

The influence of technological sequences in conventional and organic viticulture on some parameters

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Abstract

The research was conducted between 2022 and 2024 in a vineyard located within the Recaş Viticultural Center, in the Petrovaselo viticultural area. The planting distances were 2.2 m between rows and 1 m between vines within a row, resulting in a planting density of 4,545 vines per hectare. Four grape cultivars were studied: two high-quality white wine cultivars, 'Italian Riesling' and 'Chardonnay', and two high-quality red wine cultivars, 'Cabernet Sauvignon' and 'Fetească Neagră'. The experimental treatments were based on key viticultural practices that significantly impact physiological and technological indicators, which are applied differently in conventional and organic viticulture, including soil management, fertilization, pest and disease control. In organic viticulture, soil management practices impose certain restrictions on the use of specific substances, such as fertilizers and pesticides, as well as limitations on fuel consumption. Therefore, these practices must be carefully defined and adapted to the soil type and environmental conditions of the viticultural area. In wet years, soil management operations, such as tillage and irrigation, become more challenging compared to drier years. Regarding organic fertilization, which restricts the use of chemical fertilizers, all organic fertilization methods studied—except for green manure—were found to be viable alternatives. Pest and disease control is the viticultural practice with the greatest differences in approach between conventional and organic viticulture. It is also the most constrained and difficult to manage due to restrictions on chemical treatments and the reliance on alternative pest management strategies in organic farming.

Keywords: grape varieties, organic farming, soil management, sugar, wood

Introduction

Given the diverse pedo-climatic conditions in which vines are grown, the diversity of varieties with distinct biological traits, as well as the influence of traditions, customs, practical expertise, and financial resources, it is difficult to establish a uniform technology for grapevine cultivation [18]. Consequently, cultivation technologies must be implemented, optimized, and tailored according to various circumstances, including the cultivated variety, the climatic and pedological conditions of each region, the growing season climate variability, and certainly the financial capabilities of each vineyard owner [19]. Considerations about health and the environment have contributed to an increase in the total area of land cultivated in organic farming system throughout the world in recent decades [33]. Management strategies, climate, and the local environment, substantially affect crop growth and development with grapevine proving to be well-suited to this agricultural system [5, 31]. To minimize the environmental impact, no synthetic chemicals are applied in organic viticulture. As therefore, instead of mineral fertilizers, humus, compost, or other organic nutrients are used for fertilization. This trend continues in crop treatments, with only sulfur and copper applied for controlling powdery mildew [14]. Fertilization methods influence plant growth and development, including morphology and chemical composition [6]. Crops benefit from nutrient-rich environment; however, excessive nutrients application reduces photosynthesis, allowing the incorporation of all nutrients absorbed as higher-molecular-weight compounds, like secondary metabolites [17]. Conventional viticulture is among the most pesticide-intensive agricultural systems [1]. For example, in France, grape production accounts for less than 3% of total agricultural land, but however consumes about 20% of total pesticide [15]. In Italy, almost 200 different

pesticides have been registered only for viticulture [7]. The intensive use of pesticides increases the systemic resistance of pests to treatments [17] and has a negative influence on beneficial organisms, including terrestrial and soil fauna and flora [25].

Grape yield in organic viticulture is comparable to other crops from conventional agriculture, and do not compromise the economic productivity [4]. On the contrary, a German study found that organic grape yield was 35.9% lower than in the conventional system, with slower vegetative development and smaller grape production [19]. This is supported by other studies, like Collins et al. (2020) [13] results from Australia vineyards, which found that production in organic viticulture is 21% lower than in conventional one and requires more investment. Other research findings indicate that in organic viticulture, soil quality is improved in comparison to conventional systems; Collins et al. (2020) [13] and Cichi et al. (2018) [11] discovered that there are more microorganisms in the soil, such as earthworms, which are more abundant in eco-viticulture. Coll et al. (2011) [12] reached the same conclusion, observing that soil organic matter and soil microbial biomass is increased in organic viticulture.

Therefore, minimizing pesticide application in vineyards and employing more environmentally friendly vineyard management has become a priority. In recent years, organic viticulture area has grown in the majority of EU member countries. It still represents a small percentage of overall agricultural land, but it is expected to grow significantly in the near future [39]. The main objective of this study was to assess the effects of various vineyard management systems—conventional and organic—on grapevine physiological and morphological development, with especially focused on grape quality and related vegetative traits, in the pedoclimatic conditions of the Recaş Viticultural Center (Petrovaselo area) during the 2022-2024 growing seasons.

Material and Method

Research was carried out from 2022 to 2024 growing seasons, within the Recas viticultural Center, in the Petrovaselo vineyards. Planting distance was 2.2 m interrows rows, and 1 m between vines on row, resulting a density of 4,545 vines per hectare. Four cultivars were evaluated: two for superior white wines, 'Italian Riesling' and 'Chardonnay', and two for superior red wines: 'Cabernet Sauvignon' and 'Feteasca Neagra'. All vines were trained on a bilateral cordon system with mixed pruning (Guyot), and canopy management followed standard local viticultural practices. The experimental plots were established for several technological chains with a major impact on biological and technical parameters, which are carried out differently in conventional than in organic viticulture. A randomized block design was applied, with three replications per treatment and 30 vines per replicate. The experimental plots for interrow management were mechanical mowing, mechanical weeding + herbicide, organic system, and no-till (control). V1 (conventional fertilization), V2 (green fertilizers), V3 (Fertilpolina®), and V4 (Fertilpolina® + Cropmax®) were the experimental plots for fertilizing. V1 (conventional control), V2 (organic control), and V3 (mixed control) were the experimental plots for disease and pest control.

