

# Treatment of Pinot noir grapevines with nano fertilizer affecting vine health and wine composition

## Abstract

Nanofertilizer is based on microscopic particles that are more easily absorbed by the plant and metabolized more quickly. This is not only about the effect as a fertiliser, but also phytosanitary aspects were considered. Fertilizer of copper and silver in nanofertilizer was applied four times during a growing season in a Pinot noir vineyard. The effects on the grapevines were examined regarding nutrient supply, yield, health performance and wine composition. In addition, several wine tastings by means of a panel were used to try to perceive differences. No improvements could be recognized concerning health status of the plants. Despite larger changes in metabolites as propionic acid, limonene oxide, Cis Eugenol, Guajacol, some phenols and esters the sensorial evaluations do not result in huge changes. In general the wines could not be sensorially differentiated.

**Keywords:** fertilization, copper, argentum, Esca, phenols, minerals content

Volume 10 Issue 1 - 2026

Ferdinand Regner,<sup>1</sup> Erich Ferschel,<sup>1</sup> Andreas Endler,<sup>1</sup> Lukas Lankmair,<sup>2</sup> Manuel Rappold-Lang,<sup>2</sup> Ingrid Hofstetter,<sup>3</sup> Karin Korntheuer,<sup>3</sup> Christian Philipp,<sup>3</sup> Sari Sezer<sup>3</sup>

<sup>1</sup>Department of Grape Breeding, HBLA und BA für Wein- und Obstbau Klosterneuburg, Austria

<sup>2</sup>HBLA und BA für Wein- und Obstbau Klosterneuburg, Austria

<sup>3</sup>Department of Chemistry, HBLA und BA für Wein- und Obstbau Klosterneuburg, Austria

**Correspondence:** Ferdinand REGNER, Höhere Bundeslehranstalt und Bundesamt für Wein- und Obstbau Klosterneuburg, Wiener Straße 74 A-3400 Klosterneuburg, Österreich, Austria

**Received:** March 12, 2026 | **Published:** March 30, 2026

## Introduction

Grapevine nutrition is essential for sufficient growth, satisfying yield and high fruit quality. Grapevine requires 16 essential elements, primarily obtained from the soil, in the case of lack they would develop deficiency symptoms.<sup>1</sup> The main minerals are required in a larger scale and concern nitrogen, potassium, phosphorus, calcium, magnesium and sulfur. The micronutrients iron, zinc, copper, manganese, boron and molybdenum although essential, are needed in small quantities.<sup>2</sup> If one or more of these elements are scarce, vines may exhibit lack symptoms and develop foliar deficiency symptoms. As a consequence reduced growth, smaller crop yield, susceptibility to winter injury or decline can be expected.<sup>3</sup> Mineral analysis of the leaves can help to recognize specific needs and allow to create fertilization strategies.<sup>4</sup> Nitrogen (N) is essential for vegetative growth, shoot development and chlorophyll production. A lack in nitrogen reduces quantity and quality of the products. Excessive nitrogen will lead to high vigorous growth and reduced fruit quality.<sup>5</sup> Potassium (K) is crucial for sugar accumulation in berries, drought resistance, and disease resistance.<sup>1</sup> Magnesium (Mg) is essential for chlorophyll production and high fruit quality. Deficiency can cause yellowing between veins in older leaves.<sup>6</sup> Phosphorus (P) is important for root growth and for energy storage. Calcium (Ca) is needed for the formation of cell wall structure. Sulfur (S) is an essential component of proteins and enzymes.<sup>3</sup> The micronutrient copper (Cu) is a requisite for the proper growth and development of fertile vines.<sup>7</sup> Copper acts as a cofactor in various enzymes and fulfills essential reactions in photosynthesis, respiration and electron transport states.<sup>8</sup> Copper exists in biological systems in two oxidation levels. Copper as Cu<sup>+</sup> preferably binds to sulfur-containing biomolecules having a thiol or thioether group in the reduced state, whereas in the oxidized state, Cu<sup>2+</sup> reacts primarily with oxygen or imidazole nitrogen groups.<sup>9</sup> In plants, Cu plays an essential role in mitochondrial respiration, in the electron transport chain, photosynthesis, cell wall metabolism and lignin synthesis, and has a pivotal function in oxidative stress response and hormone signaling. Carbon dioxide assimilation and ATP production are other key functions administered by Cu in plants.<sup>10</sup> Copper is a structural component of various regulatory proteins. The ability of Cu to gain

