



Physiological and yield responses of apple trees to combined organic and phosphate fertilization under sandy loam soil in Babil Governorate, central Iraq

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ABSTRACT

Soil fertility depletion and non-optimal fertilization are key problems in apple orchards established in a semi-arid environment, which directly affect fruit yields and quality. This experiment investigated the effect of organic and phosphorus fertilization, either alone or in combined on yield, fruit quality and physiological properties for apple trees (*Malus domestica* L.) cultivated in central Iraq. The experiment was carried out using a factorial randomized complete block with three replicates; the factors were three levels of organic fertilizer (0, 2.5 and 5 kg tree⁻¹) and three phosphate doses (0, 100 and 180 g tree⁻¹). The total fruit yield was also substantially enhanced under integrated fertilization to 85.0 kg tree⁻¹, higher by 112.5% with respect to control (40.0 kg tree⁻¹). Fruit quality traits were also improved, increasing in diameter from 69.8 to 82.3 mm and firmness increased from 6.2 to 8.7 kg cm⁻² with the highest content of soluble solids (from 12.1 to 15.2 °Brix). Leaf nutrient contents (N, P and K) and some physiological parameters were also enhanced such as chlorophyll content (2.18 mg g⁻¹ FW) and net photosynthetic rate (18.7 μmol CO₂ m⁻² s⁻¹). Activities of key enzymes were highest in combined fertilization treatment, where Rubisco and SOD activities were higher up to 4.2 and 22.4 U mg⁻¹ protein, respectively. In general, combined organic and phosphate fertilization is a promising approach that can improve apple yield and fruit quality in semi-arid ecosystems.

الاستجابات الفسيولوجية والإنتاجية لأشجار التفاح للتسميد العضوي والفوسفاتي المشترك تحت ظروف تربة مزيجة رملية في محافظة بابل ، وسط العراق

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الخلاصة

يُعد استنزاف خصوبة التربة وعدم كفاءة التسميد من المشكلات الرئيسية في بساتين التفاح المزروعة في البيئات شبه الجافة، مما يؤثر بشكل مباشر في إنتاجية الثمار وجودتها. هدفت هذه التجربة إلى دراسة تأثير التسميد العضوي والفوسفاتي منفرداً أو بشكل متكامل في الحصول، وجودة الثمار، والصفات الفسيولوجية لأشجار التفاح (*Malus domestica* L.) المزروعة في وسط العراق. نُفذت التجربة وفق تصميم القطاعات العشوائية الكاملة العاملية وبثلاث مكررات، حيث تضمنت العوامل ثلاث مستويات من السماد العضوي (0، 2.5، و 5 كغم شجرة⁻¹) وثلاث جرعات من السماد الفوسفاتي (0، 100، و 180 غم شجرة⁻¹). أظهرت النتائج أن الحصول الكلي للثمار قد تحسن بشكل ملحوظ تحت التسميد المتكامل ليصل إلى 85.0 كغم شجرة⁻¹، بزيادة قدرها +112.5% مقارنة بمعاملة السيطرة (40.0 كغم شجرة⁻¹). كما تحسنت صفات الجودة الثمرية، إذ ارتفع قطر الثمرة من 69.8 إلى 82.3 ملم، وزادت الصلابة من 6.2 إلى 8.7 كغم سم⁻²، مع ارتفاع محتوى المواد الصلبة الذائبة من 12.1 إلى 15.2 درجة بريكس. كذلك تحسنت تراكيز العناصر الغذائية في الأوراق (N و P و K) وبعض المؤشرات الفسيولوجية، مثل محتوى الكلوروفيل (2.18 ملغم غم⁻¹ وزن طازج) ومعدل التمثيل الضوئي الصافي (18.7 ميكرومول CO₂ م⁻² ثا⁻¹). وكانت أنشطة الإنزيمات المضادة للأكسدة الأعلى في معاملة التسميد المتكامل، حيث بلغت فعالية إنزيمي Rubisco و SOD نحو 4.2 و 22.4 وحدة ملغم⁻¹ بروتين، على التوالي. وبشكل عام، يُعد الجمع بين التسميد العضوي والفوسفاتي نهجاً واعداً يمكن أن يعزز إنتاجية التفاح وجودة ثماره في النظم البيئية شبه الجافة. الكلمات الافتتاحية: سماد عضوي؛ سماد فوسفاتي؛ التفاح (*Malus domestica* L.)؛ عنصر أساسي؛ البستنة المستدامة.

INTRODUCTION

Apple (*Malus domestica* L.) is a temperate fruit crop of great economic importance throughout the world, but with stringent climatic and soil demands for sustained yield. Apple trees require, among other tree species, a minimum of chilling hours in winter to achieve sufficient bloom and fruit production (Özmen, 2016; Ciruela, 2020). Although apple growing has been concentrated mostly in different northern regions, where the proper dormancy chilling hours were met with retarded flowering occurrence, such conditions are now available also elsewhere in Iraq as in Babil region on account of advancements that have been recently made in horticulture and by introducing a new low-chill varieties (Al-Ma'thidy & Shehab, 2021).

