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Türkiye ve Sırbistan'da Meyve İşleme Verimliliği ve Posanın Değerlendirme Potansiyelinin Veriye Dayalı Analizi

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ÖZ

Bu çalışma, üzüm (*Vitis vinifera L.*) ve erik (*Prunus domestica L.*) üretiminde önde gelen üretici ülkelerden Türkiye ve Sırbistan'da ortaya çıkan üzüm ve erik posalarının üretim, işleme ve değerlendirme potansiyelini veri temelli bir yaklaşımla incelemesi amaçlanmıştır. Çalışma kapsamında elde edilen bulgular, bu yan ürünlerin döngüsel biyoekonomi çerçevesinde sürdürülebilir ancak büyük ölçüde değerlendirilmeyen biyokütle kaynakları olduğunu göstermektedir. Çalışmada, açık erişimli ulusal ve uluslararası istatistik veri tabanları ile literatüre dayalı olarak geliştirilen veri temelli bir metodolojik çerçeve kullanılmıştır. Tüm veri işleme, istatistiksel analizler ve görselleştirmeler, yapılandırılmış tarımsal veri setlerine uygunluğu, hesaplamaların şeffaf biçimde izlenebilmesi ve kullanıcılar arasında tekrarlanabilirliği nedeniyle tercih edilen Microsoft Excel (Microsoft Corp., Redmond, WA, ABD) yazılımı kullanılarak; ağırlıklı olarak tanımlayıcı istatistikler ve formül tabanlı hesaplamalar aracılığıyla gerçekleştirilmiştir. 2020–2024 dönemine ait tarımsal üretim verileri, endüstriyel işleme oranları, posa miktarları ve atık yönlendirme düzeyleri bu kapsamda değerlendirilmiştir. Bulgular, Türkiye'de yılda yaklaşık 451×10³ ton üzüm posası, Sırbistan'da ise 34×10³ ton erik posası üretildiğini; buna karşın her iki ülkede de değerlendirme oranlarının %5'in altında kaldığını göstermektedir. Biyokimyasal veriler, her iki posanın da selüloz, hemiselüloz, pektin ve fermente edilebilir şekerler açısından zengin olduğunu ve bu nedenle bakteriyel selüloz, nanoselüloz ve pektin bazlı biyopolimer üretimi için uygun ve sürdürülebilir hammaddeler olduğunu ortaya koymaktadır. Ancak yetersiz biyorafineri altyapısı ve sınırlı endüstriyel entegrasyon, bu potansiyelin hayata geçirilmesini engellemektedir.

Data-Driven Analysis of Fruit Processing Efficiency and Pomace Valorization Potential in Türkiye and Serbia

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ABSTRACT

This study examines the production, processing, and valorization potential of grape and plum pomaces generated in Türkiye and Serbia, two leading producers of grapes (*Vitis vinifera* L.) and plums (*Prunus domestica* L.), using a data-driven approach, and demonstrates that these by-products represent sustainable yet largely underutilized biomass resources within the framework of the circular bioeconomy. The findings obtained within the scope of this study indicate that these by-products represent sustainable yet largely underutilized biomass resources within the framework of the circular bioeconomy. All data processing, statistical analyses, and visualizations were performed using Microsoft Excel (Microsoft Corp., Redmond, WA, USA), primarily through descriptive statistical methods and formula-based calculations, selected for its suitability for structured agricultural datasets, transparent traceability of calculations, and reproducibility across users. Agricultural production data for the period 2020–2024, including industrial processing ratios, pomace quantities, and waste diversion levels, were evaluated within this framework. The findings indicate that approximately 451×10^3 tons of grape pomace are generated annually in Türkiye, while Serbia produces about 34×10^3 tons of plum pomace; however, valorization rates in both countries remain below 5%. Biochemical evidence shows that both pomaces are rich in cellulose, hemicellulose, pectin, and fermentable sugars, making them suitable and sustainable feedstocks for the production of bacterial cellulose, nanocellulose, and pectin-based biopolymers. Nevertheless, insufficient biorefinery infrastructure and limited industrial integration continue to hinder the realization of this potential.

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Introduction

Large volumes of organic waste are produced by the food processing and agricultural sectors worldwide, which not only present environmental challenges but also offer valuable resources for the development of sustainable materials (Casquete et al., 2022; Galante et al., 2025). Agricultural and food processing wastes represent a major environmental and economic challenge in both Türkiye and Serbia.

Agricultural residues can be valorized in several ways to provide energy, biomaterials, and soil additives that benefit both the environment and the economy. Conventional management practices including open burning and landfilling not only waste valuable resources but also emit particulate matter and greenhouse gases (Yaman, 2012; Ünlü et al., 2023). Recent advances in biotechnology and materials science have made it feasible to convert lignocellulosic residues into biofuels (biogas, bioethanol, and biodiesel), biopolymers, and activated carbons (Dhyani and Bhaskar, 2018; Awogbemi and Von Kallon, 2022a; Işıtan, 2025). Composting and anaerobic digestion remain key biological routes, reducing organic load while producing nutrient-rich fertilizers and renewable energy (Negi et al., 2022; Ivanović et al., 2025). While chemical and enzymatic procedures facilitate the manufacture of nanocellulose, activated carbon, and other high-value bioproducts, thermal conversion techniques like pyrolysis and gasification enable the recovery of bio-oils and syngas (Ioannidou and Zabaniotou, 2007; Dhyani and Bhaskar, 2018; Koul et al., 2022; Bednárek et al., 2024; Zielińska and Bułkowska, 2024).