or lose electrons enables it to affect the flow of electrons in the photosynthetic process. Copper is a redox-active transition metal required in several physiological and biochemical processes in plants.<sup>9</sup> At optimum levels, Cu is recognized as a crucial micronutrient for all organisms, a cofactor in many enzymes such as polyphenol oxidase, cytochrome-c-oxidase, laccase, amino oxidase and plastocyanin.<sup>11</sup> Copper also performs critical functions in oxidative phosphorylation, iron metabolism, protein trafficking, and transcription. The interchange between Cu<sup>+</sup> and Cu<sup>2+</sup> may result in generation of toxic reactive oxygen and other hydroxyl radicals. These free oxygen radicals can damage essential biomolecules like DNA, RNA, proteins and others.<sup>12</sup> Copper is harmful when it occurs in excess of optimal concentrations. Excess accumulation can destabilize membrane integrity, decrease photosynthesis and alter enzyme activity, which results in growth inhibition as well as other detrimental effects in plants.<sup>13</sup> Due to its binary character in plants, Cu is involved in a complicated system of uptake, transport, utility, toxicity, and detoxification.<sup>13</sup> Hence, it is crucial to screen the biophysicochemical roles of Cu in soil and plant systems to understand its putative beneficial and detrimental impacts. At either excess or deficient levels, Cu can lead to abnormalities or dysfunction in plant development and growth by severely disturbing critical physiological processes. Therefore, for proper development and growth Cu must be acquired, transported, and distributed throughout the plant and its levels must be regulated within different cells and organelles.<sup>14</sup> Vines are susceptible to Cu toxicity, displaying metabolic disturbances and growth inhibition at levels just above those considered normal in tissue.<sup>15</sup> To maintain sufficient quantities of essential metal ions, plants possess membrane transport systems for carrying out homeostasis to regulate optimal concentrations. Insufficiency of Cu in plants mainly affects reproductive organs and younger leaves, while other symptoms like necrosis, chlorosis, leaf distortion and stunting, inhibition of root growth are triggered by higher levels.<sup>16</sup> Regarding significant releases and accumulation of Cu in viticultural soils and its potentially toxic effects, particularly to vines. The role of Cu in inducing toxicity via ROS production and induction of various defense mechanisms is discussed.<sup>17</sup> Many studies have summarized the adverse effects of excess Cu on germination, growth, photosynthesis, and antioxidant response in agricultural crops.

Its inhibitory influence on mineral nutrition, chlorophyll biosynthesis, and antioxidant enzyme activity has been verified.<sup>18</sup> Under natural conditions, the average copper concentration in soil varies between 6 and 80 mg/kg.<sup>19</sup> Frequently used copper as fungicide and other plant protection measures has resulted in Cu accumulation in soil.<sup>20</sup> In vineyards, continuous application of Cu-based fungicides has caused substantial Cu accumulation in soil, which presents a serious environmental and toxicological concern.<sup>16</sup> Accumulated Cu in soil cannot be degraded biologically or chemically and poses a threat to the environment, food security and human health. High soil Cu (20–100 mg/kg) concentrations are known to impart toxic effects to soil microorganisms and hinder the mineralization of macronutrients such as phosphorus (P) and nitrogen (N). The presence of Cu excess decreases P availability to plants;<sup>21</sup> furthermore, levels of available trace elements like Fe and Zn may decline as copper accumulates in soil. Nevertheless Cu fungicides are essential for organic viticulture to protect against downy mildew.<sup>22</sup> Cu residues in must can influence the fermentation and depending on the yeast proliferate disturbing -SH compounds.<sup>23</sup>

**Silver** (Ag) is not considered an essential nutrient for grapevines or most higher plants. Unlike elements such as copper, zinc, or iron, silver does not play any known biochemical or physiological role in plant nutrition.<sup>3</sup> While silver is not required for plant growth, it has been studied and occasionally used in agronomic or postharvest applications, mainly for its antimicrobial or hormone-modulating properties, rather than as a nutrient.<sup>24</sup> Certain silver compounds — especially silver thiosulfate or silver nitrate - can block ethylene receptors in plants.<sup>25</sup> Ethylene is the hormone associated with fruit ripening, abscission, and stress responses. In some vine research, foliar sprays of silver compounds were tested to reduce berry drop or delay senescence, but such practices are not common in commercial viticulture due to toxicity and regulation concerns.<sup>26</sup> Silver ions have strong antibacterial and antifungal properties.<sup>27</sup> Silver nanoparticles or ionic silver have been researched for reducing postharvest spoilage of table grapes, suppressing pathogens such as *Botrytis cinerea* (gray mold). However, these applications are postharvest treatments, not root or foliar nutrition.<sup>28</sup> Silver is phytotoxic at relatively low concentrations. High levels can cause leaf burns, chlorosis, or inhibited root growth.<sup>29</sup> Due to environmental and food safety regulations, silver is not approved as a fertilizer or growth stimulant in most countries. Despite that fact it was used to treat Esca infected vines for recovering.<sup>30</sup> It can be summarized that Silver is not a nutrient for grapevines. Its role is limited to experimental or antimicrobial applications and should not be considered as an aspect of vine nutrition. Furthermore nothing is reported about the influence on the metabolites of grapevine.

## Materials and Methods

### Experimental setup

The plot of the experimental setup features a sandstone weathering soil typical for the area, with a higher clay content, medium sorption capacity, and skeletal inclusions. The experimental plot has a shallow soil, which is limited at a depth of 30 cm by a massive, skeleton-rich layer. It is a south-facing slope, classified with an approximately 40% gradient. The row orientation is north-south. The vines were planted in 2006 using a spade planting method and were between their seventeenth and nineteenth year at the time of the experiment. The individual treatments were randomized, and the active substances were applied to four plots each. The grape variety used was Pinot Noir clone INRA 115.<sup>31</sup> Rootstocks Kober 5BB, SO4, and Paulsen

1103 were used for planting. The spacing per vine was 3.2 x 1 m, corresponding to a planting density of approximately 2,800 vines per hectare. The training system corresponds to a medium-high wire-frame training, with trunk height at about 70 cm and the canopy height at about 130 cm.<sup>32</sup> The standard pruning in the vineyard was done on a cane with around ten buds, not counting the hidden buds. During the winter, every second vine inter row was sown with a rye-vetch mixture, and during the growing season, the natural ground cover was regularly mulched. The area under the vines was kept free of weeds using herbicide. Canopy management was limited to tying the shoots into the wire and a single operation of cutting the tip. Overall, the vineyard could be considered sufficiently vigorous. No leaf removal in the fruit zone or cluster thinning was performed.

