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Waste-free production of non-alcoholic wine as a sustainable technology

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Abstact. The growing demand for non-alcoholic wines, along with issues related to waste disposal and environmental pollution amid military conflicts, natural disasters, and industrial emissions, necessitates the implementation of environmentally sustainable technologies in the winemaking industry. This article presents the concept of zero-waste production of non-alcoholic wine as an innovative approach that integrates the principles of circular economy and sustainable development. A comprehensive utilization of grape raw materials is proposed for the production of non-alcoholic wine, food concentrate, and ethanol, which enhances both the environmental and economic efficiency of the production process.

1. Introduction

In the 21st century, the food industry, particularly the winemaking sector, is undergoing a profound transformation driven by environmental, economic, and social challenges. In the context of climate change, depletion of natural resources, and increasing environmental pollution, society is increasingly turning to the principles of sustainable development, which emphasize the harmonious coexistence of economic activity with the natural environment. Within this framework, the implementation of a circular economy is gaining special importance—a model that prioritizes the efficient use of resources, reuse of raw materials, and minimization of waste.

At the same time, consumer interest in healthy lifestyles and functional food products is growing. Among these is non-alcoholic wine, which has gained popularity as an alternative to traditional alcoholic beverages among drivers, pregnant women, athletes, Muslim communities, and individuals who follow conscious consumption practices. However, traditional wine production, even of non-alcoholic varieties, remains a significant source of waste—such as pomace, skins, seeds, stems, and lees—that is often not recycled but disposed of, creating an additional burden on ecosystems.

This situation is further exacerbated in countries affected by war or undergoing post-crisis recovery, such as Ukraine. The war has caused not only the physical destruction of vineyards and processing facilities but also logistical complications, market losses, and investment shortages. Under such conditions, it is critically important to optimize production processes, reduce costs, minimize waste, and at the same time create products with high added value.

One innovative response to these challenges is the technology of zero-waste non-alcoholic wine production. This approach is based on the comprehensive use of all grape components—not only for producing the wine itself but also for manufacturing food concentrates, extracting purified ethanol for use in the food, cosmetics, or energy industries, and producing biofuels. This strategy not only reduces the environmental impact but also creates new economic opportunities for producers.

Thus, the development and implementation of a zero-waste model in non-alcoholic wine production is not merely a technological innovation but part of a broader environmental and economic strategy that aligns global trends in sustainable development with local needs for the recovery and modernization of Ukraine's agro-industrial complex.

2. Materials and Methods

As part of the research, a technological model for zero-waste production of non-alcoholic wine was developed and tested. This model involves the comprehensive utilization of grape raw materials with subsequent extraction of valuable components from both the primary and by-products of winemaking. The research focused on berries of technical varieties of red and white grapes harvested at full technological ripeness in the southern regions of Ukraine. The raw material met

standard parameters for sugar content (18–22% by mass), titratable acidity (5–7 g/dm³), and a phenolic profile characteristic of the variety.

The primary processing included crushing, pressing, and fermentation of the grape must according to the standard winemaking scheme. After fermentation was complete, the resulting wine was subjected to dealcoholization using vacuum distillation. This method was chosen as the most effective for preserving volatile aromatic compounds and the sensory characteristics of the product, owing to the use of reduced pressure and a temperature regime of 30–40 °C. The process resulted in a reduction of ethanol content to a level not exceeding 0.5% vol., in compliance with the standards for non-alcoholic products. The resulting distillate, enriched with alcohol up to 70–80%, was additionally purified by filtration and rectification to assess its suitability for use in the production of food, cosmetic, and energy products [1].

The remaining grape pomace, including skins, seeds, and stems, was dried at 40 °C and ground to a homogeneous state for further analysis of biologically active compounds. The total polyphenol content in the samples was determined spectrophotometrically using the Folin–Ciocalteu reagent, with results expressed in mg of gallic acid equivalent per gram of dry weight (mg GAE/g). The flavonoid content was measured using the aluminum chloride method, with results expressed in mg of rutin equivalents per gram of dry weight (mg RE/g). Additionally, the chemical composition of the distillate was analyzed using gas chromatography, while the organoleptic properties of the final non-alcoholic wine were evaluated by a tasting panel using a 20-point scale adapted for alcohol-free beverages.

All results were subjected to statistical processing using OriginPro 2022 software. To determine the significance of differences between samples, Student's t-test was applied with a significance level of $p < 0.05$. The study enabled a detailed characterization of the effectiveness of the main production stages and assessed the potential of by-products for the creation of innovative value-added products within the framework of a zero-waste winemaking strategy.

3. Results and Discussion

According to national estimates, Ukraine's winemaking industry generates more than 210 thousand tons of by-products annually, which accounts for over 22% of the total mass of processed raw materials. This is illustrated by the pie chart (Fig. 1), which shows that only 78% of the grape mass is directly used in wine production, while the remainder constitutes waste that often remains unutilized or is disposed of inefficiently.