The Babil Province is also an intermediate agroecological zone with semi-arid climate and less winter chilling (Noori, 2024). Despite these limitations, apple production is receiving more attention in this region as a means to diversify horticultural production and enhance local food security. Nevertheless, orchard productivity in Babil is highly hindered by soil fertility constraints especially low organic matter (OM) content and imbalanced essential nutrients whereas phosphorus (P) deficiency remains among the most critical factors limiting root system development, tree vigor and fruit quality (HUSSEIN & GÜLSER, 2023; Owied, 2025). Therefore, in order to promote apple productivity under these transitional conditions, it is essential to concentrate on sustainable nutrient management for the betterment of soil fertility. It is well known that organic amendments help to alter soil structure and increase the water retention capacity, promote microbial activity, and enrich nutrient flows in the rhizosphere (Turhan & Özmen, 2021). Simultaneously, phosphate fertilizers are crucial for root development, ATP-related energy metabolism and reproduction in fruit trees (Abobatta & Abd Alla, 2023) The integrated use of organic and inorganic fertilizers has been recently recommended for the maintenance of soil fertility and enhancing crop yield (Paramesh *et al.*, 2023).

While there are many known beneficial effects of the individual application of an organic amendment or phosphate fertilization, little research under field conditions has been done to determine how these management practices interact in arid and semiarid agroecosystems such as central Iraq where soils are low in both organic matter and nutrients (Tubeileh & Thomas, 2023). Improved understanding of these integrated fertilization practices is important in order to promote nutrient practices that maximize yield potential while maintaining long-term soil health in climate-challenged environments.

Therefore, this investigation was designed to assess the impact of the addition of organic and phosphate fertilizers at varying rates (applied alone or in combination), on vegetative growth, leaf attributes and fruit yield off apple trees grown at Babil Governorate. The results are hoped to serve as a scientific reference for optimizing fertilization practices allowing the establishment of sustainable climate-resilient apple production in other comparable semi-arid areas.

MATERIALS AND METHODS

Experiment site and plant material

The experiment was conducted during two successive growing seasons (2023- 2024), in a certified private Nursery at Al-Mahawil district, Babil Governorate, Iraq which is located between 32.6456° N and 44.3958° E with an altitude of about 29 m above sea level. The treatment was carried out on 4-year-old apple (*Malus domestica* L. c v. Ibrahimi) carried out pyramid leaders to some kind of canopy shape for vigorous growth and balance between tree characters; 6 × 6 m apart to have enough light distribution all over the orchard (and across the trees, too) and air movements inside it (Dallabetta, 2014). All trees received the same horticultural practices (management of irrigation and fertilization, integrated pest management—IPM—and pruning as needed) in order to minimize environmental variability as much as possible and maintain consistent experimental conditions (Selahvarzi *et al.*, 2025).

Climatic Conditions During the Experimental Period

Detailed meteorological data were also recorded during the experiment to take into consideration possible environmental effects on plant physiological responses and fertilizer efficiency. Climatic parameter was obtained from a certified meteorological station affiliated with the Iraqi General authority for Meteorology and Seismic Monitoring in Babil Governorate. The study area is under the semi-arid climatic regime represented by hot and dry summers as well as cool winters. Average daily air temperatures of the two growing seasons (March to August) in 2023 and 2024 were between 22°C in early spring and 38°C at the peak of mid-summer. Relative humidity varied between 30% and 60%, representing usual seasonal variations. The average daily solar radiation was about 19 MJ·m⁻²·day⁻¹, which favored active photosynthesis. Rainfall was minimal; it did not enter into the calculations for needing regular irrigation. Summary of the monthly climatic variables are shown in Table 1.

Table 1. Monthly mean climatic conditions recorded at the experimental site in Babil Governorate, Iraq, during the growing seasons (March-August) of 2023 and 2024.

Month	Avg. Temperature (°C)	Relative Humidity (%)	Solar Radiation (MJ·m ⁻² ·day ⁻¹)	Rainfall (mm)
March	22	55	17	2
April	26	50	19	0
May	31	45	20	0
June	36	35	21	0
July	38	30	21	0
August	37	32	20	0

Note: Means are based on two consecutive growing seasons (2023 and 2024). Weather measurements were recorded by an automatic weather station at the experimental site.

Soil and irrigation water characterization

Pre-field treatments, composite soil (0-30 cm) and irrigation water samples were collected in a cross-sample to serve as baseline for their physicochemical properties. (Abate, 2025) The soil was of medium fertility and described as sandy loamy, while the irrigation water had quality suitable for use in horticulture. The detail properties of the experimental soil and irrigation water are listed in Table 2, Table 3 other than above. These baseline data are important to make comparisons with the effects of organic and phosphate fertilizer applications on plant growth, nutrient dynamics, and soil–water relations.