Observations and assessments were conducted on the experimental plots concerning the following parameters: vegetative growth per vine, grape yield per vine and grape production, grape must acidity, sugar content in grape must, total sugar per hectare, and economic performance indicators. The economic evaluation included total production expenses per hectare, production cost per kilogram of grapes, total production value, and net profit. These indicators allowed comparison of the economic efficiency for conventional and organic vineyard management systems. All economic data were averaged over the 2022–2024 period. Harvest was conducted at full technological maturity for each cultivar, and grape must analyses were performed according to OIV (International Organisation of Vine and Wine) standards. Data obtained from field and laboratory measurements were statistically processed using analysis of variance (ANOVA) to determine the significance of treatment effects. When significant differences were observed, Tukey's Significant Difference (HSD) test was applied for mean separation at a probability level of $p < 0.05$. All statistical computations were carried out using XLSTAT (Addinsoft, Paris, France, 2024.1), integrated with Microsoft Excel, which enabled both parametric and descriptive analyses. Results are presented as mean \pm standard deviation (SD), and treatment effects are discussed based on their statistical significance and agronomic relevance.

Results and Discussion

The development of soil management systems has evolved over time, progressing from the bare soil field, which required repeated mechanical operations with agricultural equipment, to the herbicides applications, subsequent combinations of mechanical weeding and herbicides use, and finally, vineyard floor management by mowing. Each of these systems presents advantages and disadvantages; however no single approach can be considered universally optimal [3]. Over three-years of investigation (Table 1), the 'Italian Riesling' cultivar exhibited an average annual vegetative growth rate of 10.31 m per vine under the mowing

treatment and 10.86 m per vine under the bare soil (control) treatment. The organic soil management system recorded the second-highest vine growth performance, with an average of 10.81 m per vine. Regarding the proportion of mature cane wood, the highest value was observed in the bare soil treatment (89.59%), followed by the organic soil management treatment (88.99%) and the tillage + herbicide treatment (86.82%). For the 'Chardonnay' cultivar, both the annual vegetative growth and the percentage of mature cane wood showed trends similar to those observed in 'Italian Riesling'. In this variety as well, the bare soil (control) treatment achieved the highest percentage of mature cane wood, followed by the organic soil management and tillage + herbicide treatments.

Table 1. Influence of soil management system on cane wood maturation (2022–2024)

Cultivar	Soil management system	Total annual growth (m/vine) ± SD	Mature wood (m/vine) ± SD	Mature wood (% of total) ± SD
Italian Riesling	Bare soil (C)	10.86 ± 0.42 ^a	9.73 ± 0.38 ^a	89.59 ± 2.5 ^a
	Mechanical weeding + herbicide	10.70 ± 0.39 ^{ab}	9.29 ± 0.36 ^{ab}	86.82 ± 2.8 ^{ab}
	Mechanical mowing	10.31 ± 0.37 ^c	8.59 ± 0.33 ^c	83.31 ± 2.7 ^c
	Organic	10.81 ± 0.41 ^a	9.62 ± 0.37 ^a	88.99 ± 2.6 ^a
Chardonnay	Bare soil (C)	10.12 ± 0.36 ^a	8.81 ± 0.32 ^a	87.05 ± 2.4 ^a
	Mechanical weeding + herbicide	9.96 ± 0.35 ^{ab}	8.51 ± 0.30 ^{ab}	85.44 ± 2.5 ^{ab}
	Mechanical mowing	9.57 ± 0.33 ^b	7.70 ± 0.29 ^b	80.45 ± 2.9 ^b
	Organic	9.95 ± 0.34 ^{ab}	8.51 ± 0.31 ^{ab}	85.52 ± 2.6 ^{ab}
Fetească Neagră	Bare soil (C)	16.21 ± 0.53 ^a	13.39 ± 0.45 ^a	82.60 ± 2.9 ^a
	Mechanical weeding + herbicide	15.97 ± 0.51 ^{ab}	12.81 ± 0.42 ^{ab}	80.21 ± 2.8 ^{ab}
	Mechanical mowing	15.59 ± 0.50 ^b	11.91 ± 0.40 ^b	76.39 ± 3.2 ^b
	Organic	15.99 ± 0.52 ^{ab}	13.21 ± 0.44 ^a	82.61 ± 2.7 ^a
Cabernet Sauvignon	Bare soil (C)	15.38 ± 0.49 ^a	13.21 ± 0.43 ^a	85.89 ± 2.6 ^a
	Mechanical weeding + herbicide	15.16 ± 0.47 ^{ab}	12.71 ± 0.41 ^{ab}	83.83 ± 2.5 ^{ab}
	Mechanical mowing	14.90 ± 0.46 ^b	12.10 ± 0.39 ^b	81.20 ± 2.8 ^b
	Organic	15.26 ± 0.48 ^{ab}	12.97 ± 0.42 ^a	84.99 ± 2.6 ^{ab}

*Means followed by different letters (a–c) differ significantly according to Tukey's HSD test ($p < 0.05$)

Average annual vegetative growth for the 'Fetească Neagră' cultivar, varied across treatments over the three-years of research. The growth rate ranged from a minimum of 15.59% in the mowed soil management to a maximum of 16.21% in the bare soil (control). The organic management system exhibited the second-highest average growth rate at 15.99%. Despite the inherently vigorous nature of the 'Fetească Neagră', all treatments demonstrated favorable average wood maturation rate, indicating successful lignification with no associated issues. The bare soil (control) treatment recorded the highest proportion of mature wood, reaching 82.6%. The results from organic management plot followed closely with 81.61%, while the mowed soil management treatment yielded the lowest maturation rate, at 76.39%. The influence of the experimental treatments was more emphasized on the quantitative parameters (e.g., yield and growth) than on the qualitative parameters of the grapes (Table 2). Under the specific pedoclimatic conditions of Petrovaselo, the efficacy of biological soil management was found to be the most comparable to that of the bare soil treatment (control). Conversely, the use of herbicides, and especially the practice of mowing, resulted in the weakest performance regarding quantitative vine parameters [2,18].

