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TECHNICAL FRAMEWORK FOR SUSTAINABLE VALORIZATION OF VINEYARD BY-PRODUCTS THROUGH SMALL-SCALE PROCESSING TECHNOLOGIES

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Abstract

The management of vineyard by-products represents an important environmental challenge in viticultural regions, where large quantities of organic residues are generated annually. From an environmental engineering perspective, the sustainable valorization of these by-products offers significant opportunities for reducing waste streams while improving resource efficiency. This paper proposes a technical framework for the sustainable valorization of vineyard by-products through the implementation of small-scale processing technologies. The framework integrates engineering criteria such as processing efficiency, energy demand, and technological adaptability with environmental considerations including waste reduction, resource recovery, and alignment with circular economy principles. The proposed approach is illustrated through a representative application scenario focusing on grape seed processing for oil production, highlighting the potential of small-scale technologies to convert viticultural residues into value-added products. The results emphasize the role of appropriately selected processing technologies in minimizing environmental pressure associated with vineyard waste and supporting sustainable agricultural systems. The framework provides a structured basis for further applied research and technology development in viticulture-related waste management.

Key words*: environmental engineering, grape seed valorization, sustainable processing, vineyard by-products, waste reduction.*

INTRODUCTION

The expansion of the global wine industry has led to a substantial increase in the generation of organic residues, particularly vineyard by-products such as grape pomace, stalks, and lees. These materials, which may account for up to 30% of the initial processed grape mass, represent a significant environmental challenge due to their high organic content and rapid biodegradability (Bustamante et al., 2008; Nirmal et al., 2025).

The accumulation of such residues, especially during harvest seasons, creates pressure on local waste management systems and raises concerns related to greenhouse gas emissions, soil contamination, and inefficient resource utilization (Moletta, 2005; Beres et al., 2017). Romania ranks among the top ten wine-producing countries in the European Union, with approximately 180,000 hectares of vineyard area and an annual wine production exceeding 4 million hectolitres (OIV, 2023). This production volume generates substantial quantities of grape pomace estimated at over 150,000 tons per year, the management of which represents a persistent challenge for small and medium-sized wine producers, particularly in viticultural regions such as Muntenia, Moldova, and Oltenia where processing infrastructure remains limited.

From an environmental engineering perspective, the management of vineyard by-products requires a transition from conventional disposal practices to integrated valorization strategies. Traditional approaches, including composting, distillation, or uncontrolled land spreading, often fail to fully exploit the resource potential of these materials and may generate secondary environmental impacts if not properly controlled (Negro et al., 2003; Provenzano et al., 2024). In addition, the high moisture content and biochemical activity of grape pomace can accelerate fermentation processes, leading to greenhouse gas emissions and the formation of leachates containing organic acids and phenolic compounds (Dwyer et al., 2014; Teixeira et al., 2014).

Recent advances in circular economy research emphasize the importance of transforming agri-food residues into value-added products, thereby reducing waste streams and improving overall system efficiency (Galanakis, 2012; Mirabella et al., 2014). In the context of viticulture, vineyard by-products are increasingly recognized as a source of valuable compounds, including lipids, polyphenols, dietary fibers, and antioxidants, which can be recovered through appropriate processing technologies (Rockenbach et al., 2011; Fontana et al., 2013). Such approaches contribute not only to waste reduction but also to the development of sustainable bio-based value chains aligned with European circular economy policy objectives (Puglia et al., 2021; Abbate et al., 2025).

Grape pomace, the main residue of the winemaking process, consists of seeds, skins, and stems that retain a significant fraction of the original grape constituents after juice extraction. Its composition varies depending on grape variety, climatic conditions, and processing techniques, but consistently includes compounds with high industrial and nutritional value (Pardo et al., 2009; Martin et al., 2020). Among these fractions, grape seeds are of particular interest due to their oil content, typically ranging from 8% to 15% on a dry matter basis, and the presence of bioactive molecules with antioxidant properties (Malićanin et al., 2014; Kapcsándi et al., 2021). These characteristics make grape seeds suitable for valorization through mechanical or physico-chemical extraction processes, with cold-pressed grape seed oil increasingly recognized as a high-value functional food ingredient.