Agricultural residues and food industry by-products accounted for a significant share of Türkiye's total waste generation, which reached 109,200×10^3 tons in 2022, yet much of this potential resource remains underutilized (CEIC, 2021). According to the Biomass Energy Potential Atlas (EIGM, 2021), approximately 74.6% of Türkiye's renewable biomass potential originates from agricultural residues, corresponding to nearly 34,000×10^3 tons of oil equivalent per year. Despite this, biomass contributes only about 1% of national electricity generation (IRENA, 2019), revealing a considerable gap between potential and utilization. This underlines the need for sustainable conversion routes such as composting, biogas production, and biopolymer synthesis from lignocellulosic residues (Yaman, 2012; Ünlü et al., 2023).

Similarly, in Serbia, annual food waste is estimated at 770×10^3 tons (UNECE, 2022) with more than 90% disposed in landfills due to limited recovery infrastructure. In addition, the agricultural sector generated 88.2×10^3 tons of waste in 2022 (STAT, 2025). Fruit production represents a cornerstone of Serbian agriculture, contributing around 6% of national GDP (Zelenović et al., 2023). Serbia ranks among Europe's leading producers of plums (430.2×10^3 tons) and raspberries (127×10^3 tons) (Subić et al., 2021; FAOSTAT, 2023). Despite this enormous output, only a small fraction of agro-industrial residues is valorized, primarily through local composting or use as animal feed (Ketin et al., 2021). Serbia's sustainable biogas potential is largely derived from livestock manure, crop residues and fruit by-products, and it is estimated that if all these wastes are used properly, the country's electricity needs could be met by 15%. Nevertheless, infrastructure limitations and policy fragmentation hinder large scale adoption of circular economy practices (Vukelić et al., 2023).

The economic potential of agricultural waste valorization is equally significant. In Türkiye, utilizing even 20% of agricultural residues for bioenergy could offset nearly 5% of national natural gas imports (EİGM, 2021), while biocomposite production using crop-based fillers can reduce manufacturing costs by up to 30% compared to synthetic materials (Avşar and Çevik, 2023). Similarly, in Serbia, expanding biogas facilities to process available agro-residues could generate rural employment and contribute to national energy independence (Vukelić et al., 2023; Belošević et al., 2024).

Among the various agro-industrial residues, grape and plum pomaces stand out as abundant and compositionally rich substrates for biotechnological valorization. Grape pomace, consisting mainly of skins, seeds, and stems, accounts for nearly 20–25% of the total grape weight after processing, and is rich in cellulose, hemicellulose, lignin, pectin, phenolic compounds, and residual sugars (Varış et al., 2000; Bekar, 2016; Malićanin et al., 2025; Milinčić et al., 2025; Chedea et al., 2025). Similarly, plum residues, generated during juice, jam, and brandy production, are composed of fibrous pulp, stone fragments, and carbohydrates that can serve as feedstocks for microbial fermentation and enzyme-assisted hydrolysis (Subić et al., 2021). Both residues have been traditionally discarded or used as low-value animal feed, yet their biochemical composition provides a promising foundation for conversion into bio-based materials such as bioplastics, biochar, or bacterial cellulose.

The objective of this study is to present a thorough quantitative evaluation of the production of grapes (*Vitis vinifera L.*) and plums (*Prunus domestica L.*) together with their industrial processing levels and valorization potential in Türkiye and Serbia. In addition to assessing the sustainability implications in relation to the EU Green Deal framework (EC, 2019) and the United Nations Sustainable Development Goals (SDGs) 9, 12, and 13 (UN, 2019), the research incorporates agricultural production information for the years 2020–2024 with industry-specific processing ratios, pomace yield models, and economic contribution calculations. This study is the first cross-national quantitative analysis that simultaneously estimates pomace quantities for two major fruit industries, models the economic outputs and contributions of industrial processing, identifies pathways for valorization based on the biochemical properties of grape and plum residues, and connects agricultural production patterns with circular bioeconomy indicators pertinent to regional sustainability transitions.

Materials and Methods

Materials

Grape (*Vitis vinifera L.*) and plum (*Prunus domestica L.*) have been selected as target materials in Türkiye and Serbia due to their high production volumes, significant processing rates, and their substantial sectoral contribution and export relevance. As shown in Figure 1a, Türkiye ranks among the world's top grape-producing countries (typically within the top six), with an annual production exceeding $3{,}500\times10^3$ tons, while Serbia is one of the world's leading plum producers, generally ranking among the top five globally with an annual production exceeding 400×10^3 tons (FAOSTAT, 2023). These production levels contribute significantly to national revenues (Figure 1b) and also generate large quantities of industrial by-products: Grape pomace constitutes approximately 20-25% of processed fruit and contains cellulose, hemicellulose, lignin, pectin, and phenolic compounds (Bekar, 2016; Megías-Pérez et al., 2023), while plum processing produces 12-18% solid residue rich in pectin and fermentable sugars suitable for biopolymer synthesis (Subić et al., 2021; Nirmal et al., 2023). The high availability and favorable biochemical composition make these residues particularly suitable for evaluating biopolymer valorization potential in both countries.