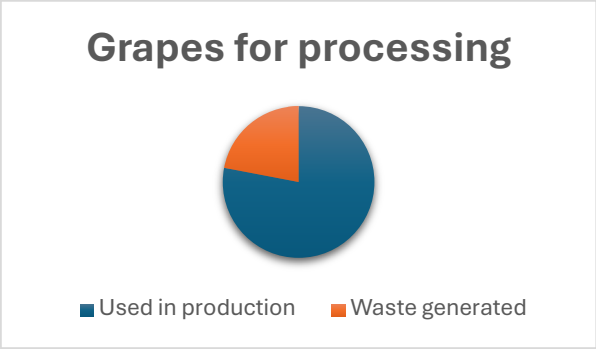

Figure 1. Share of winemaking waste in total raw materials

These wastes contain a significant amount of valuable components—sugars (fructose, glucose), phenolic compounds, as well as ethanol—which makes them a promising raw material for secondary processing. Ignoring this raw material means not only environmental risks but also a loss of potential added value for enterprises.

One of the richest sources of such biologically active substances is grape pomace, which includes skins, seeds, and remnants of pulp. To assess its bioactive potential, the content of polyphenols and flavonoids in red and white pomace was analyzed. The results of these measurements are shown in Figure 2.

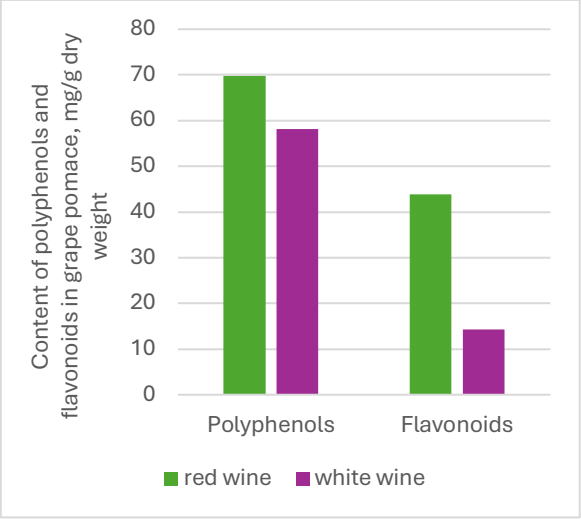

Figure 2. Content of polyphenols and flavonoids in grape pomace (mg/g dry weight)

These results indicate an exceptionally high potential of red pomace as a raw material for the production of antioxidant concentrates, extracts for healthy nutrition, as well as ingredients for cosmetic products. This level of bioactivity allows for the creation of value-added products, ensuring both environmental and economic efficiency.

However, to make the production truly zero-waste, it is necessary to consider the key technological stage — wine dealcoholization — which presents both advantages and challenges. One of the most effective methods is vacuum distillation, which enables the removal of 50–60% of ethyl alcohol at temperatures of 30–40°C, while preserving the organoleptic properties of the product. Nevertheless, this method requires a

significant amount of energy, which raises concerns about its environmental sustainability unless renewable energy sources are used [3].

Figure 3 presents a comparative evaluation of the two main dealcoholization methods: vacuum distillation and reverse osmosis — based on two criteria: organoleptic quality and energy consumption.

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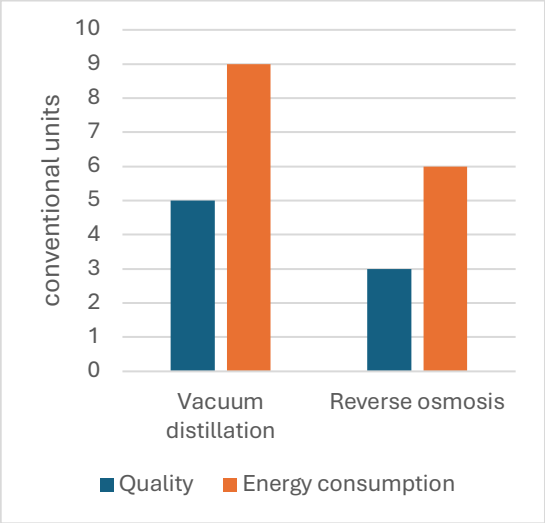

Figure 3. Comparison of dealcoholization methods

This highlights the need to optimize energy consumption while preserving the sensory properties of non-alcoholic wine. It is advisable to implement hybrid systems, reuse heat, and transition to green hydrogen or biogas as energy sources.

In addition to non-alcoholic wine, the full use of grape raw materials enables the production of other valuable products. For example, purified ethanol can be used in pharmaceuticals or as fuel for bioethanol engines. Grape pomace can serve as a source of food concentrates, antioxidants, probiotic ingredients, as well as biomass for compost or biogas production.

A particularly noteworthy example is the French company TotalEnergies, which has already introduced to the market a 100% renewable fuel—Excellium Racing 100—produced from winemaking waste. This approach enables over a 65% reduction in CO_2 emissions from racing cars, demonstrating the practical effectiveness of a zero-waste cycle in real-world production.

4. Conclusions

Waste-Free production of non-alcoholic wine represents a sustainable technology that combines innovation, environmental responsibility, and economic efficiency. A single technological process can yield three types of products: non-alcoholic wine, ethanol for further processing, and a food concentrate rich in antioxidants. This allows the wine industry not only to enhance its environmental sustainability but also to significantly expand its capabilities in response to current global challenges—contributing to the development of a circular economy and meeting consumer demand for healthy and environmentally safe nutrition.

5. References

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