### Climate

The annual average temperature during the trial years 2023 and 2024 was 12.6°C and 17.8°C respectively during the growing season. The annual average precipitation for the years 2010 to 2020 was 540 mm, but in the trial year 2023, precipitation was significantly higher at 650 mm and in 2024 at 698 mm. However, the heavy rainfall in September 2024 occurred after the grape harvest. Heat summation (Huglin) shows a clear difference 2050°C in the 2023 and 2322°C in the 2024. Data were collected using local weather station (Adcon Telemetry, Klosterneuburg). An important aspect of the local climate is the wind-exposed location in the Danube Valley. Plant protection was carried out according to integrated pest management, with eight applications annually.

### Experimental design

Three fertilizer combinations were applied with 4 replications of 36 vines each. This allowed for sufficient use of representative vines. One combination (A) was treated 4 times with the following fertilizers: Agro Argentum Bor 2% boron and 1% colloidal silver, Agrocyprium 3% copper, Agroferrum 15% iron, Agrocalcium 20% (BH Solutions GmbH, Remshalden DE). Dilutions of 0.05% and 0.02% (copper and iron) were prepared for application. Second combination (C) was a pure colloidal nano-copper oxide preparation (Merck, Darmstadt, DE) and 0.5% Fertilleader Viti (6.2% P<sub>2</sub>O<sub>5</sub>, 12.6% K<sub>2</sub>O, 1% B) and was applied simultaneously with the first combination also 4 times. The control (K) was not treated. Application times were BBCH 53, 69, 73, and 79. The amounts of nano fertilizer used in this study are not comparable with conventional applications and are 10 times less. On one hand, it was no goal to reduce the yield for the experiments.<sup>33</sup> On other hand, the vineyard tended to moderate yields, so that a physiological balance could be achieved anyway without additional treatments. The harvested crop was weighed and examined for rot infestation. Rosé wine was produced in order to shorten the ripening phase and to minimize the influence of vinification. The must was analyzed for sugar content, titratable acidity, and pH. Finally, the yield behavior and ripeness were evaluated. The health assessment during the growing season was limited to the occurrence of fungal diseases, Esca, and other graft-transmissible diseases such as phytoplasma.<sup>34</sup> While Esca could only be detected in this facility in the last experimental years before the project began, it had been observed for a longer time that vines showed symptoms of phytoplasmas. It turned out that infected leafhoppers had transmitted Stolbur phytoplasma.<sup>35</sup> Symptomatic vines (Esca and Stolbur) were excluded from agricultural evaluation and grape processing. The vinification of each variant was carried out, in order to be representative, from a mixture of grapes from several vines.<sup>36</sup>

## Chlorophyll evaluation

The chlorophyll content is an indicator of a plant's vitality and was evaluated to better assess the nutrient status of the vines. Differences in chlorophyll content were expected due to the additional fertilization. A handheld SPAD 502 device (Konica Minolta Sensing Europe B.V., Munich, Germany) was used, which determines the absorption of light in the leaf and thus allows conclusions to be drawn about the chlorophyll content. The use of this measurement is helpful for estimating the nutritional status as well as deficiencies, possible over-fertilization, and nitrogen supply. Fifty measurements were taken per experimental repetition and 200 individual measurements per variant.

## Leaf analyses

Leaf analysis provides information about the current nutritional status of the plant and shows the composition of the leaf. For this purpose, thirty leaves per fertilizer combination were collected during the 3rd assessment.<sup>1</sup> The leaves were dried at 105°C, ground, and analyzed as described by Fardossi et al.<sup>6</sup>

## FTIR

The measurement principle of an FTIR device is based on infrared technology and utilizes the fact that substances contained in wine absorb infrared radiation at a specific wavelength. For each substance to be quantified, the absorption of different wavelengths or wavelength ranges is used.<sup>37</sup> The analysis of standard parameters such as alcohol, sugar, and acidity was carried out using FTIR ("Winescan", Foss, Lillroed Denmark) (<http://www.gerber-instruments.com/de/lieferwerke/foss/weinanalytik/winescan.html>).