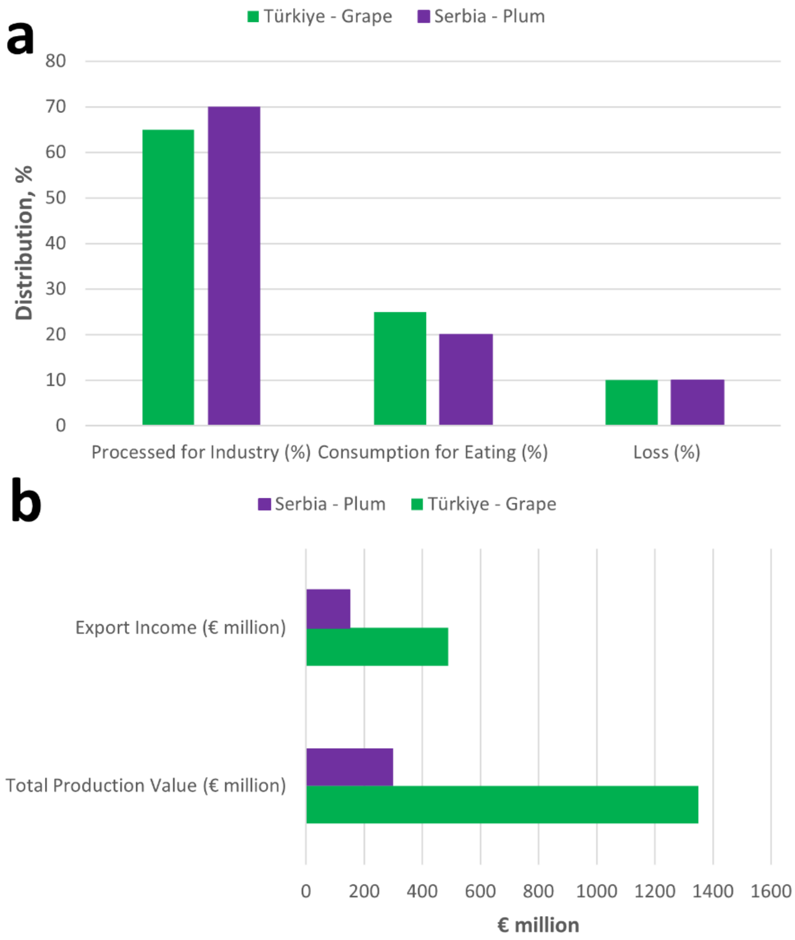

Figure 1. Comparative global production profiles of grapes and plums (a) and corresponding sectoral economic indicators for Türkiye (grapes) and Serbia (plums) (b) (FAOSTAT, 2023; UN, 2023; StatAgri, 2024)

Data Sources and Methodological Framework for Data Collection and Processing

In this study, a data-driven methodological framework was adopted to evaluate fruit processing efficiency and pomace valorization potential. All of the data utilized in this study were obtained from publicly accessible secondary sources. From 2020 to 2024, agricultural production data for grapes and plums were gathered from publicly accessible national and international databases, such as FAOSTAT, TÜİK, and the Statistical Office of the Republic of Serbia (STAT). These databases provided annual national-level production figures. All production statistics were standardized into uniform annual units (tons) to ensure cross-country comparability. Industrial processing ratios (R_{proc}) for grapes and plums were obtained from sector-specific reports and peer-reviewed literature rather than statistical databases. These ratios reflect dominant processing pathways, such as the production of wine, juice, and vinegar for grapes in Türkiye and brandy for plums in Serbia.

FAOSTAT provided country-level data on grape and plum production for the years 2020–2023, and CEIC and the Turkish Statistical Institute (TÜİK) provided supplementary agricultural indicators for Türkiye. The Statistical Office of the Republic of Serbia (STAT) provided corresponding agricultural output and processing data for Serbia (IRENA, 2019, 2020, 2022; TÜİK, 2020; CEIC, 2021; EİGM, 2021; UNECE, 2022; FAOSTAT, 2023; StatAgri, 2024; STAT, 2025). Sectoral reports and peer-reviewed scientific literature were used to determine processing ratios, pomace generation rates, and the average biochemical makeup of grape and plum wastes (Bekar, 2016; Tarım ve Orman Bakanlığı, 2020; Subić et al., 2021; Megías-Pérez et al., 2023; Tariş Üzüm, 2025;). In order to facilitate cross-national comparability and subsequent residue-potential calculations, all statistics were harmonized to annual production units (tons).

Sectoral averages were used to calculate the percentage of harvested produce that entered industrial processing for each fruit species. Because grapes are widely used in the production of wine, juice, molasses, and vinegar, they generally showed higher processing rates than plums. According to published studies, pomace generation rates are between 20-25% for processed grapes and between 12-18 % for plums, depending on the type of product. In this study, fixed residue coefficients of 20% (grape) and 15% (plum) were applied.