Various technological pathways have been explored for the recovery of valuable compounds from vineyard residues, including solvent extraction, supercritical fluid extraction, enzymatic treatment, and mechanical pressing (Passos et al., 2010; Mushtaq et al., 2020). While these methods demonstrate high recovery efficiencies under controlled conditions, their implementation is often limited to industrial-scale operations requiring significant capital investment, energy input, and specialized infrastructure (Cerutti et al., 2013; Spigno et al., 2017). Consequently, their applicability in small and medium-sized vineyards remains restricted, and access to valorization technologies for farm-level operators continues to be a barrier to sustainable by-product management.

In contrast, small-scale processing technologies offer a promising alternative by enabling decentralized valorization directly at the source of biomass generation. Such systems can reduce transportation requirements, lower associated emissions, and facilitate the integration of valorization processes into local agricultural practices (Laufenberg et al., 2003; Ahmad et al., 2020). Mechanical screw pressing, for example, represents a relatively simple and energy-efficient method for oil extraction that can be adapted to farm-level applications without the use of chemical solvents, with specific energy consumption values reported below 0.15 kWh per kilogram of processed seeds under optimized conditions (Kamal-Eldin, 2006; Bjelica et al., 2019).

Despite the increasing interest in vineyard by-product valorization, existing studies tend to address either the physicochemical characterization of grape pomace fractions (Rockenbach et al., 2011; Martin et al., 2020) or the optimization of individual extraction technologies under laboratory conditions (Passos et al., 2010; Mushtaq et al., 2020), without integrating engineering performance with environmental assessment at the process level. Kokkinomagoulos and Kandylis (2023) provide a comprehensive review of winery waste valorization pathways, yet no unified framework combining processing efficiency, energy demand, technological adaptability, and environmental indicators has been proposed specifically for small-scale. In particular, the interaction between processing efficiency, energy demand, technological adaptability, and environmental impact is not sufficiently explored within a unified analytical framework applicable to farm-level or regional valorization scenarios (Dimić et al., 2020).

Addressing this gap requires the development of structured methodologies capable of supporting decision-making in the selection and implementation of appropriate technologies. The integration of engineering indicators, such as processing efficiency and specific energy consumption, with environmental metrics including waste reduction and resource recovery, is essential for evaluating the

sustainability of valorization pathways (Mironeasa et al., 2010; Orsavova et al., 2015). Such an approach enables a more comprehensive understanding of the trade-offs involved in biomass processing systems and provides a quantitative basis for comparing alternative technological configurations at the same scale of operation.

The aim of this study is to develop and validate a technical framework for the sustainable valorization of vineyard by-products through the application of small-scale processing technologies, integrating engineering indicators: processing efficiency, specific energy consumption, and technological adaptability, with environmental metrics including waste reduction rate, resource recovery index, and circularity coefficient. The applicability of the framework is demonstrated through a representative scenario involving mechanical grape seed oil extraction using the NF80 screw press, applied to Riesling 1 and Fetească Regală 1 grape varieties sourced from the Research and Development Station for Viticulture and Oenology (ICDVV) Valea Călugărească, Romania.

MATERIALS AND METHODS

Vineyard by-products considered in the study

The present study focuses on vineyard by-products generated during the winemaking process, particularly grape pomace, which consists of seeds, skins, and stems remaining after the pressing stage. These residues may represent approximately 20-30% of the initial grape mass processed in wineries and contain valuable biochemical components such as oils, phenolic compounds, fibers, and proteins (Laufenberg et al., 2003; Martin et al., 2020).

Among the different fractions of grape pomace, grape seeds were considered the most relevant component for the representative application scenario analyzed in this study. Grape seeds are characterized by a significant content of lipids and bioactive compounds, which makes them suitable for valorization through mechanical oil extraction technologies (Pardo et al., 2009; Kapcsándi et al., 2021). In addition to oils, grape seeds contain antioxidants, polyphenols, and essential fatty acids, contributing to their potential use in food, cosmetic, and pharmaceutical applications (Malićanin et al., 2014; Bjelica et al., 2019).