The main objective of vineyard management is to improve grape quality, and the condition of the vineyard floor—whether controlled by tillage, cover crops, or mowing—is an important but complex issue influencing vine physiology. Principal Component Analysis (PCA) was used to map these intricate connections.

The Principal Component Analysis (PCA) biplot (Figure 1), which accounted for 96.23% of the total variance, revealed a clear differentiation among grape cultivars and vineyard management systems, highlighting the combined influence of genotype and agronomic practices on grape composition and yield. The distribution of samples along the first two principal components demonstrates that soil management intensity

and nutrient availability strongly influence the physiological balance between sugar accumulation and acidity, consistent with the findings of Döring et al. (2015) [19] and Collins et al. (2020) [13].

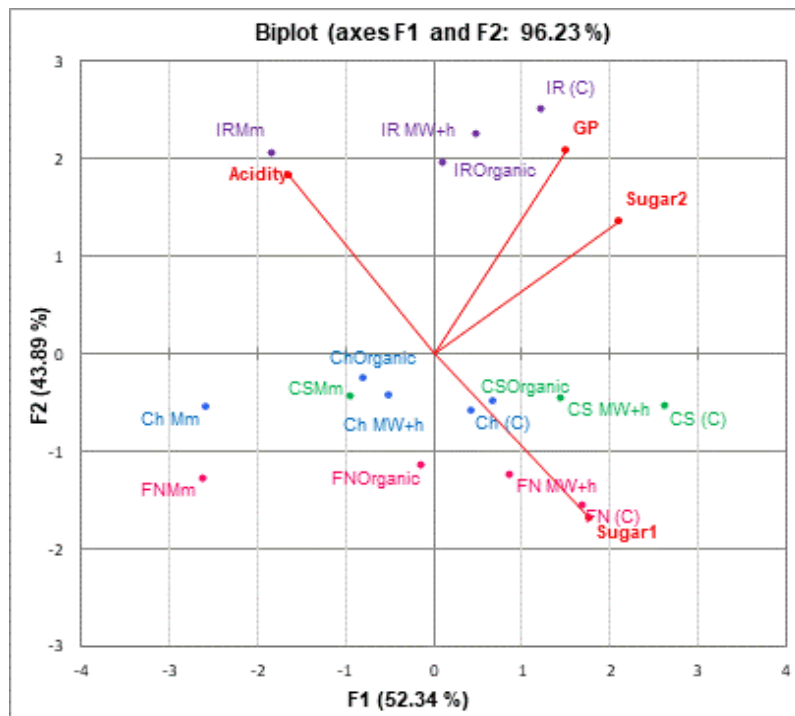


Figure 1. PCA diagram for grape quality relationship with vineyard floor management across 2022-2024 growing seasons in Petrovaselo area ('Cabernet Sauvignon' (CS), 'Feteasca Neagra' (FN), 'Chardonnay' (Ch), 'Italian Riesling' (IR); Bare soil (C) Mechanical weeding (MW) + herbicide(h), Mechanical mowing (Mm), Organic; Sugar 1 = sugar from grape must (g/l), Sugar 2 = total sugar (kg/ha))

'Cabernet Sauvignon' (CS) clustered near the vectors associated with high sugar concentration and yield under both conventional (bare soil) and semi-intensive (mechanical weeding + herbicide) systems, reflecting its efficient photosynthetic performance and carbohydrate accumulation. This pattern corroborates the observations of Rogiers et al. (2022) [33], who reported that conventional management enhances berry ripening through improved nitrogen and potassium uptake. Conversely, CS samples from organic and mowing treatments exhibited moderate sugar levels and a more balanced vegetative-reproductive ratio, suggesting improved physiological stability and reduced metabolic stress, as also noted by Guerra et al. (2024) [23] in organically managed vineyards.

'Fetească Neagră' (FN) displayed a strong positive correlation with sugar accumulation and a negative one with acidity, indicative of high metabolic activity and sensitivity to canopy and nitrogen management. Maximum sugar accumulation was observed in control plots, while similar performance under mechanical weeding + herbicide conditions reflects the cultivar's adaptability to reduced-input systems. In contrast, organic and mowing treatments resulted in slower ripening and higher acidity, aligning with the findings of Vršič et al. (2024) [38] and Geng et al. (2022) [22], who associated organic systems with delayed sugar accumulation due to moderated nutrient mineralization and microbial competition.

Among white cultivars, 'Chardonnay' (Ch) and 'Italian Riesling' (IR) showed distinct adaptive patterns. 'Chardonnay' under control and mechanical weeding + herbicides conditions exhibited balanced sugar-acid ratios, typical of aromatic, fresh wine profiles, whereas samples from organic and mowing treatments aligned with the acidity vector, suggesting enhanced acid retention and moderated sugar buildup. Comparable outcomes were described by Lazcano et al. (2020) [26] and Döring et al. (2015) [19], linking low-input systems to improved acid stability via restrained canopy vigor and cooler microclimates. 'Italian Riesling', a late-ripening cultivar, consistently retained high acidity, particularly under organic management, corroborating its genotypic tendency toward slower ripening in nutrient-limited soils [35]. The PCA further distinguished four management-related clusters: bare soil (C) - characterized by high sugar content and yield with reduced acidity, representative of intensive mineral nutrition and accelerated ripening; mechanical weeding + herbicide (MW+h)