Modeling Industrial Processing Levels

Production trends of grapes and plums and their total economic contribution (EC)

Each fruit category's industrial processing levels were determined by multiplying annual production numbers by country-specific processing ratios. Grape processing in Türkiye comprises the manufacturing of wine, vinegar, pekmez (molasses), dried grapes, and industrial juice extraction. Brandy or plum spirit (rakija), jam, juice, compotes, and dried fruits are the main products of plum processing in Serbia. Plum spirit, which represents the dominant end use of plums in Serbia, was inscribed on the UNESCO Representative List of the Intangible Cultural Heritage of Humanity in 2022, reflecting its cultural and socio-economic importance (Trajković et al., 2025). These fruit processing chains generate considerable pomace residues, which are currently treated as waste despite their high biochemical potential. The percentage of residue left over after industrial extraction was represented by literature-based factors that were used to estimate pomace generation. Depending on the processing route, reported pomace yields range from 20–25% for grapes and 12–18% for plums. Economic analysis included two components: Raw product economic value, based on average market prices (€/ton) and value-added industrial contribution, reflecting the revenue generated through processed products. Value-added multipliers were derived from national wine industry reports (Türkiye), plum brandy sector statistics (Serbia), export price datasets, and previously published studies (Pecot and Watt, 1975; Salunkhe and Kadam, 1995; Ioannidou and Zabaniotou, 2007; Keshk, 2014; Tarım ve Orman Bakanlığı, 2020; Ataseven, 2025; Tariş Üzüm, 2025).

All data processing, statistical analyses, and visualizations were performed using Microsoft Excel (Microsoft Corp., Redmond, WA, USA), primarily through descriptive statistical functions and formula-based calculations, which was selected due to its suitability for structured agricultural datasets, transparent traceability of calculations, and reproducibility across users.

The industrial processing output (IPO) and pomace yield coefficient (PM)

The percentage of yearly fruit production that goes into the wine, brandy, juice, vinegar, jam, and other fruit-processing operations is known as the industrial processing output, or IPO. IPO was determined using:

$$IPO = P_{total} \times R_{proc} \quad (1)$$

where P_{total} and R_{proc} refer to the total annual fruit production ($\times 10^3$ tons) and industrial processing ratio (decimal) accordingly.

The amount of solid residue (annual produced pomace mass, PM) remaining after industrial processing was calculated using the pomace yield coefficient (Y_{pom}) :

$$PM = IPO \times Y_{pom} \quad (2)$$

The values used in the calculations were obtained from the literature (Salunkhe and Kadam, 1995; Tarım ve Orman Bakanlığı, 2020; Subić et al., 2021).

Waste Diversion Rate (WDR)

The waste diversion rate (WDR, %) quantifies the proportion of pomace that is valorized ($PM_{valorized}$) (e.g., composting, animal feed, extraction, energy use), compared to the total pomace generated (PM_{total}):

$$WDR = \frac{PM_{valorized}}{PM_{total}} \times 100 \quad (3)$$

Approximately 2–5% of grape pomace in Mediterranean and European wine industries is valorized, while plum pomace is even more underutilized, with only small fractions used for feed or fuel (Subić et al., 2021; Carpentieri et al., 2023; Kokkinomagoulos and Kandylis, 2025).

Results

Grape and plum production trends in Türkiye and Serbia and their total economic contribution

As illustrated in Figure 2, both Türkiye and Serbia rank among the world's top producers of grapes and plums, respectively. In Türkiye, the annual grape production is around 4,200×10^3 tons, ranking the country sixth worldwide (TÜİK, 2020). Manisa, Mardin, and Denizli rank first in terms of vineyard area (Ataseven, 2025). Fruit production is currently Serbia's most competitive agricultural industry and plums are the most significant fruit species in terms of both production volume and land area covered by plantations (Subić et al., 2021; Katarina et al., 2024; Gajić et al., 2025).

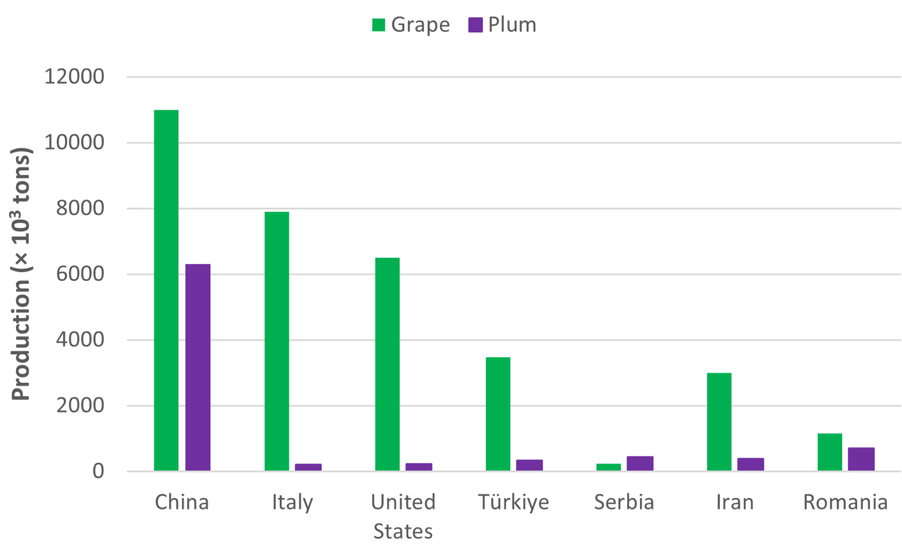

Figure 2. Global Production Comparison of Grapes and Plums (Average 2020–2024, ×10^3 tons) (TÜİK, 2020; FAOSTAT, 2023; UN, 2023; StatAgri, 2024; Tariş Üzüm, 2025)