## Total phenols

The Folin–Ciocalteu staining is based on the formation of a dark blue color from phosphotungstate and phosphomolybdate acid, which absorbs light at 760 nm. The samples are irradiated in the process, causing the light intensity to decrease depending on the strength of the staining. What is actually determined is the antioxidant capacity and not just the phenol concentration. The detection limit, on the other hand, is a total phenol concentration that can be reported with sufficient precision.<sup>38</sup>

## Phenols composition

Using the HPLC method, the phenols were separated, identified, and quantified using standard reference substances.<sup>39</sup> This analytical procedure has proven to be the best for elucidating the phenol composition. In terms of selectivity, specificity, sensitivity, time and cost expenditure, as well as solvent consumption, it is the most advantageous method.<sup>40</sup> A photoactive sensor at the end of the column measures the amount via light refraction.<sup>41</sup>

## Aromatic compounds

A total of approximately 60 aroma compounds from the aroma groups esters, C6 compounds, higher alcohols, carboxylic acids, and free monoterpenes were determined using three different methods. Two gas chromatographs from Agilent Technologies (Santa Clara, USA) were used for the analysis of the various aroma compounds. The methods for quantifying the 14 relevant monoterpenes, the 32 ester compounds, and the determination of the most abundant aroma compounds, such as relevant higher alcohols, relevant short- and medium-chain carboxylic acids, carbonyl compounds, and ester compounds, are analogous to those published by Philipp et al.<sup>42–44</sup>

## Sensory evaluation

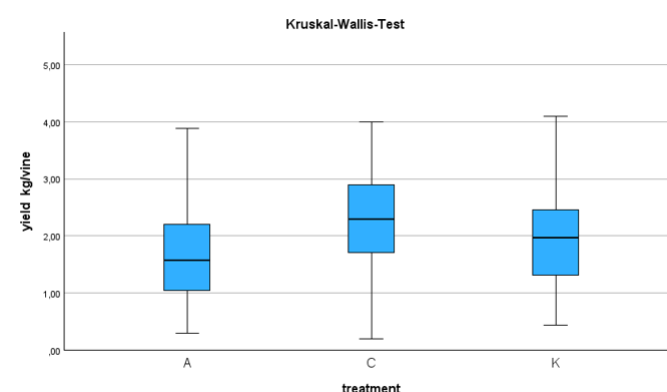
The wines obtained from for the different fertilizer combination treatments were produced in the same way according to a standardized winemaking procedure.<sup>33</sup> Each wine was produced in duplicate, and both wines were subjected to evaluation. Pure cultured yeast was used, predominantly in a reductive manner (initial sulfuring of the must with 80 mg/l SO<sub>2</sub>), and fermentation was carried out promptly. The fermentation temperature was set at 18°C. After fermentation was complete, the racked wine was cool stored in glass carboys. Before tasting, the wine was clarified by filtration through a Seitz K 150-layer filter (Pall Seitz-Schenk Filter Systems GmbH, Bad Kreuznach, DE). Each wine was presented repeatedly and evaluated using an unstructured scale<sup>45</sup> for specific characteristics such as fruitiness, color, extract, and overall impression. As a second assessment method, the wines were ranked.<sup>46</sup> In this process, 6 wines from the 3 fertilizer combinations were evaluated based on their overall impression. This allows differences that are perceptible but not precisely definable to be included in the evaluation.<sup>47</sup> The tastings were conducted by a tasting panel of eight trained members. The analytical must and wine parameters were recorded only in rough terms.

Statistical analysis was carried out using the program SPSS (Version: Statistics 29.0; IBM, Vienna, Austria). Data were examined for variance and normal distribution. Non-normally distributed data were analyzed using a Kruskal-Wallis test. Means were assessed using the LSD test ( $P < 0.05$ ). The graphical representation of the data was done using SPSS and Microsoft Excel (Microsoft Austria GmbH, Vienna, Austria).

## Results and discussion

### Harvest parameters and leaf characteristics

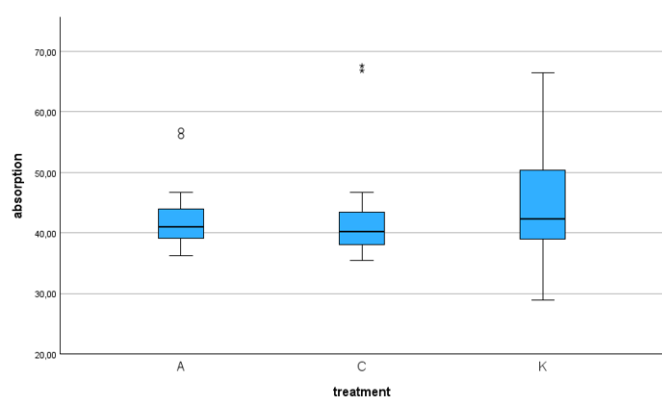
In 2024, the yield per vine across the different treatments was closer than in 2023. While 2024 showed no significant differences, the 2023 harvest yielded higher weights for the "Standard" and "Cu application" treatment (Figure 1).



**Figure 1** Yield per vine and treatment in 2023.

Values for sugar, acid, and pH were more homogenous in both years. The differences were minimal, and no changes to harvest parameters were detectable due to the treatments.

Chlorophyll measurements highlighted optical differences between the three treatments. The average SPAD value for treated variants was approximately 42, compared to 45 for the untreated control (Figure 2).



**Figure 2** Light absorption (SPAD) due to chlorophyll content.

The applications led to a decrease in reflected light. This change in leaf composition was also visible: treated leaves appeared darker than the untreated ones (Picture 1-3).