Table 2. Physico-chemical properties of the surface soil (0-30cm) at the experimental site

Parameter	Value	Unit
Soil texture	Sandy loam (Sand 65%, Silt 25%, Clay 10%)	—
pH	7.1	—
EC	1.4	dS m ⁻¹
Organic matter	3.1	g kg ⁻¹
Available nitrogen (N)	28.7	mg kg ⁻¹
Available phosphorus (P)	0.52	mg kg ⁻¹
Available potassium (K)	40.0	mg kg ⁻¹

Note: Soil samples were collected from the top 0–30 cm strata before application of treatments and analyzed as per standard soil testing methods, based on USDA-FAO protocols. Values are averages of mean values on a composite sample basis from experimental plots.

Table 3. Chemical properties and quality evaluation of irrigation water applied in the experiment

Parameter	Value	Unit
pH	7.3	—
EC	1.2	dS m ⁻¹
Nitrate-N (NO ₃ -N)	12.3	mg L ⁻¹
Orthophosphate-P (PO ₄ - P)	0.15	mg L ⁻¹
Potassium (K ⁺)	1.8	mg L ⁻¹
Na ⁺	104	mg L ⁻¹
Ca ²⁺	60	mg L ⁻¹
Mg ²⁺	12	mg L ⁻¹
Sodium Adsorption Ratio (SAR)	3.2	—

Note: Irrigation water samples were collected from a local groundwater well and analyzed for nutrient content and salinity hazards. Water quality parameters fall within acceptable limits for horticultural use according to FAO irrigation water standards.

Experimental set up and agronomic practices

The factorial experiment was carried out on field in a Randomized Complete Block Design (RCBD) with three replications for statistical reliability. The experimental factors included two types of fertilizers: organic and phosphate, each applied at three levels. Organic fertilizer (well-decomposed cattle manure) was administered at rates of 0, 2.5, and 5 kg tree⁻¹. The compost manure used was collected from a certified local livestock farm in Babil Governorate province, Iraq. The physicochemical characteristics of composted cattle manure applied as organic fertilizer are summarized in Table 4. Phosphate fertilizer was SSP (20% P₂O₅) provided by the State Company for Fertilizers, Southern Region, Iraq and utilized at 0, 100 and 180 g. tree⁻¹ levels of phosphorus application. Organic fertilizer was applied to the root area at the beginning of growth season which could improve soil basal fertility. Phosphate fertilizer input was divided into two equal doses: the first at bud break, and the second at the beginning of flowering to match nutrient availability with crucial phenological phases. Three apples' trees under uniform management per replicate served as an experimental unit, giving a total of 27 trees in the experiment. Pest management and irrigation were implemented uniformly in all treatments as part of the agronomic practices used. Irrigation was carried out by a drip system, and the emitters were placed around each tree. Irrigations were applied every three days and amounts adjusted according to seasonal ET rates and maintained in relation to the desired soil moisture level. All apple grafted trees, being 4 years at time of the experiment, were physiologically most suited for investigating fertilizer responsiveness as they were well established and not senescent.

Table 4. Baseline physicochemical composition of the organic fertilizer (composted cattle manure) applied in the field experiment.

Parameter	Value	Unit
Moisture content	22.0	%
pH	7.6	—
EC	3.2	dS m ⁻¹
Organic Carbon	36	% (dry basis)
Total nitrogen (N)	1.8	% (dry basis)
Total phosphorus (P ₂ O ₅)	1.2	% (dry basis)
Total potassium (K ₂ O)	2.1	% (dry basis)
Organic matter	45.0	%
C/N	20.5	—
Bulk density	0.65	g cm ⁻³

Note: Physicochemical analyses of the organic fertilizer were conducted on a dry weight basis following standard protocols for organic amendment characterization (AOAC, 2019).

Plant Physiological, Biochemical, and Fruit Quality Measurements

For a thorough evaluation of the physiological, biochemical and yielding aspects in apple trees as influenced by applied fertilization treatments, the selected set of measurements was analyzed at critical phenological stages. Total chlorophyll content in leaves was assessed using nondestructively SPAD-502-meter and spectrophotometric analysis of extracted pigments, allowing an accurate diagnosis of the photosynthetic pigment status (Nurbaiti *et al.*, 2025). The net photosynthetic rate (P_n, $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) was measured with a portable infrared gas analyzer to assess the functional photosynthesis potential of each treatment (Zhang *et al.*, 2021).

Biochemical assessments were carried out to quantify the activities of key antioxidant enzymes in fresh leaf tissues, with emphasis on ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco, U mg⁻¹ protein) and superoxide dismutase (SOD, U mg⁻¹ protein). These enzymes were determined using well-established and validated enzymatic assay procedures (Lyu *et al.*, 2023).