Grapes are among Türkiye's most important fruit crops, generating large quantities of pomace during wine, juice, vinegar, and jam production. These residues are rich in sugars, cellulose, and lignin, making them excellent candidates for microbial fermentation and bacterial cellulose (BC) production. Approximately 3,400×10^3 tons of grapes were produced on 3.7 million decares of land during the 2023/2024 production season. According to FAO data, grapes are one of the most produced fruits globally, with a total yield exceeding 87,000×10^3 tons per year, generating approximately 20% solid waste (grape pomace) during wine and juice production (Bekar, 2016; FAO, 2025). Approximately 11–12% of this production is used for wine, vinegar, and molasses manufacturing, leading to the generation of nearly 600×10^3–800×10^3 tons of grape pomace annually (Bekar, 2016; Tarım ve Orman Bakanlığı, 2020). After processing, depending on the grape variety and processing step, 15–25% of the remaining material consists of grape pomace, comprising approximately 50% skins, 25% seeds, and 25% other solid residues (Bekar, 2016; Varış et al., 2000) (Bekar, 2016; Varış et al., 2000).

In Serbia, over 80% of the plums that are produced is utilized to make brandy, with the remainder being used for freezing, drying, or making jam and other confections. Fresh consumption accounts for only a small proportion (Direk and Spahic-Vukojevic, 2021; Subić et al., 2021). Plum pomace contains a soluble fraction of 7–13% and a total dietary fiber content of 38–49% (Milala et al., 2013). A large number of by-products, including plum stones with high potential value for sustainable utilization, are produced during the processing of plums. Because of their advantageous structure and chemical characteristics, plum stones, which are mostly composed of cellulose, hemicellulose, and lignin and contain about 61.1% carbon, are regarded as a promising lignocellulosic biomass for numerous uses (Usmonova and Salikhanova, 2024; Gajić et al., 2025).

Figure 3a, compiled from TÜİK, and STAT data, shows the annual grape and plum production in Türkiye and Serbia between 2020 and 2024. Türkiye consistently maintained high grape production levels (>3,000×10^3 tons/year), while Serbia remained a major global producer of plums (>325×10^3 tons/year). Observed interannual variations support the reliability of both residues as continuous feedstock sources.

As shown in Figure 3b, approximately 2,200×10^3 tons of grapes and 300×10^3 tons of plums are processed annually in Türkiye and Serbia, respectively. Following industrial processing, approximately 20% of the grape mass and 15% of the plum mass remain as pomace. Despite their rich lignocellulosic composition, these by products are not sufficiently utilized. These residues have the potential to be important raw materials for the circular economy. Currently, most of grape and plum pomace residues in both Türkiye and Serbia are disposed of in landfills, used as low-value animal feed, or left to decompose in open fields. These practices fail to utilize the biochemical potential of these residues and often result in environmental burdens. Improperly managed food and fruit processing wastes undergo uncontrolled microbial degradation, leading to the release of methane (CH_4) and carbon dioxide (CO_2), both potent greenhouse gases contributing to climate change (USDA, 2024). Additionally, leachates generated during decomposition can contaminate soil and groundwater, while excessive organic matter accumulation can result in eutrophication in nearby water bodies (EEA, 2025).