- displaying balanced sugar and yield performance with a reduced environmental footprint, supporting transitional sustainability [30]; mechanical mowing (Mm) - marked by intermediate acidity and moderate sugar levels, reflecting controlled vigor and stable canopy microclimates; and organic - producing lower sugars and yields but higher acidity and improved environmental resilience, in agreement with Collins et al. (2020) [13] and Mania et al. (2021) [28]. The PCA confirms that while vineyard management practices significantly modulate vine physiology, cultivar-specific traits—such as ripening kinetics, nutrient-use efficiency, and stress tolerance—ultimately determine the magnitude and direction of response. These findings emphasize the necessity of adopting site- and cultivar-specific viticultural strategies that integrate productivity with sustainability goals, aligning with emerging paradigms in climate-smart viticulture [21,37]. The red wine cultivars accumulated substantial amounts of sugars, with values that were relatively similar. While vineyard floor management exerted a measurable influence on grape quality, the effect was less pronounced overall. In all cultivars, the treatment involving mowing soil management resulted in significantly lower quality parameters compared with the control. Although the control treatment exhibited the highest energy consumption and carbon emissions, it also produced the most favorable quality outcomes. This observation was anticipated, as the control relied on more rigorous weed suppression and benefited from enhanced soil heat accumulation associated with intensive soil loosening.

Soil management expenditures (Table 2) represent a major component of total production costs per hectare and therefore exert a strong influence on overall profitability. Reducing these costs through work optimization, minimizing the number of operations, and performing soil interventions at the most appropriate time leads to a decrease in expenditures associated with this technological chain, ultimately contributing to maximized profit.

Table 2. The influence of the soil management system on the average profit 2022-2024

Soil management	Total expenses (lei/ha)	Cultivars	Grape production value (lei/ha)	Profit (lei/ha)	Difference from control (lei/ha)
Bare soil (C)	9534	'Italian Riesling'	23045	13511	-
		'Chardonnay'	19978	10444	-
		'Feteasca Neagra'	29856	20322	-
		'Cabernet Sauvignon'	32015	22481	-
Mechanical weeding (MW) + herbicide (h)	9056	'Italian Riesling'	22379	13323	-228
		'Chardonnay'	19587	10531	87
		'Feteasca Neagra'	29278	20222	-100
		'Cabernet Sauvignon'	31079	22023	-458
Mechanical mowing (Mm)	8103	'Italian Riesling'	20802	12699	-852
		'Chardonnay'	18156	10053	-391
		'Feteasca Neagra'	26321	18218	-2104
		'Cabernet Sauvignon'	29574	21471	-1010
Organic	8871	'Italian Riesling'	32784	23913	10362
		'Chardonnay'	28802	19931	9487
		'Feteasca Neagra'	37988	29117	8795
		'Cabernet Sauvignon'	40502	31631	9150

The grape production value per experimental plot exhibited high levels per hectare, ranging from 28,802 lei for the 'Chardonnay' cultivar to 40,502 lei for 'Cabernet Sauvignon'. Within the organic management system, 'Fetească Neagră' achieved the second-highest production value, reaching 37,988 lei per hectare. Profitability followed a similar pattern, with red cultivars generating higher profit margins than white cultivars, a trend also influenced by the price premium for red wine grapes. The highest profit values were recorded, in descending order, for 'Cabernet Sauvignon', 'Fetească Neagră', and 'Italian Riesling' [29]. Organic soil management resulted in positive profit differentials per hectare compared with the control treatment across all cultivars.

Conversely, the soil-management strategy based on mowing, although associated with the lowest operational costs per hectare, produced the lowest outcomes in both production value and profit. Under this management system, the highest production values were recorded for the 'Cabernet Sauvignon' and 'Fetească Neagră' cultivars. The bare soil (control) system ranked second for most cultivars for both grape production value and profit. This positioning was influenced, by its relatively higher production costs or by the

comparatively lower market price of the grapes. The profit for this soil-management experimental plot ranged from 10,053 lei/ha for the ‘Chardonnay’ cultivar to 21,471 lei/ha for ‘Cabernet Sauvignon’.

Notably, the mechanical weeding + herbicide treatment produced higher profits than the control only for the ‘Chardonnay’ and ‘Fetească Neagră’ cultivars. Across the three-years of research, the herbicide-based maintenance system proved markedly inferior to the control, similar to the mowing system, both in terms of production value and net profit. The differences relative to the control were significantly negative, reaching -2,104 lei/ha in ‘Fetească Neagră’. The experimental soil-management approaches tested in this study were designed as sustainable alternatives to conventional fertilization, offering potential agronomic and environmental benefits. However, because these strategies have been rarely implemented in this form in Romanian viticulture, extended multi-year trials are required to fully capture climatic variability and provide robust long-term recommendations.

For the influence of fertilization system on the wood maturation, the principal component analysis (PCA) biplot (F1 = 73.15%, F2 = 26.81%; cumulative variance is 99.97%) effectively differentiates grapevine cultivar responses to soil fertilization strategies in relation to total annual shoot growth and matured shoot length (Figure 2).