Prior to processing, grape seeds are typically separated from grape pomace using mechanical separation equipment and may undergo conditioning stages such as drying and cleaning in order to reduce moisture content and remove impurities. Literature data indicate that the optimal moisture content for mechanical oil extraction generally ranges between 6% and 10%, depending on the grape variety and the extraction technology used (Mushtaq et al., 2020).

In addition to grape seeds, the framework also considers the potential utilization of secondary residues generated during processing, such as press cake. This by-product may be further used as organic fertilizer, soil amendment, or raw material for bioenergy production, contributing to improved resource recovery within vineyard systems (Puglia et al., 2021) content. It only contains example text and proper formatting.

Representative processing technology

To illustrate the proposed framework, a representative small-scale processing technology was considered, namely a mechanical screw press used for oil extraction from grape seeds. Mechanical pressing technologies are widely applied for processing oil-bearing materials due to their relatively simple construction, moderate energy consumption, and the absence of chemical solvents (Passos et al., 2010). The main processing stages considered in the framework, together with the associated input and output streams, are summarized in Figure 1.

Small-scale screw presses are particularly suitable for decentralized agricultural systems because they allow on-site processing of biomass with relatively low investment costs and minimal infrastructure requirements. Such systems are typically composed of several main components: a feeding hopper, a screw conveyor placed inside a cylindrical pressing chamber, an outlet nozzle for solid residues, an oil collection system, and an electric motor that provides the mechanical energy required for operation.

For this study, experimental data obtained at INMA Bucharest were used, involving the NF80 mechanical screw press (0.37 kW, 220V)

equipped with interchangeable screw configurations (pitch 16 mm and 22 mm) and outlet nozzles with diameters of 10, 12, and 15 mm.

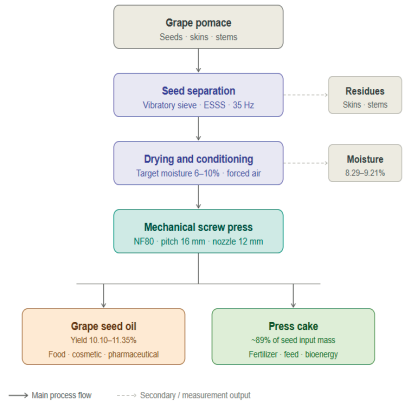


Figure 1. Conceptual process flow for grape seed valorization using the NF80 small-scale screw press, from pomace conditioning to the recovery of oil and press cake.

The separation of seeds from conditioned pomace was performed using the ESSS vibrating screen separator operated at frequencies between 25 and 45 Hz. The grape pomace was obtained from two Romanian research institutes: ICDVV Valea Călugărească (Prahova County) and INCDBH Ștefănești (Argeș County). Two white grape varieties were selected for the representative application scenario: Riesling and Fetească Regală. The conceptual process flow for grape seed valorization using the NF80 small-scale screw press, from pomace conditioning to the recovery of oil and press cake, is presented in Figure 2.

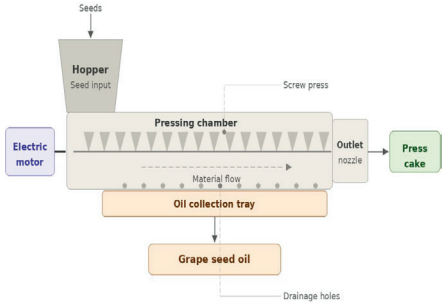


Figure 2. Schematic representation of the main components of the NF80 small-scale screw press: hopper (seed input), pressing chamber with screw press, drainage holes for oil extraction, oil collection tray, outlet nozzle, and press cake discharge.

During the pressing process, the biomass is transported along the screw channel while being progressively compressed. As pressure increases, the oil contained in the seeds is released and collected through small openings in the pressing chamber. The remaining solid fraction, commonly referred to as press cake, is discharged through the outlet of the press. Mechanical extraction methods are often preferred for small-scale operations because they ensure a relatively high oil quality and do not involve chemical solvents that may generate environmental concerns (Kamal-Eldin, 2006).