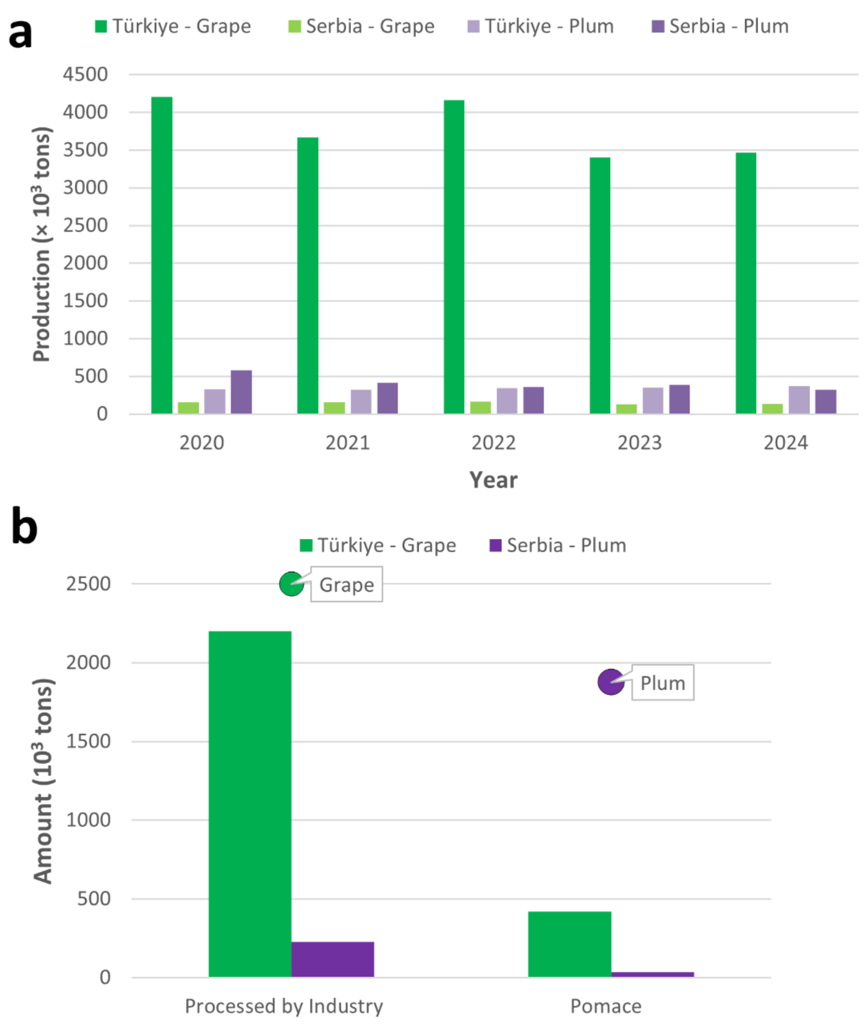

Figure 3. (a) Annual grape and plum production in Türkiye and Serbia (2020–2024) and (b) Industrial processing and pomace generation of grape and plum in Türkiye and Serbia ($\times 10^3$ tons) (Milala et al., 2013; TÜİK, 2020; Direk and Spahic-Vukojevic, 2021; Subić et al., 2021; FAOSTAT, 2023; UN, 2023; StatAgri, 2024; Tariş Üzüm, 2025).

Therefore, the valorization of grape and plum residues in Türkiye and Serbia represents not only an environmental necessity but also a strategic economic opportunity that is related to sustainability with regional development. The following sections present the quantitative results of production trends, processing levels, residue generation, and the biopolymer valorization potential of these residues.

Country-based industrial processing yield (IPO), pomace yield coefficient (PM), and waste diversion rate (WDR) for grapes and plums

The industrial processing output (IPO) was calculated using Equation (1) and 2024 grape and plum production values (Figure 3a): For Türkiye $P_{total}=3468\times10^3$ and for Serbia $P_{total}=325\times10^3$ tons. As can be seen in Figure 1a, for Türkiye grapes (R_{proc}= 0.65) driven by wine, vinegar, pekmez, and industrial juice processing (Bekar, 2016; Tarım ve Orman

Bakanlığı, 2020). For Serbian plum, (R_{proc}= 0.80), reflecting the dominance of brandy production (Direk and Spahić-Vukojević, 2021; Subić et al., 2021). The amounts of grapes and plums used in industry, along with their respective pomace quantities (Y_{pom}), were assumed to be 20% and 15% for Türkiye and Serbia, respectively (Figure 3b).

WDR is widely used in circular economy and waste management frameworks as an indicator of material recovery efficiency and resource circularity. However, at present, only a very small portion of grape residues (approximately 3% in the Mediterranean region) is used for compost, animal feed, or low-value fuel, while the majority is underutilized or managed as waste (Carpentieri et al., 2023). According to recent estimates for the EU wine industry; the wast majority of residues is still dumped in landfills or scattered over fields as low-value waste (Kokkinomagoulos and Kandylis, 2025). Despite this biochemical richness, plum pomace is still largely underutilized in Serbia and other producing nations; the majority of residues are inefficiently burned, dumped in the open, or used as animal feed. Studies frequently characterize plum pomace as a "under-exploited" or "low-value" by-product in relation to its chemical potential, while quantitative evaluations of valorized fractions are still rare in the literature (Milala et al., 2013; Subić et al., 2021).

Based on these studies, $PM_{valorized}$ was assumed to be 22×10^3 tons for grape pomace and 1.7×10^3 tons for plum pomaces for Türkiye and Serbia, respectively (WDR =5% for both fruit pomaces) as summarized in Table 1 (Milala et al., 2013; TÜİK, 2020; Direk and Spahic-Vukojevic, 2021; Subić et al., 2021; FAOSTAT, 2023; UN, 2023; StatAgri, 2024; Tariş Üzüm, 2025). Strengthening the valorization pathways for these large quantities of waste, particularly those related to biopolymer synthesis, bioactive extraction, and carbon-neutral material production, will significantly support regional bio-based industries and circular economy plans.

Table 1. Parameters used to estimate industrial processing output, pomace generation, valorization level, and waste diversion rate for grapes (Türkiye) and plums (Serbia)

	Units	Türkiye - Grape	Serbia - Plum
The industrial processing output (IPO)	10^3 tons	2254	228
Annual generated pomace (PM)	10^3 tons	451	34
Valorized pomace ($PM_{valorized}$)	10^3 tons	22	1.7
The waste diversion rate (WDR)	%	5	5

Biochemical Characteristics and Valorization Potential of Grape and Plum Pomaces for Biopolymer Applications

Thermal conversion techniques such as pyrolysis and gasification allow for the recovery of bio-oils and syngas, while chemical and enzymatic methods support the production of nanocellulose and other high-value bioproducts. These processes collectively align with circular economy principles by maximizing resource recovery and minimizing environmental impacts. Recent studies have demonstrated that lignocellulosic residues from fruit processing can serve as efficient feedstock not only for bacterial cellulose, but also for biogas, bioethanol, and biochar production—offering a closed-loop solution within the circular economy (Awogbemi and Von Kallon, 2022a; Chilakamarry et al., 2022).

