

The protein content of coffee beans is important because amino acids are the precursors to the aromatic compounds formed during roasting, such as pyrazines and pyrroles. A 2023 study found that the protein content of green coffee beans was 12.84 ± 0.82 g/100 g, compared with 13.28 ± 0.27 g/100 g after roasting; the difference lies within the standard deviation. The slightly higher value after roasting is consistent with water loss during roasting, which concentrates protein in the beans (Lodz University of Technology, 2023).

Surface fat is of technological importance because it can accumulate on grinding equipment. The study found that the amount of surface fat residue on grinder elements relative to the weight of ground coffee was 0.04 g/100 g for raw coffee and 0.25 g/100 g for roasted coffee (Lodz University of Technology, 2023). Grease build-up can necessitate more frequent cleaning of equipment and increase the consumption of detergents, water and energy. Therefore, assessing surface fat can inform the design of a more efficient, less resource-intensive production process.

This is particularly relevant in the context of coffee silverskin, as it contains not only the fibrous fraction, but also proteins, lipids, and phenolic compounds. The literature emphasises that the content of proteins and functional groups can affect interfacial adhesion in composites and that the chemical composition of silverskin can determine the mechanical properties of materials (Hejna, 2020; Wronka et al., 2025).

Microbiological quality and loss reduction

Ensuring microbiological safety is essential for both product quality and resource efficiency, as unstable or contaminated batches result in avoidable losses of raw materials, energy and packaging. The 2023 study found that the total bacterial count was 1.5 ± 0.3 × 10^2 colony-forming units per gram (CFU/g) in green coffee and 30 ± 5 CFU/g in roasted coffee. The total counts of fungi and *Escherichia coli* were both below 10 CFU/g (Lodz University of Technology, 2023).

The macerated coffee study also indicated very good microbiological quality. The total bacterial count decreased from (1.5 ± 0.2) × 10^4 CFU/g in green coffee to 80 ± 10 CFU/g after maceration in the dried-fruit infusion and to below 10 CFU/g after maceration in wine and after roasting. Coagulase-positive staphylococci and sulphite-reducing bacteria were below 10 CFU/g in all samples. Neither fungi, including potentially toxigenic moulds, nor Escherichia coli were detected; their levels were below the respective detection limits (Lodz University of Technology, 2022). These results suggest that maceration, drying and roasting can be performed in a way that maintains microbiological stability.

Microbiological safety is not just a parameter of food quality. It is also an element of efficient resource management, as a stable process reduces rejects, raw material and energy losses, and the need to dispose of contaminated batches. In the case of coffee silverskin, its low moisture content and limited perishability mean that it can be accumulated as a raw material, provided that appropriate hygiene and storage conditions are maintained (Hejna, 2020).

Coffee maceration in the sustainable use of coffee raw materials

The results highlight several ways in which coffee maceration could contribute to the more sustainable processing of coffee biomass.

Firstly, maceration allows the bean matrix to be modified in a controlled manner, including partial reductions in caffeine and trigonelline, changes in the profile of organic acids, and changes in colour and sensory parameters. Therefore, it should be considered a processing operation that modifies the plant matrix rather than simply a flavouring step.

Secondly, the results emphasise the importance of optimising the drying process. As this stage is energy intensive, the target moisture content should be selected according to how the coffee will be handled afterwards. Beans intended for immediate roasting may require a different endpoint to material intended for storage, creating an opportunity to avoid unnecessary energy use.

Thirdly, the good microbiological quality observed after maceration and roasting indicates that the process can be conducted without

compromising microbiological safety. From a resource-efficiency perspective, this reduces the risk of batch rejection due to microbiological instability.

Fourthly, maceration produces a liquid side stream that may contain leached bioactive compounds. Rather than classifying this stream solely as process wastewater, its chemical composition should be analysed to determine whether valuable compounds can be recovered or whether the liquid can be further utilised within a circular-economy framework.

Fifthly, roasting releases coffee silverskin. When maceration precedes roasting, a key research question is whether prior contact with the liquid medium changes the composition, surface properties or processing suitability of this by-product. This establishes a direct link between the maceration project and further environmental and materials research.

The principal technological, environmental and side-stream implications of the results are summarised in Table 3.

Valorisation of coffee silverskin after roasting

Although this article primarily focuses on coffee maceration, its findings should be interpreted within the broader context of coffee biomass utilisation. Coffee silverskin is the dry outer layer released from the bean during roasting and is therefore a directly recoverable roasting by-product. Its relatively low moisture content and chemical composition support investigation of cascade valorisation in environmental and materials engineering (Gottstein et al., 2021; Bianchi et al., 2024). This by-product contains bioactive compounds associated with the coffee matrix, including caffeine, chlorogenic acids, caffeic acid, ferulic acid, gallic acid and flavonoids (Głowacka et al., 2018; Hejna, 2020). The literature also reports a high fibre content, predominantly insoluble, together with a significant protein content, which supports its potential use as a filler in bio-composites (Hejna, 2020).

From an environmental engineering perspective, coffee silverskin can be used in a variety of applications. The first is the recovery of bioactive compounds, particularly phenols and chlorogenic acids. Using supercritical CO_2 with ethanol as a co-solvent reduces the need for traditional solvents and is part of the green extraction concept (Marzorati et al., 2023). Secondly, silverskin can be used as a filler in polymeric materials, acting as a lignocellulosic additive and potential antioxidant stabiliser (Hejna et al., 2021). A third potential application is in wood-based and building materials. Studies on using coffee silverskin as an alternative filler in plywood production have shown that adding small amounts of 1–5% can improve mechanical properties, whereas adding larger amounts can reduce bond strength (Wronka et al., 2025). While this suggests that silverskin has potential applications, its proportion, particle size, moisture content and compatibility with the matrix require optimisation.