In addition, the concentrations of essential macronutrients in leaves, including nitrogen (N), phosphorus (P), and potassium (K), were determined following wet digestion. Nutrient contents were then measured using spectrophotometric and flame photometric techniques to provide insight into plant nutrient uptake and overall nutritional status (Mertoğlu & Kırca, 2025). At commercial maturity, the following quality parameters of all analyzed fruit per tree (number of fruit/tree) were registered: number, average weight (g), and size expressed as diameter (mm), length (mm), firmness

(kg cm⁻²) and TSS (%) determined by a refractometer in °Brix using standard horticultural tools/instrumentation appropriate to each evaluation procedure (MORARIU *et al.*, 2025). All measurements were taken in concordance with the international horticultural and laboratory standards in order to provide reliable, reproducible, and sound scientific data. This made it possible for the chosen datasets to work as foundations for robust statistical analyses on the effects of fertilization treatment affecting both apple tree physiology and agronomy.

Statistical Analysis

All data were subject to two-way ANOVA of the main and interaction effects of organic, phosphate fertilizer treatments. Data was also checked for normality and equality of variances, and once the assumptions were met ANOVA actioned. The differences between treatment means were tested with the Tukey's Honest Significant Difference (HSD) test at $p < 0.05$. All values were expressed as means $\pm$ SD and calculated in the mean. All statistical analyses were performed using SPSS version 25.0 (IBM Corp, Armonk, NY, USA) and R Statistical Software version 4.3.0 (R Core Team; 2023), with the purpose of ensuring methodological adequacy of the analyses and analysis power.

RESULT AND DISCUSSION

The data illustrated in Figure 1 clearly demonstrate the substantial influence of both organic and phosphate fertilization, as well as their interaction, on the total yield of apple trees. Application of increasing rates of organic fertilizer resulted in a consistent improvement in yield across all phosphate levels. At the highest organic rate (5 kg tree⁻¹), the mean yield ranged from 67.0 kg tree⁻¹ (without phosphate) to 85.0 kg tree⁻¹ (with 180 kg ha⁻¹ phosphate), compared to only 40.0 kg tree⁻¹ in the unfertilized control. This corresponds to a 112.5% increase in total yield with the integrated application of both fertilizers (5 kg organic + 180 kg phosphate) over the control. Similarly, the highest phosphate rate (180 kg ha⁻¹) independently boosted yield at every organic fertilizer level, with yields rising from 77.0 kg tree⁻¹ (zero organic) to the aforementioned 85.0 kg tree⁻¹ (5 kg organic), compared to the control values at each organic rate. These results highlight the central role of phosphorus in supporting energy transfer, nucleic acid synthesis, and root system development—factors essential for enhanced yield (Liu, 2021). The effect of the interaction between organic and phosphate fertilization was particularly noteworthy synergistic. The highest productive treatment (5 kg organic + 180 kg phosphate) was significantly superior over all single treatments. This may be due to the power of organic amendments to improve phosphorus availability, and probably this result is related to improved soil structure; increased microbial activity; mobilization of previously unavailable phosphate forms (Bamdad *et al.*, 2022).

In addition, organic fertilizers improve water-holding capacity, recycling of nutrients and supply a wide range of micro- and macronutrients whilst phosphate fertilisers directly stimulate root development and sugar mobilisation. These effects when combined enforces a stronger vegetative and reproductive growth, better photosynthetic potential followed by overall increase in fruit yield (Debele, 2021).

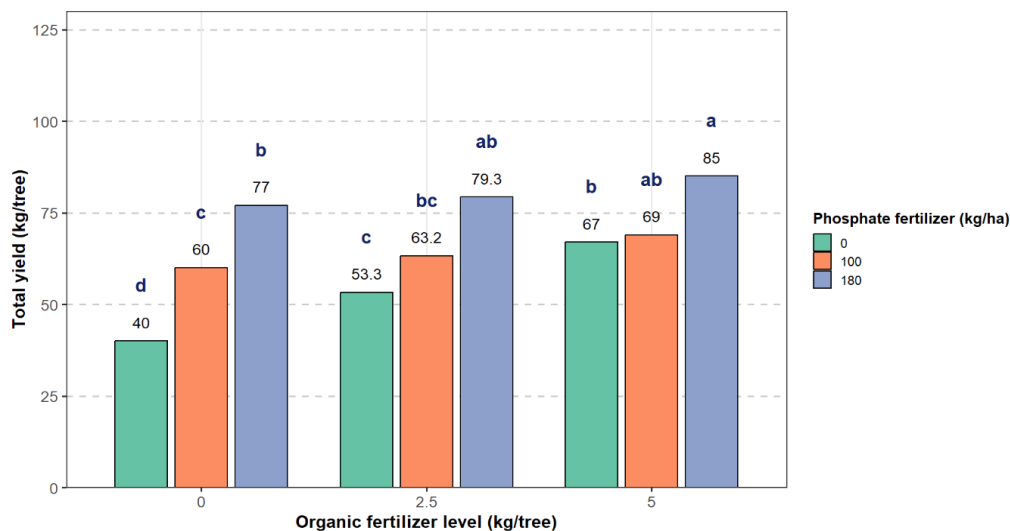


Figure 1. Effect of organic and phosphate fertilizer rates and their interaction on the total yield (kg tree⁻¹) of apple trees. Different letters above the bars indicate significant differences between means according to LSD test at $p \leq 0.05$.