Beyond direct energy and material value, agricultural waste utilization enhances rural livelihoods, stimulates innovation in small and medium enterprises, and supports carbon-neutral growth strategies under the European Green Deal (EC, 2019). In recent years, both Türkiye and Serbia have aligned their agricultural strategies with the European Green Deal and the Circular Economy Action Plan, emphasizing the recovery and reuse of organic residues. As emerging economies with rich agricultural outputs, they share similar challenges, including inadequate biorefinery infrastructure, low public awareness, and limited financial incentives for waste valorization. Yet, their combined potential for bio-based innovation, particularly in fruit waste utilization, offers a promising pathway toward achieving the UN Sustainable Development Goals (SDGs 12 and 13) (UN, 2019).

Bacterial cellulose (BC), a nano-structured polysaccharide synthesized by certain acetic acid bacteria such as *Komagataeibacter xylinus*, has attracted significant attention due to its high purity, crystallinity, tensile strength, and biocompatibility (Iguchi et al., 2000; Shah et al., 2013). It serves as a sustainable alternative to plant-derived cellulose for applications in biomedical materials, food packaging, and environmental remediation. The production of BC typically relies on glucose-based substrates, but fruit processing wastes rich in fermentable sugars can serve as cost-effective and eco-friendly alternatives, substantially lowering production costs (Ul-Islam et al., 2012; Shah et al., 2013; Jozala et al., 2016; Khan et al., 2023). Recent studies have demonstrated successful BC production using grape, apple, and citrus pomaces as carbon sources, achieving yields comparable to or higher than those obtained from synthetic media (Çakar et al., 2014; Keshk, 2014).

Mechanical characteristics (e.g., tensile strength, elongation at break), thermal stability (glass transition, melting, and decomposition temperatures), barrier performance (moisture and oxygen permeability), and biodegradability and sustainability attributes (renewable resource, carbon footprint) are the main factors that determine the biopolymer potential of biomass feedstock. These criteria are frequently applied in the literature to evaluate whether biopolymers are appropriate for specific applications in environmental technologies, biomaterials, and packaging (Shah et al., 2013; Jozala et al., 2016). As a result, the overall "potential" of a polymer or precursor feedstock is often assessed case by case, based on the demands of the intended application in biopolymer research.

Nevertheless, when assessing food and agricultural waste as raw materials for the production of biopolymers, the emphasis shifts from final material properties (mechanical or thermal) to the biochemical composition of the raw biomass, specifically its structural polysaccharide content that can be transformed into biopolymers based on cellulose or pectin. Thus, biochemical composition (cellulose, hemicellulose, and pectin), extractives, ash, and lignin ratios are also considered as key feedstock quality indicators in current biorefinery and residue valorization studies (Awogbemi and Von Kallon, 2022a; Awogbemi and Von Kallon, 2022b; Chilakamarry et al., 2022).

In this regard, the biochemical properties of grape and plum pomace, specifically their cellulose, hemicellulose, pectin, and fermentable sugar content, can be used to evaluate the biopolymer valorization potential of these materials. Thus, three criteria commonly reported in the literature were used in this study to assess the potential for valorization: (i) pomace availability; (ii) biochemical compatibility; and (iii) practical valorization capability, all of which are supported by recent studies on bio-based material production.

The main biochemical and operational variables that determine the possibility for producing biopolymers from grape and plum pomace are compiled in Table 2. Türkiye's grape pomace is particularly well suited for BC production due to its higher usability and sugar-rich composition. Despite being generated in relatively lower quantities, Serbian plum pomace offers significant prospects for nanocellulose and pectin-based biopolymers due to its high dietary fiber and lignocellulosic content. Both wastes currently exhibit very low valorization rates (below 5%), indicating substantial untapped potential within circular bioeconomy frameworks.

Table 2. Biochemical and practical indicators for evaluating grape (Türkiye) and plum (Serbia) pomace valorization potential for biopolymer production

Criterion	Indicator and Relevance for Biopolymer Production	Pomace		Key References
		Grape	Plum	
Availability	PM - Determines feedstock supply for continuous biopolymer production	High (≈451×10³ tons/year)	Moderate (≈34×10³ tons/year)	Bekar, 2016; Subić et al., 2021
	WDR - Indicates extent of underutilization and circularity potential	Very low (~3–5%)	Very low (<5%)	Carpentieri et al., 2023; Kokkinomagoulos and Kandylis, 2025
Biochemical Suitability	Cellulose (%) - Structural polysaccharide essential for BC, NC, bioplastics	~20–25%	~18–22%	Gajić et al., 2025; Ul-Islam et al., 2012; Milala et al., 2013; Çakar et al., 2014; Keshk, 2014; Ogrizek et al., 2021; Megías-Pérez et al., 2023; Usmonova and Salikhanova, 2024; Kokkinomagoulos and Kandylis, 2025
	Hemicellulose (%) - Supports biopolymer formation	12–18%	14–20%	
	Pectin (%) - Key precursor for pectin films, hydrogels, edible coatings	~6–10%	~10–15%	
	Fermentable sugars - Direct carbon source for BC fermentation	High (glucose, fructose)	Moderate (sorbitol, polyols)	
Valorization Feasibility	Existing industrial pathways - Lower processing cost if compatible with industry infrastructure	Wine, juice, and vinegar industries provide continuous feedstock	Brandy production	Subić et al., 2021
	Suitability for BC fermentation - Determines feasibility of microbial valorization	Demonstrated high BC yields	Limited studies and high potential but under-investigated	Çakar et al., 2014; Keshk, 2014
	Suitability for nanocellulose - Depends on cellulose/lignin balance and extractability	Good (skin/seed lignin manageable)	Good (lignocellulose high but extractable)	Chilakamarry et al., 2022