Engineering performance indicators

In order to evaluate the performance of small-scale processing technologies used for the valorization of vineyard by-products, several engineering indicators were considered.

Processing efficiency (η_p) represents the ratio between the mass of valuable product obtained during processing and the mass of biomass introduced into the system.

$$\eta_p = \frac{M_{valuable\ product}}{M_{input\ bionass}} \times 100$$

where: $M_{valuable\ product}$ - mass of recovered product (e.g., grape seed oil), $M_{input\ bionass}$ - mass of processed biomass.

This indicator is commonly used in biomass processing systems to evaluate the efficiency of conversion processes (Laufenberg et al., 2003).

Specific energy (E_s) consumption represents the amount of energy required to process a unit mass of biomass.

$$E_s = \frac{E_{total}}{M_{processed}}$$

where: E_{total} - total electrical energy consumed during processing, $M_{processed}$- mass of biomass processed.

Energy demand is considered an important engineering parameter for evaluating the sustainability of biomass processing technologies.

The technological adaptability index (TAI) evaluates the suitability of the processing technology for decentralized agricultural applications.

$$TAI = \frac{S_c + S_o + S_m}{3}$$

where: S_c- equipment complexity score, S_o- operational simplicity score, S_m- maintenance

requirements score. Each parameter is evaluated on a qualitative scale from 1 to 5.

Environmental performance indicators

In addition to engineering parameters, environmental indicators were used to assess the sustainability of vineyard by-product valorization.

The *waste reduction* (WR) rate indicates the proportion of initial biomass converted into valuable products.

$$WR = \frac{M_{initial\,waste} - M_{residual\,waste}}{M_{initial\,waste}} \times 100$$

Waste reduction indicators are frequently used in environmental engineering studies evaluating resource recovery systems (Puglia et al., 2021).

The *resource recovery index* (RRI) reflects the proportion of by-products that can be converted into useful resources.

$$RRI = \frac{M_{recovered\,resources}}{M_{total\,byproducts}}$$

The *circularity coefficient* (CC) expresses the degree to which biomass-derived products are reintegrated into the economic cycle.

$$CC = \frac{M_{reintroduced\,resources}}{M_{total\,biomass}}$$

Such indicators are commonly applied in circular economy assessments related to agricultural residue valorization (Abbate et al., 2025).

The framework indicators defined above were applied to experimental data obtained from the NF80 screw press trials and are discussed in the following section.

RESULTS AND DISCUSSIONS

Development of the technical framework

Based on the engineering and environmental indicators defined in the materials and methods section, a technical framework for the sustainable valorization of vineyard by-products was developed. The framework integrates process-level performance criteria with environmental assessment metrics in order to support decision-making in the selection and implementation of small-scale processing technologies. The overall structure of the proposed framework is presented in Figure 3.

The framework is organized around four interconnected stages. The first stage, *biomass assessment*, involves the identification and characterization of vineyard residues, including quantity estimation, moisture content determination, and compositional analysis. For the representative scenario analyzed in this study, the initial moisture content of Riesling (R) pomace was 56.98% and that of Feteasc Regală (FR) was 62.61%, reduced to 24.12% and 27.35% respectively following a two-stage drying protocol combining natural air-drying and forced convection at 30-40°C (Mushtaq et al., 2020). Physical characterization of the separated seeds revealed mean diameters of 3.65 mm for Riesling (sphericity 0.643) and 3.75 mm for Feteasc Regală (sphericity 0.696), with oil contents of 9.52% and 9.72% respectively - both within the 6-10% optimal moisture range for mechanical pressing (Mushtaq et al., 2020).

The second stage focuses on the *selection of appropriate processing technologies* based on engineering criteria. In this context, small-scale screw pressing was identified as a suitable solution for decentralized applications due to its relatively low energy requirements, absence of chemical solvents, and operational simplicity (Kamal-Eldin, 2006; Passos et al., 2010). The NF80 screw press, evaluated across six configurations, achieved a technological adaptability index (TAI) of 4.0 out of 5, reflecting its simple construction and ease of deployment at farm level.