The findings of this study indicate that the different fertilization regimes had a significant effect on the main yield components, namely the number of fruits per tree and the average fruit weight, as shown in Figure 2. When the highest rates of both organic and phosphate fertilizers were applied in combination, the highest fruit number was recorded at 236 fruits per tree, representing a 69.1% increase compared to the control treatment (140 fruits tree⁻¹). This improvement is attributed to the effectiveness of integrated nutrient management in supporting floral development and improving fruit set; the simultaneous supply of both organic matter and phosphorus promotes nutritional balance in the rhizosphere and sustains the enzymatic activity essential for cell division and the formation of flowers and fruits (Srivastava *et al.*, 2021). The application of organic fertilizer alone (5 kg tree⁻¹) led to increase in number of fruits to 210 fruits per tree (50.0% increase) due to improvement in soil aggregation and microbial activity, following the application of organic matter. This enhances the mineralization of organic materials and reduces nitrogen loss, as well as maintaining a humid and balanced flowering and fruiting rhizosphere (Farooqi *et al.*, 2023). Similarly, phosphate fertilization 180 kg ha⁻¹ increased it to 222 fruits per tree (58.6 % increase) and this may be associated with a prime function of P in ATP for cell division, proper flower growth and fruit set. Phosphorus also stimulates uptake of other nutrients and assimilation of carbohydrates into fruitlets (Panigrahi *et al.*, 2024). Regarding the mean fruit weight, then the highest value was obtained under integrated fertilization (360 g fruit⁻¹), followed by the control (+32.4%, with 272 g fruit⁻¹) as shown in Fig. 3. This benefit can be associated with the synergistic action of organic and phosphate fertilizers in enhancing P availability and mobility of other essential micro-elements (K, Mg). This in-turn increases root uptake capacity through microorganism activation and by production of organic acids by beneficial microorganisms (Bamdad *et al.*, 2022).

For the individual treatments, the use of organic fertilizer alone (5 kg tree⁻¹) raised the average fruit weight to 315 g fruit⁻¹ (a 15.8% increase over the control), as also shown in Figure 3. This result is attributed to the enhancement of soil structure and microbial activity, which improve the availability of essential macro- and micronutrients required for fruit development and filling (Al-Khazrji *et al.*, 2023; Shihab *et al.*, 2023). Phosphate fertilization at 180 kg ha⁻¹ increased the average fruit weight to 330 g fruit⁻¹ (a 21.3% increase), reflecting the essential role of phosphorus in supporting the physiological processes required for carbohydrate synthesis and allocation to the fruits, as well as in promoting cell division and increasing cell size within the fruit (Liu, 2021).

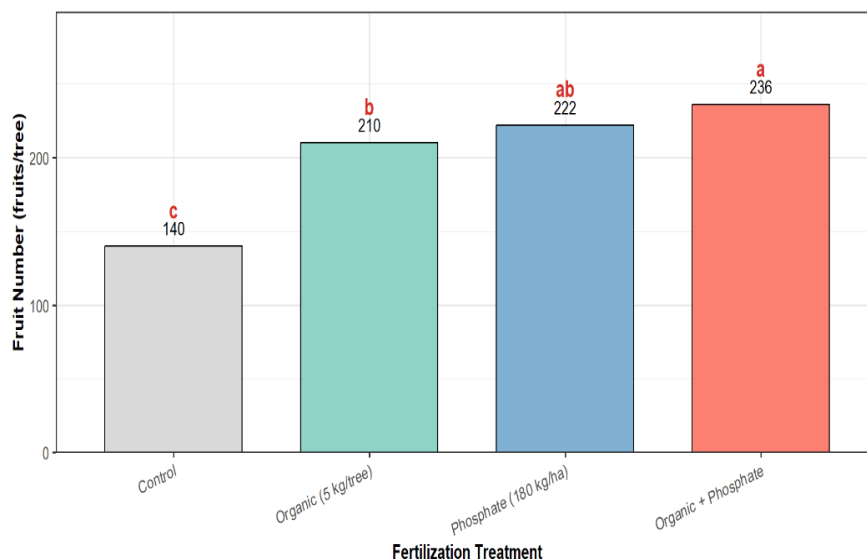


Figure 2. Fruit number per apple tree under different fertilization treatments. Bars with different letters indicate statistically significant differences according to LSD test at $p \leq 0.05$.