HBLA und Bundesamt  
Klosterneuburg  
Wein- und Obstbau

**K control**

**A Agrocyprium**

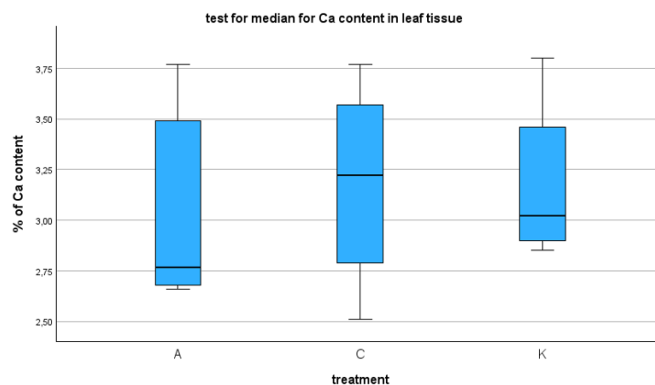
**C Nanocopper**



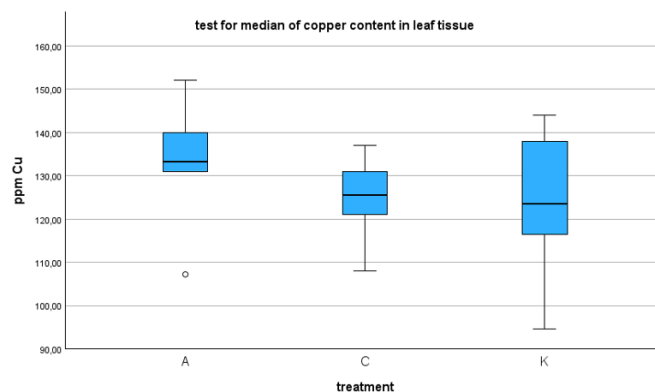
The “Agrocyprium” treatment, in particular, developed a darker green hue than the others. However, measurement variability of treatment K was so high that no statistically difference to control K could be achieved under the given conditions. Tendentially, the application of colloidal copper increases absorption.

### Nutrient analysis and plant health

**Leaf analysis (2023–2024):** In the 2023: All samples showed deficiencies in nitrogen (N), potassium (K), and phosphorus (P). Conversely, magnesium (Mg) and calcium (Ca) (Figure 3) levels were too high, which may have partially caused the other mineral deficiencies.(Table1)Copper (Cu) (Figure 4) and zinc levels were excessive regardless the treatment.



**Figure 3** Content of Ca in the leaf tissue.



**Figure 4** Content of copper in the leaf tissue.

**Table I** Mineral content of leaf tissue. Samples were taken during development of berries at the stage of BBCH 73-75

Treatment	N %	K %	Mg %	Ca %	P %	Fe ppm	Cu ppm	Zn ppm	Mn ppm
Agrocypr.	2,0	0,7	0,5	3,6	0,1	119,4	114,9	77,7	86,2
Cu	1,9	0,7	0,5	3,6	0,1	116,6	142,0	81,1	66,0
standard	2,0	0,6	0,5	3,5	0,1	105,5	102,4	76,3	81,4
ideal range	2,25-2,75	1,2-1,4	0,25-0,5	2,5-3,5	0,19 - 0,24	60 - 300	6 - 20	25 - 60	30-300

In the 2024 values approached optimal levels, though a symptomless deficiency of N and K remained across all samples. Phosphorus (P) levels hovered around the lower threshold, which still represents an adequate supply. Trace nutrients were in the optimal range with no detectable difference in Cu supply.

The Agrocyprium treatment showed lower manganese (Mn) in both years. However, its iron (Fe) content was slightly higher in 2024, which can be explained by the iron content in the Agrocyprium treatment itself.

### Disease assessment

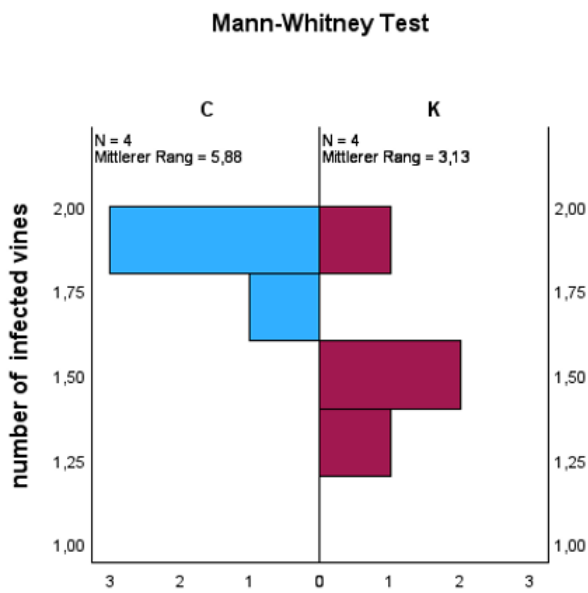
**Downy mildew (Peronospora):** In 2023, despite regular plant protection measures weak symptoms appeared across all treatments

despite low Cu applications and an Integrated Production (IP) program. No differences were noted between variants. No infections occurred in 2024.