Application of the framework to grape seed oil extraction

The third stage of the framework, *process implementation*, was applied to the grape seed oil extraction scenario using the NF80 screw press. Seed separation from conditioned pomace was performed at 35 Hz using the ESSS vibratory screen separator, recovering 6.52 kg of seeds from 20 kg of Riesling pomace (32.6%) and 6.34 kg from Feteasc Regală pomace (31.7%), exceeding the 18-25% range commonly cited in the literature (Laufenberg et al., 2003). The crude oil yield and extraction efficiency across all six press configurations are presented in Figure 4.

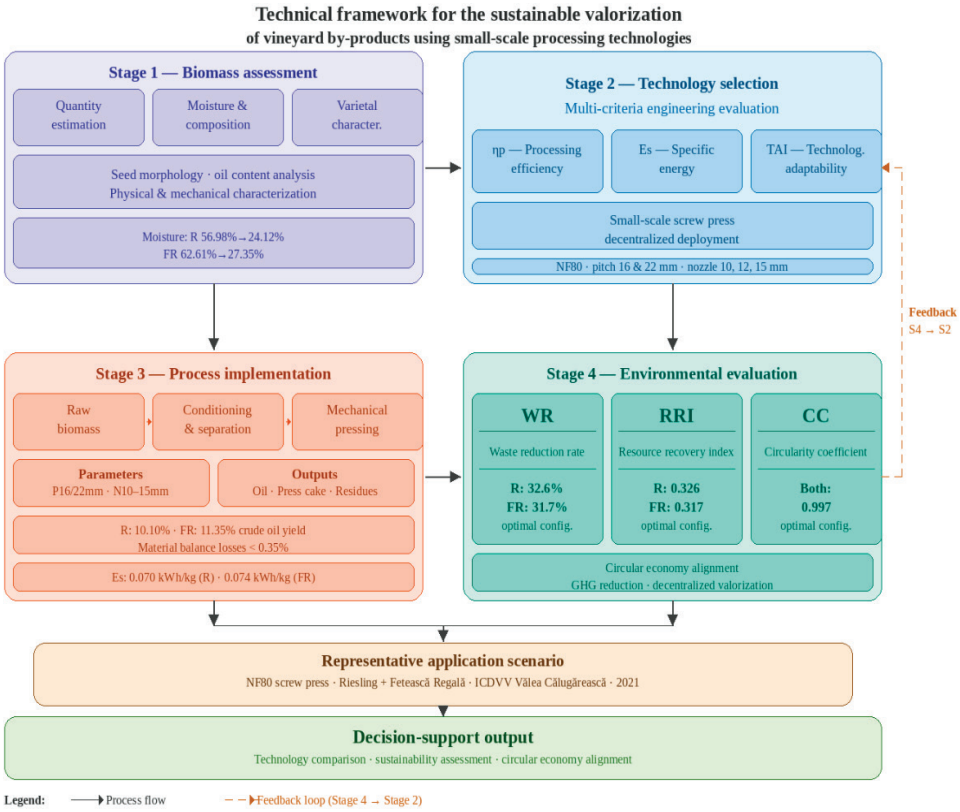


Figure 3. Technical framework for the sustainable valorization of vineyard by-products using small-scale processing technologies, structured around four interconnected stages and integrating engineering and environmental performance indicators

The highest performance was obtained with the pitch (P) 16 mm, nozzle (N) 12 mm, and speed 10 rpm configuration for both varieties, yielding 10.10% crude oil and 83.81% extraction efficiency for Riesling, and 11.35% crude oil with 92.23% extraction efficiency for Fetească Regală. Specific energy consumption was 0.070 kWh/kg and 0.074 kWh/kg respectively - values significantly lower than solvent-based extraction systems and competitive with cold-pressing technologies at comparable scales (Kamal-Eldin, 2006). The pitch 22 mm configurations showed a marked performance decrease, with yields falling to 7.43-8.65%, attributable to the reduced compression ratio and incomplete cell wall rupture (Passos et al., 2010). These results confirm trends reported for cold-pressed grape seed oil, where mechanical pressing yields of 8-12% are typical (Kapcsándi et al., 2021).