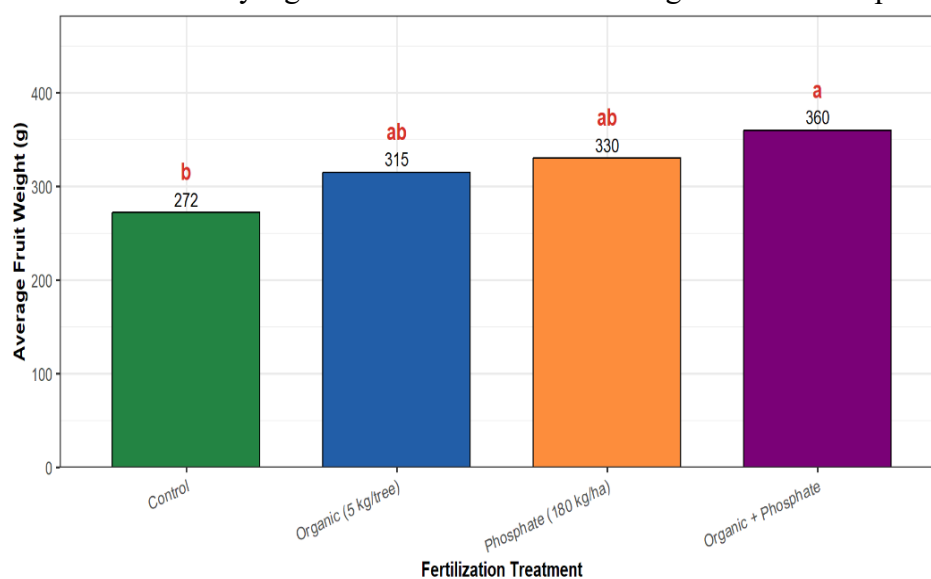


Figure 3. Average fruit weight (g) of apple trees under different fertilization treatments. Bars with different letters indicate statistically significant differences according to LSD test at $p \leq 0.05$.

Experiment results confirmed that combined utilization of organic and phosphate fertilizers significantly increased physical quality properties of apple fruit (Table 5). Fruit diameter was found to be 82.3 mm under this regime, an enhancement of 17.9% over the control (69.8 mm), and fruit length was noted as 78.5 mm, that is about 18.9% higher than the control (66.0 mm). This increase in fruit size can be attributed to the synergistic effects of organic fertilizer—which boosts both cation exchange capacity and structural conditions of soil—and phosphate fertilizer, which stimulates cell division and elongation through the stimulation of energy metabolism. Cumulatively, these factors generate a nutrient-rich and water abundant in hull, which stimulates the sugar and starch translocation from leaves to fruit during its development (Gu *et al.*, 2021). Alternatively, the fruit firmness with IF (8.7 kg cm^{-2}) was highest, and it increased by 40.3% in comparison to control (6.2 kg cm^{-2}). The background for this improvement stems mainly from the higher availability of calcium and magnesium in the soil when receiving integrated fertilization, with calcium in particular playing a role by strengthening the pectic bonds between cell walls. This improvement imparts higher firmness and resistance to physical damage or softening during postharvest handling and storage (Zhandybayev *et al.*, 2024). Regarding SSC (soluble solids content), the Forster proved to obtained the highest mean value with 15.2 °Brix, which was 25.6% higher than that of control treatment (12.1 °Brix). This increment is due to the increased photosynthesis provided by the enhanced chlorophyll content and enzymatic activity which resulted on more accumulation of soluble sugars in these fruits. The increased P availability could also contribute to improve the translocation of sugars from leaves to fruit tissues by increasing ATP production, and the higher activity of enzymes involved in sugar and vitamin biosynthesis caused by the increase of the supply of essential micronutrients (Xian *et al.*, 2024). The single organic and phosphate fertilizer treatments also showed substantial improvement in the investigated traits: 77.0 mm was the average fruit diameter of plants subjected to the organic only treatment, which was 10.3% higher than controls, while it was 79.4 mm for plants treated with phosphates alone (13.8% increase). The SSC contents were found to be 13.8 and 14.5 °Brix, respectively, compared with the control (12.1 °Brix). These results indicate that the effects of organic and phosphate fertilizers on apple fruit physical and chemical properties are independent. However, when they are simultaneously applied, the highest productivity and fruit quality is achieved due to synergistic activation of complex physiological and microbiological mechanisms that promote nutrient uptake, sugar accumulation, and improvement of fruit cell structure (Zhuang *et al.*, 2024).

Table 5. Effect of organic, phosphate, and combined fertilization treatments on fruit diameter, length, firmness, and soluble solids content (SSC) of apple fruits.

Treatment	Fruit Diameter (mm)	Fruit Length (mm)	Firmness (Kg cm ⁻²)	SSC (°Brix)
Control	69.8 ± 2.1 (c)	66.0 ± 1.8 (c)	6.2 ± 0.3 (c)	12.1 ± 0.5 (c)
Organic	77.0 ± 2.6 (b)	71.3 ± 2.0 (b)	7.6 ± 0.4 (b)	13.8 ± 0.6 (b)
Phosphate	79.4 ± 1.9 (ab)	75.0 ± 2.3 (ab)	8.1 ± 0.3 (ab)	14.5 ± 0.4 (ab)
Organic + Phosphate	82.3 ± 2.3 (a)	78.5 ± 1.7 (a)	8.7 ± 0.5 (a)	15.2 ± 0.5 (a)

Note. Values are presented as mean ± standard deviation (n = 3). Within each column, values followed by different letters indicate statistically significant differences among treatments according to LSD test at $p \leq 0.05$.