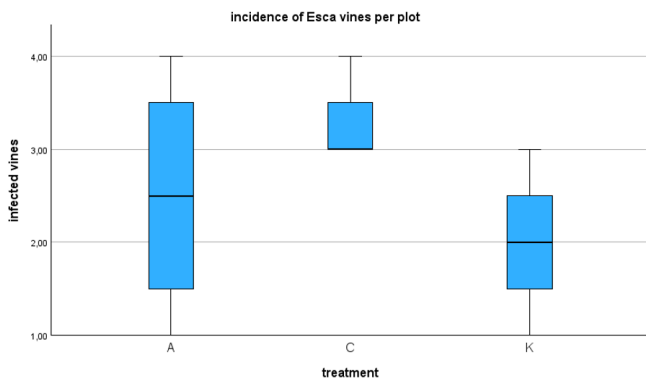
Esca: Visual assessments for Esca indicated that the applications provided no protection.

2023: Treatment C showed significantly higher infestation than the Control or Variant A (Figure 5).

2024: Treated combinations A and C showed higher (though not statistically significant) Esca rates (Figure 6).

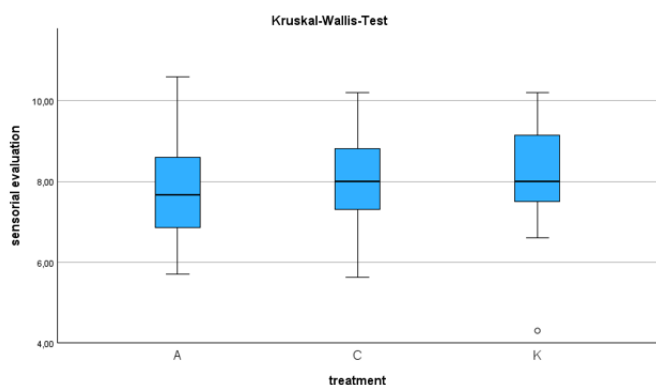


**Figure 5** Comparison of Esca infected vines in treatment C and K in vintage 2023.



**Figure 6** 2024 comparison of Esca symptoms.

**Sensory evaluation (Tasting):** With the 2023 vintage two separate panels (eight and six trained tasters) using triangle, ranking, and unstructured scale tests found no perceptible sensory differences between the wines (Figure 7)



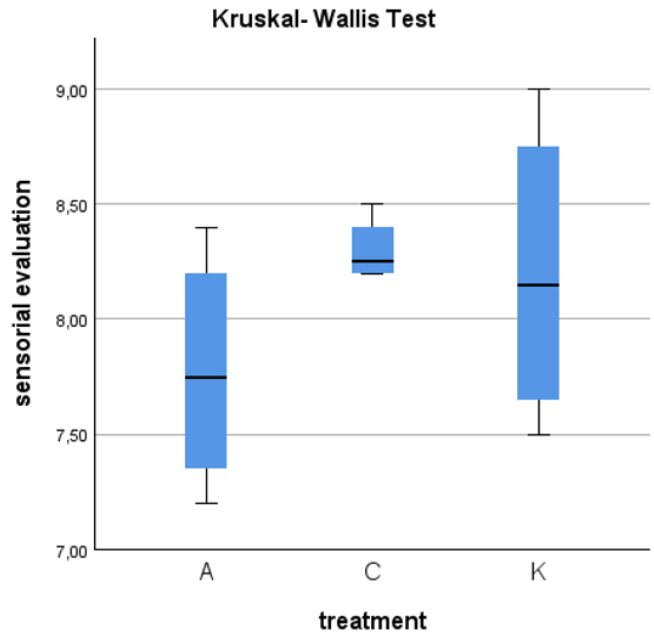
**Figure 7** Evaluation of total sensorial impression by unstructured scale for wines of vintage 2023.

With the 2024 vintage the wines were distinguishable in triangle tests.

Treatment A vs. K: Tasters could distinguish them but were split on which was better.

Treatment K vs. C: Wines of C was rated significantly worse.

However, an unstructured scale test with four replications showed not statistically result that any one wine was inferior (Figure 8).



**Figure 8** Evaluation of total sensorial impression by unstructured scale for wines of vintage 2024.

**Chemical wine analysis:** The analysis of wine components showed only few minor differences overall, with higher alcohols and acids remaining largely homogenous (Tables 2-4).

**Table 2** Main changes in wines of treated fertilizer combinations

Category	Key findings
Acids	The control treatment had higher propionic acid than A or C, suggesting applications might restrict microbial activity in favor of yeast fermentation.
Terpenes	Fertilization A had the highest total content, though the control reached significantly higher values for cis-limonene oxide.
Esters	Fertilization A (and to some extent C) showed lower total amounts of various esters (e.g., Ethylhexanoat). This may be a vine reaction to the shared nano-copper content.
Volatile Phenols	These showed the strongest differences. Fertilization C saw significant increases in compounds like Dimethoxyphenol and Guajacol. (Table 3)
Phenols	Results were inconsistent between 2023 and 2024. In 2023, A and C had lower total phenols and lower Resveratrol. In 2024, C had higher total phenols and Tyrosol, while A showed lower Resveratrol but higher Catechin. (Table 4)