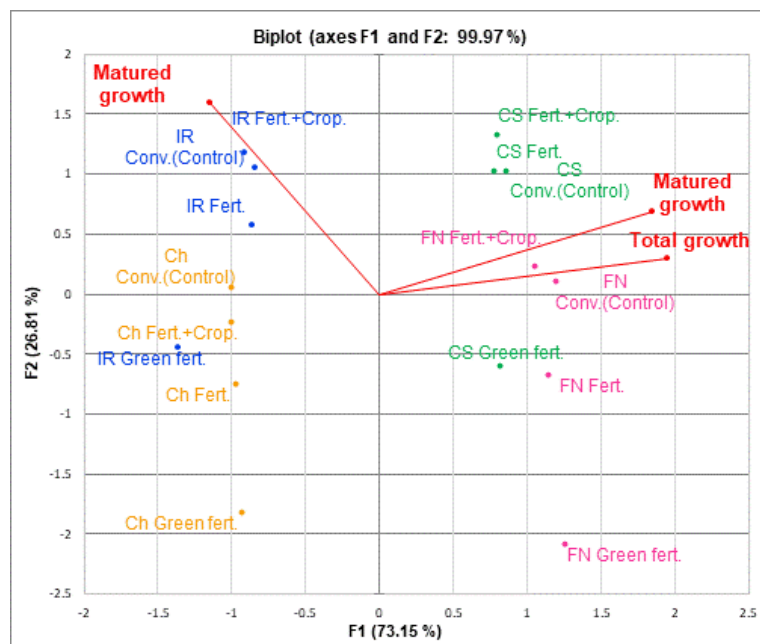


Figure 2. The PCA diagram for the influence of fertilization system on the wood maturation (2022 – 2024) (‘Cabernet Sauvignon’ (CS), ‘Fetească Neagră’ (FN), ‘Chardonnay’ (Ch), ‘Italian Riesling’ (IR); Bare soil (C) for Conventional (Control), Green fertilization (Green fert), Fertilpolina (Fert) and Fertilpolina + Cropmax (Fert. +Crop)

The first axis (F1) explains most of the variability, separating treatments according to overall vegetative vigor and wood maturation capacity, while the second axis (F2) distinguishes treatments based on the efficiency of growth maturation, expressed as the proportion of mature wood relative to total shoot length.

‘Cabernet Sauvignon’ (CS) treatments reflect the highest total and matured shoot growth among cultivars. The conventional control, Fertilpolina, and Fertilpolina + Cropmax treatments confirm their superior capacity to stimulate both vegetative vigor and shoot lignification. In contrast, green fertilization treatments for CS shifted slightly downward on F2, indicating reduced maturation efficiency despite moderate growth. Similar trends were observed for ‘Fetească Neagră’ (FN), displayed slightly lower scores than CS, suggesting high growth potential that is more sensitive to nutrient availability under green fertilization. The highest performance for FN occurred under conventional and Fertilpolina + Cropmax regimes, while green fertilization resulted in a reduced proportion of matured shoots.

White cultivars demonstrated distinct behavior; ‘Chardonnay’ (Ch) was the cultivar with the lowest total and matured growth among other cultivars. Although the conventional treatment yielded relatively balanced development, all organic variants, particularly green fertilization, reduced lignification capacity, underscoring ‘Chardonnay’s’ lower vigor and higher sensitivity to nutrient stress.

'Italian Riesling' (IR) indicate moderate vigor but efficient shoot maturation, particularly under conventional and Fertilpolina + Cropmax treatments. However, green fertilization again resulted in reduced maturation, mirroring 'Chardonnay's' response.

Organic nutrient systems based on Fertilpolina—especially when combined with the biostimulant Cropmax—enhanced vegetative growth and maturation in a manner comparable to or exceeding conventional mineral fertilization. Conversely, green fertilization alone proved insufficient to sustain balanced growth, particularly for vigorous red cultivars.

These findings highlight cultivar-specific nutrient responses, confirming that 'Cabernet Sauvignon' and 'Fetească Neagră' exhibit high vigor and wood maturation potential optimally expressed under protein-based organic fertilization with biostimulant support, while white cultivars, especially 'Chardonnay', require more targeted and nutrient-rich organic inputs for optimal performance. The results reinforce the agronomic feasibility of Fertilpolina-based systems in premium viticulture, in line with recent evidence supporting organic nutrient inputs and biostimulants for improving vine growth and physiological balance [9, 16, 34]. Furthermore, the variability in cultivar responses underscores the need for cultivar-adapted soil management programs, consistent with recent studies emphasizing genotype–environment–management interactions in vineyard sustainability strategies [24, 36].

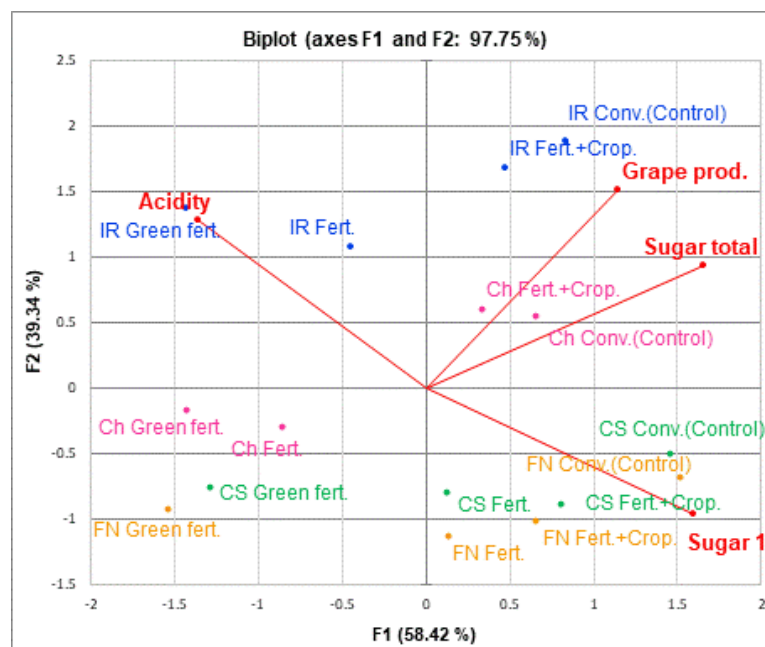


Figure 3. PCA diagram for the influence of the fertilization system on the average grape production and quality 2022-2024 ('Cabernet Sauvignon' (CS), 'Fetească Neagră' (FN), 'Chardonnay' (Ch), 'Italian Riesling' (IR); for Conventional (control), Green fertilization, Fertilpolina and Fertilpolina + Cropmax influence on grape production (kg/ha), acidity (g/l H₂SO₄), sugar1 (g/l) sugar total (kg/ha)

The principal component analysis (PCA) biplot (F1 = 58.42%, F2 = 39.34%; cumulative variance = 97.75%) provides a comprehensive overview of the relationships between fertilization practices and key grape production and quality parameters—yield (kg/ha), acidity (g/L H₂SO₄), must sugar concentration (g/L) and total sugar accumulation per hectare (kg/ha)—for four cultivars ('Cabernet Sauvignon', 'Fetească Neagră', 'Chardonnay', and 'Italian Riesling'). Axis F1 primarily separates treatments according to sugar accumulation and grape productivity, whereas F2 differentiates samples based on acidity level, capturing the classic inverse relationship between sugar accumulation and titratable acidity. The loading vectors show strong positive correlations among grape production, total sugar content, and must sugar concentration, while acidity loads in the opposite direction, indicating that treatments promoting higher sugar synthesis and yield are associated with lower acidity.