Other potential applications discussed for coffee by-products include biomaterials, biochar and recovery of functional compounds (Lee et al., 2023; Nolasco et al., 2022). Food applications of silverskin have also been investigated (Franca et al., 2024). The priority for the current maceration project is to determine whether the silverskin

Table 3. Interpretation of coffee-maceration results in technological, environmental and side-stream terms

Results area	Technological conclusion	Environmental significance	Direction of side-stream development
Moisture	Drying conditions determine the stability of the semi-finished product	Reduce energy consumption	Silverskin moisture control before storage and processing
pH and acidity	Maceration and roasting change the acid profile	Fewer defective batches thanks to process control	Evaluation of liquids after maceration as a potential source of soluble compounds
Caffeine and trigonelline	Partial transfer or degradation of compounds	Potential for recovery from the maceration medium	Analysis of the medium after maceration and silverskin fraction as sources of bioactive compounds
Phenolic acids	Roasting affects the degradation of some polyphenols	Protection and recovery of bioactive compounds	Green extraction from silverskin, e.g. sc-CO_2 with a co-solvent
Microbiology	Safe and stable product	Reduction of batch losses and disposal	Verification of hygienic conditions for silverskin collection and storage after roasting

produced from pre-macerated coffee beans differs from that produced from non-macerated coffee beans. Further work should therefore compare their chemical composition, thermal properties, morphology, sorption capacity and behaviour during bio-composite processing. The principal valorisation pathways considered for coffee silverskin are presented in Figure 1.

Potential coffee-silverskin valorisation routes and the corresponding research needs are summarised in Table 4.

Conceptual framework for sustainable processing of macerated coffee

The results support a conceptual framework for sustainable processing that incorporates bean maceration alongside the analysis of the spent medium, post-maceration drying and roasting, microbiological verification, the recovery and characterisation of coffee silverskin, and the subsequent evaluation of potential valorisation pathways. In this model maceration is just one stage in a wider coffee biomass management system.

From an environmental perspective, process performance should be assessed not only in terms of final-product quality but also in terms of raw material efficiency, energy demand and the fate of by-products. This shifts the process from a linear production model towards the cascade valorisation of coffee biomass. The magnitude of any environmental benefits should then be verified through mass, energy and life-cycle assessments.

The proposed sustainable processing sequence and its associated side streams are summarised in Table 5.



Figure 1. Potential applications of coffee silverskin in environmental engineering and the circular economy

Table 4. Potential coffee-silverskin valorisation pathways associated with the maceration project

Direction of use	Justification	Environmental significance	Link to further research
Bioactive extracts	Presence of caffeine, chlorogenic acids and phenols	Recovery of valuable compounds from waste	Comparison of silverskin from macerated and non-macerated coffee
Bio-composites and polymers	Lignocellulosic fraction, fibre, protein, antioxidants	Reduction of the share of petrochemical raw materials	Granulation, compatibilisation and degradation resistance testing
Wood-based materials	Possibility of partial replacement of traditional fillers	Valorisation of roasting by-products	Optimisation of the 1–5% addition level and moisture content
Sorbents and biochar	Porous lignocellulosic biomass	Potential water purification, pollution retention	Evaluation of specific surface area and sorption capacity after treatment
Biodegradable pots and films	Can be combined with biopolymers and plasticisers	Reduction of plastic waste	Mechanical testing, biodegradation, LCA

Table 5. Sustainable coffee processing model based on maceration and further valorisation of biomass

Process stage	Technological importance	Emerging side stream	Environmental significance
Bean maceration	Chemical profile modification, partial transfer of compounds	Maceration medium	Potential recovery of soluble compounds
Drying after maceration	Stabilisation of the semi-finished product	Water vapour, possible volatile losses	Optimisation of energy consumption
Roasting	Shaping aroma, colour and acidity	Coffee silverskin, volatile roasting products	Use of dry roasting fraction
Microbiological assessment	Product safety	Reduction in rejected batches	Reduced waste generation and disposal
Analysis of side streams	Identification of valuable fractions	Spent maceration medium, silverskin	Circular economy
Research on coffee silverskin	Development of biomaterials and bio-composites	Lignocellulosic fraction after roasting	Reduction of roasting waste

CONCLUSIONS

The available analytical results indicate that coffee maceration may modify plant biomass, affecting physicochemical parameters, selected bioactive compounds, brew colour and microbiological stability.

The analysed data indicate a slight decrease in caffeine and trigonelline levels during maceration and subsequent processing. The observed reductions in selected compounds suggest that the spent maceration medium may contain transferred bioactive constituents; however, direct confirmation requires dedicated chemical analysis of the liquid stream. Post-maceration drying is an important environmental and technological stage because the energy required depends on the target moisture content and the intended subsequent handling. Optimising this step could enhance process efficiency, though the environmental benefits would require confirmation through energy and life-cycle assessments. The analysed samples exhibited good microbiological quality consistent with the reported detection limits, with no Escherichia coli or fungi detected in the available datasets. Stable processing may therefore reduce the risk of rejected batches and associated material losses.

The coffee silverskin produced during roasting should be treated as a potentially valuable lignocellulosic by-product. The literature supports its use in the recovery of bioactive compounds, the production of polymers and wood-based composites, the manufacture of biomaterials and biochar, and in sorption applications. However, its suitability depends on its composition, moisture content, particle size and the requirements of the subsequent processing stage.

A key research priority is the direct characterization of both principal side streams generated during coffee maceration and roasting, namely the spent maceration medium and coffee silverskin. Future studies should quantify stream volumes and mass balances and compare the chemical composition, morphology, thermal behaviour and material-processing properties of silverskin obtained from macerated and non-macerated coffee beans.

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