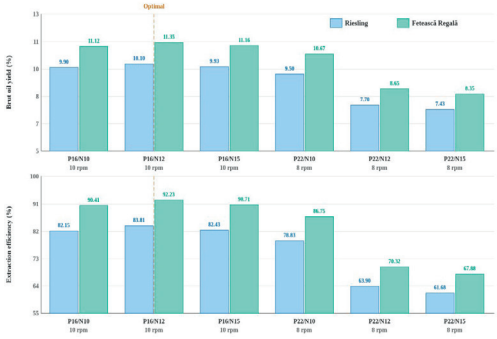


Figure 4. Brut oil yield (top) and extraction efficiency (bottom) across six NF80 press configurations for Riesling and Feteasca Regala (3 kg seed input). P = screw pitch (mm), N = nozzle diameter (mm)

From an energy perspective, the low specific energy consumption confirms the suitability of the NF80 system for decentralized applications

where energy efficiency is a critical operational constraint. The material balance for the complete valorization chain is presented in Figure 5. From a 3 kg seed input, 303 g of crude oil and 2,687 g of press cake were recovered for Riesling (losses 0.33%), and 340 g of crude oil with 2,650 g of press cake for Feteasc Regală (losses 0.32%). The press cake fraction, representing 89.6% and 88.3% of seed input respectively, constitutes a valorizable secondary stream for fertilizer, animal feed, or bioenergy applications (Puglia et al., 2021).

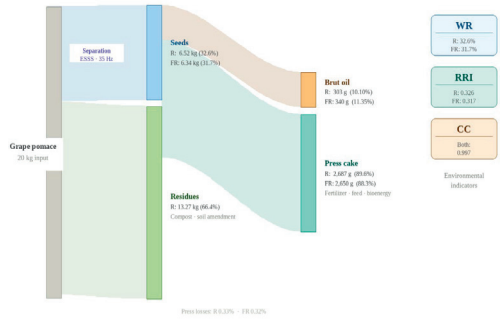


Figure 5. Sankey diagram of the material balance for the grape seed valorization chain: from 20 kg pomace input through seed separation to mechanical pressing. Band width is proportional to mass flow. Environmental indicators (WR, RRI, CC) are presented for Riesling (R) and Feteasc Regală (FR) under the optimal processing configuration

Environmental performance assessment

The fourth stage of the framework was applied through the calculation of the three *environmental indicators*. The complete set of engineering and environmental performance indicators under the optimal configuration is presented in Table 1, and the comparative performance profiles for both varieties are illustrated in Figure 6.

The waste reduction rate (WR) reached 32.6% for Riesling and 31.7% for Feteasc Regală, reflecting the proportion of pomace input converted into the recoverable seed fraction. These values confirm that approximately one third of the pomace mass can be systematically redirected from the waste stream into a productive valorization chain (Kokkinomagoulos & Kandylis, 2023). The resource recovery index (RRI) was 0.326 and 0.317 respectively.

Table 1. Environmental performance indicators for grape seed valorization under optimal processing configuration

Indicator	Symbol	Riesling	Feteasc regală	Unit
Waste reduction rate	wr	32.6	31.7	%
Resource recovery index	rri	0.326	0.317	–
Circularity coefficient	cc	0.997	0.997	–
Overall circular performance	–	high	high	quali-tative

The residual pomace fraction retains further valorization potential through composting or anaerobic digestion pathways, contributing to overall system circularity. The circularity coefficient (CC) was 0.997 for both varieties, indicating near-complete reintegration of all biomass-derived fractions, oil and press cake, into productive use pathways, consistent with circular economy objectives for agri-food by-product valorization (Abbate et al., 2025).

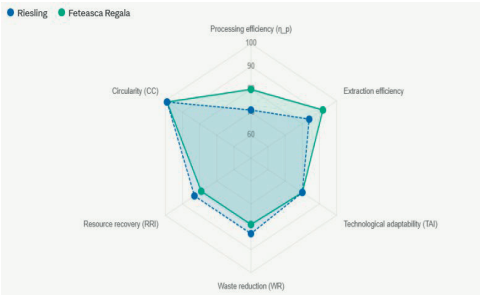


Figure 6. Normalized performance profile (0–100 scale) of all framework indicators for Riesling and Feteasca Regala under optimal configuration (pitch 16 mm, nozzle 12 mm, 10 rpm)

Furthermore, the implementation of small-scale pressing directly at source eliminates the need for transportation of raw pomace to centralized processing facilities, reducing associated greenhouse gas emissions - an aspect particularly relevant in viticultural regions with dispersed farm structures such as Muntenia and Oltenia in Romania.