'Cabernet Sauvignon' (CS) samples cluster in the lower right quadrant, aligning closely with must sugar and total sugar vectors in both conventional and organic (Fertilpolina and Fertilpolina + Cropmax) regimes. This indicates that CS consistently achieved high must sugar levels and total sugar yield under all

fertilization strategies, with organic-biostimulant supplementation further supporting sugar accumulation. Green fertilization positioned CS slightly further from sugar vectors and closer to negative F2 values, reflecting reduced acidity and moderately strong sugar responses. Overall, CS demonstrated stable productivity and high sugar accumulation capacity, corroborating its known high-vigour and late-ripening physiological profile.

'Fetească Neagră' (FN) displayed similar behavior to CS, clustering in the positive F1 region but slightly lower on F2, suggesting a tendency toward lower acidity and high sugar accumulation under conventional and organic-biostimulant inputs. Treatments using Fertipolina and Fertipolina + Cropmax closely matched conventional performance, confirming the potential of protein-based organic fertilization to sustain high technological grape quality. The green fertilization treatment, however, shifted markedly left and downward, highlighting reductions in sugar metrics and acidity, indicative of weaker ripening under reduced nutrient input. FN thus appears sensitive to nutrient limitations, requiring balanced fertilization to fully express its quality potential.

'Chardonnay' (Ch) samples grouped mainly in the central to left side of F1, reflecting moderate to lower sugar accumulation and yield relative to red cultivars. The conventional and Fertipolina + Cropmax treatments placed the variety closest to productivity and sugar vectors, while green fertilization shifted 'Chardonnay' toward lower F1 and slightly negative F2, indicating reductions in both sugar accumulation and total production. This confirms 'Chardonnay's' known responsiveness to nutrient availability and its tendency to exhibit constrained productivity under nutrient-limited systems.

'Italian Riesling' (IR) showed a distinct pattern, positioned primarily in the upper-left quadrant with a strong association to the acidity vector. This indicates that IR maintained higher acidity levels across treatments, characteristic of its varietal profile and early-ripening nature. The conventional and Fertipolina + Cropmax treatments produced improved yield and sugar performance relative to green fertilization, although the cultivar consistently favored elevated acidity. 'Italian Riesling' therefore exhibited strong maintenance of acid-sugar balance but was less efficient than red cultivars in achieving high sugar and yield under limited fertilization.

Across cultivars, organic fertilization with Fertipolina, especially when combined with Cropmax, resulted in performance comparable to conventional fertilization, supporting high sugar accumulation and production while maintaining varietal acidity profiles. In contrast, green fertilization alone frequently resulted in lower sugar metrics and, in some cases, decreased acidity, suggesting incomplete phenolic and technological maturation under reduced nutrient supply. These findings align with current literature highlighting that organic protein fertilizers and biostimulants can sustain grapevine performance and qualitative attributes when well-designed, whereas low-input systems may require careful cultivar- and site-specific adaptation [9, 24, 34]. The results demonstrate the viability of organic nutrient management in premium viticulture while emphasizing cultivar-specific nutritional demands and the importance of balanced supply to achieve optimal grape composition.

Disease and pest management is a crucial in viticulture, directly influencing key agro-biological and technological outcomes (Table 3). In growing seasons with unfavorable climatic conditions, these biotic stressors can cause substantial economic losses. Maintaining control is particularly challenging in organic viticulture systems, which are constrained by regulations limiting the use of conventional synthetic control products.

In 'Italian Riesling', the average total annual shoot and cane growth was narrow, ranging from 13.59 m per vine in the conventional control to 13.01 m per vine in the organic control. Shoot maturity rates also showed a treatment impact, decreasing from 90.79% in the conventional control to 84.39% in the organic control. This difference shows that organic management approaches have the ability to diminish the amount of mature wood, which is consistent with previous research in the region [18].

For 'Chardonnay', total annual vegetative growth varied from 11.99 m per vine in the organic control to 12.79 m per vine in the conventional control treatment. The conventional control also had the highest proportion of mature wood (88.34%), compared to 83.56% in the organic control. These results overall indicate that conventional fertilization had a positive effect on both vegetative growth and the subsequent rate of shoot lignification (wood maturation) across both cultivars, supporting previous findings on the strong influence of fertilization system on vine vigor [3].

The 'Fetească Neagră' cultivar's high genetic vigor resulted in the greatest total annual shoot growth per vine among all cultivars during the study period, ranging from 19.23 m per vine under the organic control system to 20.11 m per vine in conventional management. The vegetative vigor of 'Fetească Neagră' was associated with a lower rate of wood maturation; however, this did not necessitate compensatory measures for crop load management nor did it compromise winter hardiness.

Total annual shoot growth for the ‘Cabernet Sauvignon’ cultivar was higher than for ‘Riesling Italian’ and ‘Chardonnay’, but lower than in ‘Fetească Neagră’. In this variety, the standard control treatment had the highest influence on wood maturation, indicating the beneficial effect of balanced nutrient availability on shoot lignification and overall vegetative performance. Throughout the study, disease and pest management were the technical chains that had a major impact on shoot maturation. From this standpoint, the conventional control method proved to be the most successful, whereas biological control presented the most challenges.