In the case of using only organic fertilizer, enhanced leaf macronutrient concentration was observed and levels of N, P and K in leaves increased to 2.24%, 0.28% and 1.62%, respectively versus control value (1.96%, 0.24% and 1.45%) (Figure 4). This enhancement in root growth can be due to several convergent mechanisms: On the one hand, organic fertilizer first ameliorates soil physical properties by improving soil structure and promoting formation of fine aggregates that also improve aeration and water permeability-thus favorable to the rhizosphere environment-stimulating root growth (Negušier *et al.*, 2024). Organic matter also increases the cation exchange capacity of the soil, which enhances retention of nutrients such as N and K, reducing leaching losses; consequently, more nutrients can be made available to plant roots for longer periods (Matisic *et al.*, 2024).

Microbiologically, organic fertilization represents an abundant supply of C and energy to beneficial soil microorganisms which could result in higher population density and activity of these microorganism on the rhizosphere. These microbes can mineralize organic material, provide the plant with nitrogen and phosphorus in ready-to-use forms, as well as excreting organic acids and enzymes to help release nutrients from unavailable sources, most notably P held in soils (Fernandez *et al.*, 2016). It accounts for high phosphorus and nitrogen in leaves of the plants treated with organic fertilizer. For K, organic matter enhances its distribution and release from clay minerals through cation exchange leading a greater bioavailability (Matisic *et al.*, 2024).

Treatment with phosphate fertilizer alone also led to a significant improvement in the content of all three nutrients, and contents of N, P and K in leaves were higher to 2.33%, 0.32% and 1.74%, respectively (Figure 4). The increase in the concentration of phosphorus could be mainly that owing to the application of highly soluble phosphate fertilizers, which can be easily taken up by the roots and thus result directly in increased plant tissue (Xian *et al.* Phosphorus has been well known for its ability to promote root growth (branching) than the roots connection with soils and gaining access to other nutrients (Panigrahi *et al.*, 2024).

In addition, phosphorus is also an integral part of ATP molecules that have a central role in energy transfer between different metabolic processes, including the absorption of nitrogen and potassium in soils. This combined network of interactions is the reason why nitrogen and potassium level were found enriched from phosphate treatment, when these nutrients are not placed directly (Schroeder & Janos, 2005). Phosphorus also promotes the activity of enzymes involved in photosynthesis and organic compound synthesis that is associated with better vegetative growth and long-term productivity (Khan *et al.*, 2023; Aljumaily *et al.*, 2022).

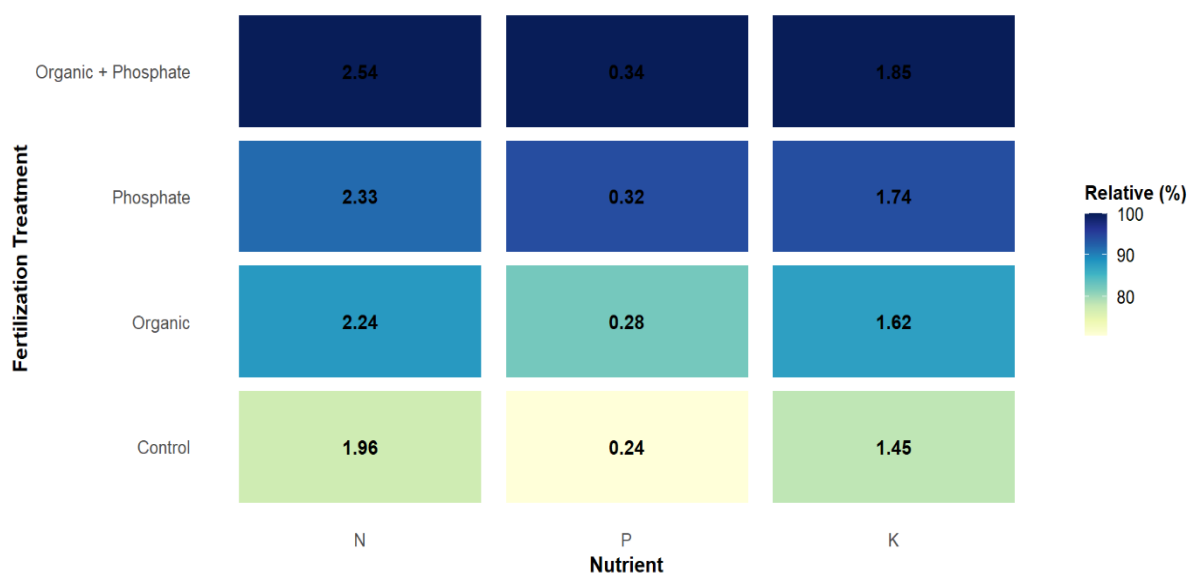


Figure 4. Normalized heatmaps of N, P and K concentration in apple leaves in response to different fertilization treatments. The colour of a specific nutrient represents the relative value of that nutrient as a percent of the highest recorded value in that nutrient. Values within each cell are means averaged (from 3 replications / treatment). The treatments consist of control (no fertilizer), single organic fertilizer, single phosphate fertilizer, and organic + phosphate fertilization.