**Table 3** Volatile Phenolic compounds ( $\mu\text{g/l}$ )

Treatment	Guajacol	trans-Whiskeylacton	4-Vinyguajacol	cis-Whiskeylacton	2,6-Dimethoxyphenol	Ethylvanillin	Sinapinaldehyd
A Agrocyprium	103,7	5,2	2213,1	0,1	214,8	8,6	4,5
C (copper)	203,0	7,1	3071,0	0,4	375,0	7,2	1,2
K control	65,6	5,4	2044,0	0,2	158,7	16,5	9,2

**Table 4** Phenols extracted from the wines ( $\mu\text{g/l}$ )

Treatment	Tyrosol	c-Coutaric	t-Coutaric	Catechin	Procyanidin BI	Syringa acid-	Epicatechin	t-Resveratrolgl.	t-Resveratrol	c-Resveratrolgl.	c-Resveratrol	total phenols g/l
Agro	23,71	3,74	4,85	7,34	7,41	3,83	3,15	0,99	0,70	6,31	1,75	0,19
Cu	23,79	3,60	4,31	5,45	6,47	3,52	2,48	1,00	0,70	6,02	1,72	0,18
control K	20,92	4,13	6,36	7,96	6,68	3,55	3,36	1,33	1,00	8,64	2,42	0,20

Usually, the treatment of vines with copper based fungicides at the legal level could render reduction in growth and yield.<sup>48</sup> On the other side improvement of winter hardiness and increase of vitamins in table grapes could be recognized.<sup>49</sup> Higher copper input decrease sugar accumulation, phenol synthesis but reinforce the appearance of C-6 compounds and aldehydes. Terpenes and C13-norisoprenoids decreased with increasing concentrations of copper treatment.<sup>50</sup> As we used minor amount of nano copper we could not observe same phenomena but some aspects as reduction of phenols (Resveratrol), terpenes (Limonene oxid) and increase in volatile phenols were similar.

## Conclusion

Overall, the application of nano-copper and Agrocyprium had little influence on leaf mineral composition and wine metabolites. Other factors are more stable or show more differences between both vintages. As there could not be recognized any improvement to the health status or the wine quality these applicants cannot be recommended for practical viticulture.

## Acknowledgments

None

## Conflicts of Interest

The authors declare no conflict of interest.

## References

- Bauer K, Regner F, Friedrich B. *Der Weinbau*. 13th ed. AV Verlag Cadmos; München, Germany, 2017.
- Winkler A, Cook J, Kliewer W, et al. *General Viticulture*. University of California Press; 1974.
- Mehofer M, Baumgarten A, Faber F, et al. *Sachgerechte Düngung im Weinbau*. 3rd ed; 2024.

- Christensen LP, Kasimatis AN, Jensen FL. *Grapevine Nutrition and Fertilization in the San Joaquin Valley*. University of California; 1978.
- Brunetto G, de Melo G, Toselli M, et al. The role of mineral nutrition on yields and fruit quality in grapevine, pear and apple. *Rev Bras Frutic*. 2015;37(4):1089–1104.
- Fardossi A, Schober V, Schmuckenschlager B. Einfluss verschiedener Unterlagssorten auf die Mg-Ernährung der Sorte Welschriesling. *Mitt Klosterneuburg*. 1996;46:221–231.
- Marastoni L, Sandri M, Pii Y, et al. Synergism and antagonisms between nutrients induced by copper toxicity in grapevine rootstocks. *Chemosphere*. 2019;214:563–578.
- Mir AR, Pichtel J, Hayat S. Copper: uptake, toxicity and tolerance in plants and management of Cu-contaminated soil. *Biometals*. 2021;34(4):737–759.
- Rengel Z, Cakmak I, White PJ, eds. *Marschner's Mineral Nutrition of Plants*. 4th ed. Academic Press; 2022.
- Schulten A, Krämer U. *Interactions between copper homeostasis and metabolism in plants*. In: Cánovas F, et al., eds. *Progress in Botany*. Vol 79. Springer; 2017.
- Yruela I. Copper in plants. *Braz J Plant Physiol*. 2005;17:145–146.
- Sánchez M, Palacios O, Buchensky C, et al. Copper redox chemistry of plant frataxins. *J Inorg Biochem*. 2018;180:135–140.
- Shabbir Z, Sardar A, Shabbir A, et al. Copper uptake, toxicity and risk assessment in soil-plant systems. *Chemosphere*. 2020;259.
- Yruela I. Copper in plants: acquisition, transport and interactions. *Funct Plant Biol*. 2009;36(5):409–430.
- Ryan BM, Kirby JK, Degryse F, et al. Copper speciation and isotopic fractionation in plants. *New Phytol*. 2013;199(2):367–378.
- Brunetto G, de Melo GWB, Terzano R, et al. Copper accumulation in vineyard soils: rhizosphere processes and agronomic practices to limit its toxicity. *Chemosphere*. 2016;162:293–307.