Table 3. The influence of the system for disease and pest control on cane wood maturation (2022-2024)

Cultivar	Disease and pest control system	Total growth (m/vine) ± SD	Matured growth (m/vine) ± SD	Matured growth (% of total)	Difference from Control (C)	Significance	DL ₅ %	DL ₁ %	DL _{0.1} %
Italian Riesling	Conventional (C)	13.59 ± 0.42	12.33 ± 0.36	90.79 ± 1.8	–	–	2.11	3.98	6.75
	Organic	13.01 ± 0.38	10.98 ± 0.33	84.39 ± 1.6	–6.40	00			
	Mixed	13.20 ± 0.40	11.60 ± 0.35	87.88 ± 1.7	–2.91	0			
Chardonnay	Conventional (C)	12.79 ± 0.39	11.30 ± 0.32	88.34 ± 1.7	–	–	1.82	3.76	6.37
	Organic	11.99 ± 0.36	10.02 ± 0.30	83.56 ± 1.5	–4.78	00			
	Mixed	12.39 ± 0.38	10.65 ± 0.31	85.95 ± 1.6	–2.39	0			
Fetească Neagră	Conventional (C)	20.11 ± 0.61	16.81 ± 0.55	83.59 ± 2.0	–	–	2.97	4.95	7.93
	Organic	19.23 ± 0.57	14.81 ± 0.50	77.01 ± 1.8	–6.58	00			
	Mixed	19.48 ± 0.59	15.64 ± 0.52	80.28 ± 1.9	–3.31	–			
Cabernet Sauvignon	Conventional (C)	19.41 ± 0.58	17.11 ± 0.53	88.15 ± 2.1	–	–	2.87	4.75	7.53
	Organic	17.84 ± 0.54	14.49 ± 0.47	81.22 ± 1.9	–6.93	00			
	Mixed	18.48 ± 0.56	15.41 ± 0.49	83.39 ± 2.0	–4.76	00			

*MT (control): Conventional pest and disease management; Organic: Certified organic treatments without synthetic pesticides; Mixed: Integrated system combining mechanical and reduced-chemical control; Significance codes: 0 = significant ($p < 0.05$); 00 = highly significant ($p < 0.01$); – = not significant; DL (LSD): Least Significant Difference; values calculated using ANOVA across 2022–2024 data.

The combined control system, which includes chemical products for the three basic treatments with organically accepted compounds for the remaining treatments, has emerged as a feasible alternative for lowering pesticide use while maintaining adequate levels of total yearly growth and wood maturity. Regardless of yearly climate variations, biological disease and pest management remains the most demanding technological process to manage, with the greatest differences between conventional and organic viticulture systems [20].

In a favorable growing season, characterized by low disease and pest pressure, well-managed biological control can yield satisfactory outcomes. Conversely, during unfavorable climate with high pathogen and pest incidence, organic control—regardless of the specific products applied—becomes considerably more difficult to manage and often results in reduced yields. Under such conditions, compensation through higher product prices or subsidies is necessary to offset the production gap compared with conventional viticulture. On average, during research, the differences observed between conventional and organic control were statistically significant in all cultivars. Organic control proved particularly challenging to manage in varieties with compact berry clusters and those with later ripening.

The PCA biplot ($F_1 = 62.60\%$, $F_2 = 36.04\%$; cumulative variance = 98.65%) illustrates (Figure 4) the relationships between grapevine cultivars and the applied disease and pest control systems—Conventional (C), Mixed, and Organic—based on four key parameters: grape production (kg/ha), must acidity (g/L H_2SO_4), sugars in grape must (Sugar 1, g/L), and total sugar yield (kg/ha). The high cumulative variance ($\approx 99\%$) confirms that the two principal components adequately describe the multivariate structure of the dataset.

Higher values on the F_1 axis are associated with increased sugar content (both reducing and total) and higher yields, indicating stronger overall physiological performance. Conversely, negative F_1 loadings are linked with elevated acidity and lower sugar accumulation, reflecting delayed or incomplete berry ripening. The F_2 axis (36.04%) separates treatments by their relative balance between vegetative vigor and fruit compositional traits, distinguishing cultivars that maintain high acidity and moderate sugar accumulation from those achieving full maturity and higher sugar deposition. Conventional control systems for all cultivars (‘Fetească Neagră’, ‘Cabernet Sauvignon’, ‘Chardonnay’, and ‘Italian Riesling’) align closely with the vectors for total sugar, reducing sugars, and grape production, indicates that chemical pest and disease control facilitated optimal berry ripening and yield, consistent with enhanced photosynthetic capacity and reduced biotic stress. Such outcomes correspond with prior findings that conventional protection systems ensure stable productivity and favorable sugar–acid ratios, particularly under high disease pressure [32].

Under conventional management, 'Fetească Neagră' (FN) and 'Cabernet Sauvignon' (CS) show the strongest relationship to sugar from grape must (Sugar 1 g/l) and total sugar (kg/ha), indicating better ripening and carbohydrate accumulation. These cultivars also show high yield potential, confirming their resilience and strong response to intensive protection strategies. The combined control system, which includes limited chemical applications with organically authorized products, places these cultivars slightly to the left of the conventional treatments, implying a minor but tolerable decline in crop yield and sugar accumulation. This intermediate position supports the concept that integrated pest management (IPM) methods can minimize synthetic input consumption while preserving grape quality [8].