Conclusion

In conclusions, grape and plum pomace in Serbia and constitute high-volume, composition-rich biomass streams that are severely underutilized and possess substantial potential for integration into a circular bioeconomy. Although Serbia produces more than 34×10³ tons of plum pomace annually and Türkiye produces more than 451×10³ tons of grape pomace annually, the rates of valorization are still remarkably low (≤5%). Given the biological suitability of these wastes, this production-utilization gap presents a significant opportunity for the development of innovative biopolymer-oriented valorization pathways.

Both pomaces are attractive substrates for the production of bio-based materials due to their high lignocellulose content. High-yield BC production has been reported to be supported by the abundance of structural polysaccharides and residual glucose/fructose found in grape pomace. In a similar vein, plum pomace is suitable for applications such as edible films, nanocellulose extraction, and pectin-based bioplastics due to its increased pectin and dietary fiber content. These findings also corroborate prior studies showing fruit-based wastes are promising feedstocks for biochar synthesis, biopolymer manufacturing, and biogas upgrading within low-cost and scalable biorefinery systems.

Despite the availability of biochemical pathways and demonstrated laboratory-scale feasibility, practical limitations continue to represent a major barrier in Serbia and Türkiye. Grape pomace is produced year-round by Türkiye's wine, vinegar, and pekmez sectors, which increases the feedstock's dependability for bio-based production. On the other hand, Serbian plum pomace is highly seasonal because brandy production is concentrated in a short processing window. Logistical issues with storage, stability, and ongoing microbial processing result from this. Despite the high biochemical richness of plum residues, these temporal constraints partially explain Serbia’s lower level of technological adoption.

Both countries have acknowledged the need to expedite the use of organic waste and have connected their agriculture plans with the EU Green Deal and the Circular Economy Action Plan at the policy and system level. However, there is still a lack of the infrastructure needed for large-scale biopolymer synthesis, such as fermentation facilities, biorefineries, and effective pre-treatment systems. Despite solid scientific evidence supporting the widespread usage of residue-based biological products, this structural deficiency leads to low recovery rates. In addition to lessening the negative effects of unchecked decomposition on the environment (methane emissions, leachate formation, eutrophication), increasing these capacities will make it possible to produce high-value materials, including BC, nanocellulose, and pectin-based composites domestically.

The comparative analysis also reveals that Türkiye has a quantitative and infrastructural advantage due to its large-scale fruit processing industry, whereas Serbia has a qualitative advantage driven by the high fiber content of plum pomace. This complementarity demonstrates how cooperative biorefinery models and information sharing between nations may be crucial in hastening regional bioeconomic changes. This complementary relationship emphasizes the potential contribution of exchange of information, shared biorefinery models, and cross-border cooperation to the acceleration of regional bioeconomic development. Both countries show outstanding potential for creating integrated value chains that promote rural economic growth, reduce the burden on waste management systems, and assist in achieving SDGs 12 and 13.

Overall, the study indicates that grape and plum pomace have high biochemical suitability for biopolymer-focused value recovery; however, targeted advancements in infrastructure, technology, and policy frameworks are required to fully unlock this potential. Both in Türkiye and Serbia, the conversion of these waste materials into BC, nanocellulose and pectin-based biopolymers offers a technically feasible and strategically compatible path towards sustainable industrial development.

Several limitations should be considered when interpreting these findings. First, the analysis is mostly reliant on secondary datasets (FAOSTAT, TÜİK, and STAT), which may introduce variability due to differences in reporting standards, crop classifications, or data update frequencies among agencies. Variation associated with climate conditions, processing techniques, and storage conditions may not be fully captured, as biochemical composition data were compiled from direct experimental analysis. Moreover, the lack of government information on waste recovery in the fruit processing industry is reflected in the recovery rates described in the literature, which are generalized estimates rather than country-specific measures. Finally, economic metrics like value-added multipliers may not accurately reflect small-scale producers or the informal processing sector because they are dependent on national reports that are currently available.

To enable more accurate modeling of biochemical conversion efficiencies, future research should experimentally evaluate biopolymer yields at the laboratory scale using grape and plum pomace collected from Türkiye and Serbia. Cross-raw material comparisons could be enhanced by creating a common biopolymer compatibility index that incorporates polysaccharide content, extraction capacity, fermentation performance, and pretreatment energy requirements. To quantify the economic and environmental benefits of the proposed valorization pathways under realistic industrial conditions, techno-economic analysis and life cycle assessment (LCA) are also required. Pilot-scale biorefinery design that emphasizes continuous processing and seasonal stabilizing techniques will be made possible by cooperation with nearby vineyards, brandy manufacturers, and food processing facilities. Including other regional fruits like pomegranate, apricot, and apple residues could further enhance bio-based innovation capacity and facilitate more extensive circular economy transitions in both nations.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Contributions

The authors declare that they have contributed equally to the article.

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