17. Ameh T, Sayes CM. The potential exposure and hazards of copper nanoparticles: a review. *Environ Toxicol Pharmacol.* 2019;71.
18. Baldi E, Miotto A, Ceretta CA, et al. Soil-applied phosphorus is an effective tool to mitigate the toxicity of copper excess on grapevine grown in rhizobox. *Sci Hortic.* 2018;227:102–111.
19. Kratz S, Haneklaus S, Schnug E. Kupfergehalte in Böden und Verhältnis zu Pflanzenschutzmitteln. *J Kult Pflanzen.* 2009;61:112–116.
20. Trentin E, Facco D, Hammerschmitt R, et al. Vermicompost and limestone reduce copper toxicity in grapevines. *Chemosphere.* 2019;226:421–430.
21. Adrees M, Ali S, Rizwan M, et al. The effect of excess copper on growth and physiology of important food crops: a review. *Environ Sci Pollut Res.* 2015;22(11):8148–8162.
22. Cabús A, Pellini M, Zanzotti R, et al. Efficacy of reduced copper dosages against *Plasmopara viticola* in organic agriculture. *Crop Prot.* 2017;96:103–108.
23. Vela E, Hernández-Orte P, Franco-Luesma E, et al. Effects of copper fining on sulfur off-odors in wine. *Food Chem.* 2017;231:212–221.
24. Mussin J, Giusiano G. Biogenic silver nanoparticles as antifungal agents. *Front Chem.* 2022;10:1023542.
25. Rodrigues AS, Batista J, Rodrigues M, et al. Advances in silver nanoparticles as antimicrobial agents. *Front Microbiol.* 2024;15:1440065.
26. Vizitiu D, Sardaescu D, Fierascu I, et al. Grapevine management using silver nanoparticles. *Materials (Basel).* 2022;15(22):8188.
27. Yan A, Zhong C. Impacts of silver nanoparticles on plants. A focus on the phytotoxicity and underlying mechanism. *Int J Mol Sci.* 2019;20(5):1003.
28. Sang Woo K, Jin Hee J, Kabir L, et al. Antifungal effects of silver nanoparticles against plant pathogenic fungi. *Mycobiology.* 2012;40(1):53–58.
29. Kumar S, Masurkar P, Sravani B. A review on phytotoxicity and defense mechanism of silver nanoparticles on plants. *J Nanopart Res.* 2023;25:54.
30. Štůsková K, Kiss T, Bytešniková Z, et al. Silver-selenium nanoparticles inhibit grapevine trunk pathogens. *Pest Manag Sci.* 2025; 81(12):7985–7994.
31. Galet P. Cépages et Vignobles de France. 2nd ed. Imprimerie Charles Dehan; 1990.
32. Schuhmann W. Amperometric enzyme biosensors based on optimised electron-transfer pathways and non-manual immobilisation procedures. *J Biotechnol.* 2002;82(4):425–441.
33. Schöffling H, Scheuden G, Faber W. Systematische Erhaltungszüchtung von Ertragsrebsorten. *Wein Wiss.* 1983;38:291–325.
34. Martelli GP. Grafitransmissible diseases of grapevine. FAO; 1993.
35. Berger J, Schweigkofler W, Kerschbamer C, et al. Occurrence of Stolbur phytoplasma in the vector *Hyalesthes obsoletus*, herbaceous host plants and grapevine in South Tyrol. *Vitis.* 2009;48(4):185–192.
36. Scholz A. Einfluss von Boden, Unterlage und Klima auf Riesling. Dissertation. Universität Bonn; 1983.
37. Thanasi V, Catarino S, Ricardo-da-Silva J. FTIR spectroscopy in wine production monitoring. *Cienc Tec Vitiv.* 2022;37(1):79–99.
38. Prior RL, Wu X, Schaich K. Standardized methods for antioxidant capacity determination. *J Agric Food Chem.* 2005;53(10):4290–4302.
39. Bird IM. High performance liquid chromatography: principles and clinical applications. *BMJ.* 1989;299(6702):783–787.
40. Lüders C, Meyer H, Rabe J. Entwicklung von Analyseverfahren für Phenole. Dissertation. Humboldt-Universität Berlin; 1999.
41. Huber E, Wendelin S, Kobler A, et al. Phenol composition and antioxidant capacity during ripening of South Tyrolean red wines. *Mitt Klosterneuburg.* 2005;55:3–21.
42. Philipp C, Nauer ST, Sari S, et al. Quantifizierung flüchtiger Esterverbindungen in Weinen. *Mitt Klosterneuburg.* 2019;69:93–114.
43. Philipp C. Charakterisierung des Aromaprofils österreichischer Weine. Dissertation. Universität für Bodenkultur; 2020.
44. Philipp C, Eder P, Sari S, et al. Vergärung mit Weinblättern und Auswirkungen auf Aroma. *Mitt Klosterneuburg.* 2024;74:131–144.
45. Weiss J, Zenz H. Reduction of panel variances by normalization procedure. *Acta Alimentaria.* 1989;18:313–323.
46. Sevenich L. *Weinsensorik.* Agrarverlag; 2005.
47. Busch-Stockfisch M. *Praxishandbuch Sensorik kompakt.* Behr's Verlag; 2015.
48. Kovacic GR, Cus F, Lesnik M, et al. The impact of copper fungicides on copper content in grapevine organs and wine. *Mitt Klosterneuburg.* 2016;66:106–112.
49. Dobrei A, Nistor E, Dobrei AG, et al. The impact of copper application timing and frequency on vineyard parameters. *Sci Pap Ser B Hortic.* 2024;68(2).
50. Li J, Wang J, Huo X, et al. Impact of copper ion concentrations on flavor quality from grapes to wine. *Food Res Int.* 2026;223:(Pt 1):117912.