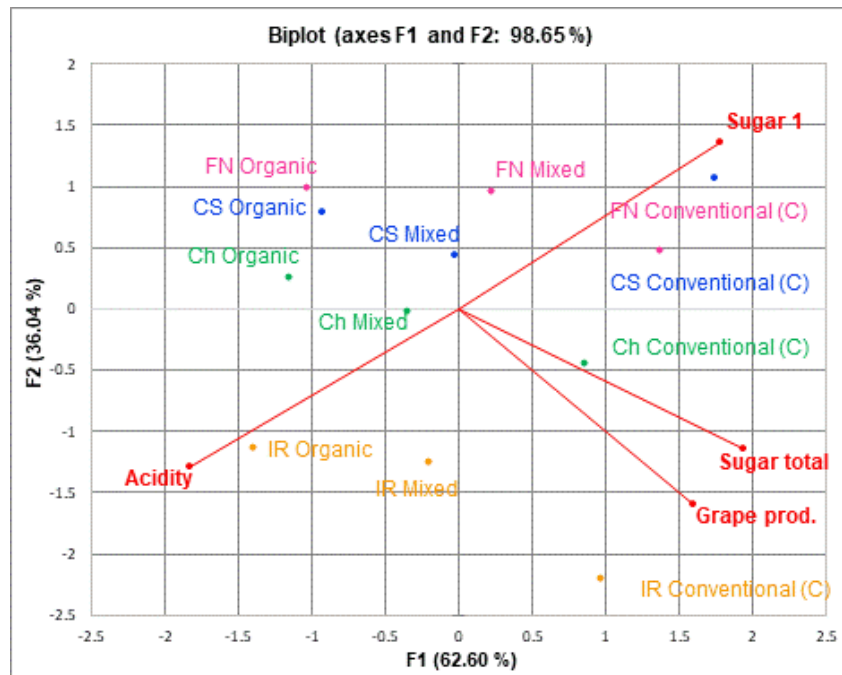


Figure 4. The PCA diagram for the influence of the disease and pest control system on the average grape production and quality 2022-2024 ((Cabernet Sauvignon (CS), Fetească Neagră (FN), Chardonnay (Ch), Italian Riesling (IR); for Conventional (control), Organic and Mixed treatments; Grape production (kg/ha), acidity (g/l H₂SO₄), Sugar1 (g/l), Sugar total (kg/ha)

The integrated control system, which merges limited chemical applications with organically approved agents, places these cultivars marginally to the left of standard treatments, indicating a small yet possible decline in grape yield and sugar accumulation. This intermediate position supports the perspective that integrated pest management (IPM) approaches might decrease chemical input use while preserving grape quality [8, 36].

'Chardonnay' (Ch) has moderate correlation with sugar-related vectors under both traditional and combined management, suggesting balanced ripening and appropriate sugar levels. Organic management shifts the cultivar's position towards the negative F1, showing less sugar accumulation and a minor rise in acidity. This reaction reflects 'Chardonnay's' recognized susceptibility to foliar disease pressure, which may decrease photosynthetic efficiency and carbohydrate transport [10].

'Italian Riesling' (IR) has the most distinct behavior, displaying on the far left of the biplot under organic and mixed treatments, near to the acidity vector. This orientation demonstrates a strong distinction between IR and red cultivars, indicating higher must acidity and reduced sugar accumulation. The traditional IR cultivar, shown on the opposite side, has the reverse pattern: increased total sugars and grape yield, which are associated with successful disease management and improved ripening. These findings are consistent with previous research, which has shown that Riesling-type cultivars are very susceptible to fungal infections and climatic stress, which has a significant impact on berry composition under organic management [27].

Organic treatments, characterized by lower grape yield, reduced sugar accumulation, and higher acidity. These outcomes reflect the challenges of maintaining vine health and optimal ripening in organic systems under disease pressure, especially during humid or pathogen-favorable years [19]. Overall, organic control leads to higher acidity and lower sugar content, especially in white cultivars ('Chardonnay', 'Italian Riesling'), due to limited disease suppression and slower ripening.

Conclusions

During the investigation period, organic soil management produced the highest average production values for all grape varieties. Beyond its positive impact on grape output, these economic advantages were facilitated by the higher market price of organically grown grapes. Organic soil management therefore provides a potential and sustainable alternative to bare soil systems, especially during climatically balanced growth seasons. Vineyard fertilization is an important technological component since grapevines are significant nutrient consumers, utilizing significant amounts of mineral elements from the soil each year to support their high biomass output. As consequently, fertilization is an essential process for restoring soil nutrients lost during vine development. Given that fertilization costs account for a major amount of overall production costs per hectare, this method must be properly optimized and scientifically controlled. Under Petrovaselo's particular meteorological and pedological circumstances, the organic fertilization schedule combining Fertilpolina and Cropmax proved to be the most successful, indicating a viable option that yields outcomes equivalent to conventional fertilization. Because the grape is so susceptible to diseases and pests, this is one of the most difficult aspects of organic viticulture to handle. The combined (integrated) pest and disease control method successfully decreases chemical input, benefiting the environment while improving the quality of wine and its byproducts. However, because these systems do not benefit from organic certification payments, their profit margins are smaller than fully organic systems. Organic and diversified pest control measures should be supported in order to reduce chemical applications, mitigate pollution, and ensure the production of high-quality grapes. Nonetheless, under unfavorable environmental circumstances, purely organic systems frequently fail to adequately manage pathogen pressure in order to sustain appropriate yield levels. In such circumstances, mixed (integrated) control, which strategically combines chemical treatments at important phenological stages, provides a realistic compromise by ensuring yield stability while lowering the impact on the environment.

Overall, the study shows that, while management approaches have a considerable impact on vine physiology and productivity, the genetic characteristics of each cultivar ultimately establish the amplitude and direction of the response. These findings underscore the importance of cultivar- and site-specific viticultural methods that balance production efficiency and environmental sustainability. Furthermore, the findings demonstrate that disease and pest management strategies have a significant impact on grape production and composition, with cultivar-specific responses connected to variations in genetic vigor, cluster morphology, and ripening dynamics. The transition to sustainable viticulture would thus benefit from integrated or mixed management options that assure fruit quality and production stability while minimising environmental damage.

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