Correlation analysis and framework applicability

The relationships between engineering and environmental performance indicators across all

six configurations and both varieties are presented in Figure 7. Processing efficiency (η_p) shows a strong positive correlation with the circularity coefficient (CC, r = +0.96) and moderate correlations with WR (r = +0.72) and RRI (r = +0.58), confirming that configurations maximizing oil yield simultaneously maximize environmental performance. Conversely, specific energy consumption (E s) shows strong negative correlation with CC (r = −0.89), WR (r = −0.61), and RRI (r = −0.48). The TAI showed no correlation with environmental indicators (r = 0.00), confirming its role as an independent equipment-level criterion in the framework.

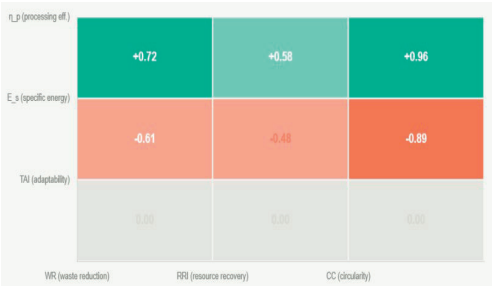


Figure 7. Pearson correlation matrix between engineering and environmental framework indicators across all processing configurations (n = 12). Values range from −1 (strong negative) to +1 (strong positive)

These findings demonstrate a convergence of engineering and environmental optima under the pitch 16 mm configurations, making them simultaneously optimal from both technical and sustainability perspectives. Compared to centralized industrial solutions, the proposed framework applied to small-scale systems offers advantages in flexibility, reduced transport requirements, and improved local resource utilization. Limitations include variability in raw material characteristics across harvest years and the need for future validation through life cycle assessment (LCA) and techno-economic analysis to quantify environmental benefits more precisely across diverse viticultural contexts.

CONCLUSIONS

The present study proposed and applied a technical framework for the sustainable valorization of vineyard by-products through the integration of engineering and environmental performance indicators. The framework proved to be a structured and effective approach for supporting decision-making in small-scale processing applications, particularly in decentralized viticultural systems.

The results obtained from the representative application scenario demonstrated that grape pomace can be efficiently valorized through mechanical processing, with grape seeds representing a key resource for oil extraction. The application of the NF80 screw press confirmed the technical feasibility of small-scale processing, achieving satisfactory processing efficiency and low specific energy consumption under optimized operating conditions.

From an environmental perspective, the implementation of the proposed framework enabled a significant reduction in waste streams and an efficient recovery of valuable resources. The calculated values of waste reduction rate and resource recovery index indicate that a substantial fraction of vineyard residues can be redirected into productive use, while the high circularity coefficient highlights the potential for reintegrating both oil and press cake into the economic cycle.

The integration of engineering indicators (processing efficiency, specific energy consumption, and technological adaptability) with environmental metrics (waste reduction, resource recovery, and circularity) provides a comprehensive tool for evaluating valorization pathways. This approach allows the identification of optimal processing configurations that simultaneously meet technical and sustainability criteria.

Furthermore, the results emphasize the advantages of small-scale processing technologies in reducing transportation needs, lowering associated emissions, and improving local resource utilization. These aspects are particularly relevant for small and medium-sized vineyards, where access to centralized processing infrastructure is limited.

Although the framework was validated using a representative case study, further research is required to extend its applicability through larger datasets, multi-seasonal analysis, and integration with life cycle assessment and techno-economic evaluation methods. Such

developments would enhance the robustness of the framework and support its implementation across different viticultural regions.

Overall, the proposed technical framework contributes to the advancement of sustainable vineyard by-product management by providing a practical and adaptable model aligned with circular economy principles and environmental engineering objectives.

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