The analysis of physiological indicators revealed a marked improvement in total chlorophyll content, net photosynthetic rate, and the activities of Rubisco and SOD enzymes in apple leaves in response to the different fertilization treatments (Table 6). The highest values were associated with the integrated (organic + phosphate) fertilization treatment, where total chlorophyll content reached $2.18 \pm 0.09 \text{ mg g}^{-1}$ fresh weight, representing an increase of 32.1% compared to the control ($1.65 \pm 0.07 \text{ mg g}^{-1}$). The sole phosphate treatment recorded $2.02 \pm 0.08 \text{ mg g}^{-1}$ (22.4% increase), while the organic-only treatment reached $1.88 \pm 0.09 \text{ mg g}^{-1}$ (13.9% increase). These results suggest a synergistic effect of organic combination fertilization, since N and Mg available from organic sources promote the biosynthesis of chlorophyll, while phosphorus gene-rates ATP needed for energy transfer in photosynthesis (Xian *et al.*, 2024).

For net photosynthetic rate (Pn), the integrated treatment achieved $18.7 \pm 0.8 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, corresponding to a 38.5% increase over the control (13.5 ± 0.6). Significant increases were also observed with phosphate (16.8 ± 0.5 ; 24.4% increase) and organic (15.9 ± 0.7 ; 17.8% increase) treatments. This improvement reflects the combined role of available nutrients in supporting photosynthetic processes and enhancing energy utilization and carbon assimilation efficiency in the leaves (Kushwah *et al.*, 2023).

The enzymatic activity was also analysed and the results revealed that Rubisco activity significantly increased in the integrated fertilization treatment (72.5% with $4.2 \pm 0.21 \text{ U mg}^{-1}$ protein) compared to the control (2.4 ± 0.12). Smaller rises were registered for the organic (3.1 ± 0.18 , 29.2%) and phosphate (3.5 ± 0.17 ; 45.8%) treatments. SOD activity was also increased by integrated fertilization, giving rise to $22.4 \pm 1.1 \text{ U mg}^{-1}$ protein (47.4% increment with respect to control, 15.2 ± 0.8); single treatments led to the following values: 18.7 ± 1.0 (23% for organic) and $20.1 \pm 0.9 \text{ U mg}^{-1}$ protein (32.2% for phosphate). These evidences suggest that the dual interaction between organic and phosphate fertilization enhances the plant antioxidant defences against oxidative stress, leading to overall improvement in leaf physiological performance.

These overall advances in physiological processes again supported the significance of balanced nutrient management on optimizing enhancement of photosynthesis and synthesis of chlorophyll; along with heightening plants' stress defense and enzyme maintenance in relation to productivity, fruit quality.

Table 6. Effect of different fertilization treatments on total chlorophyll content, net photosynthetic rate, and key enzymatic activities in apple leaves.

Treatment	Total Chlorophyll (mg g FW ⁻¹)	Net Photosynthetic Rate (Pn, $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)	Rubisco Activity (U mg ⁻¹ protein)	SOD Activity (U mg ⁻¹ protein)	Significance Indicator
Control	1.65 ± 0.07	13.5 ± 0.6	2.4 ± 0.12	15.2 ± 0.8	c
Organic	1.88 ± 0.09	15.9 ± 0.7	3.1 ± 0.18	18.7 ± 1.0	b
Phosphate	2.02 ± 0.08	16.8 ± 0.5	3.5 ± 0.17	20.1 ± 0.9	ab
Organic + Phosphate	2.18 ± 0.09	18.7 ± 0.8	4.2 ± 0.21	22.4 ± 1.1	a

Note: Values are expressed as mean $\pm$ standard deviation ($n = 3$). Within each column, different letters indicate statistically significant differences among treatments according to LSD test at $p \leq 0.05$.

The above visualized evidence was also supported by the clustered correlation heatmap (Figure 5) which constructed from integrated expression network of apple leaves under different nutrient treatments. The high coefficient of correlation ($r > 0.98$) obtained in most of the studied

parameters especially for total chlorophyll content, net photosynthetic rate and Rubisco-SOD enzyme activities as well as the whole yield clearly suggests that any effect accrued from gain from these traits are always associated with concurrent advantaging by others which cross beyond economic acceptable level. This finding reflects a sophisticated regulatory network, where the physiological activity and nutrient flux are interconnected towards the achievement of productive potential.

The tight interrelation between chlorophyll content, photosynthesising activity and yield was emphasised to promote the higher level of photosynthetic capacity that would translate into more efficient use of light energy by transforming it in the desired end products - sugars, starches etc. This is in fact one of the major predictors of fruit weight and size (Valentinuzzi *et al.*, 2019). In that, the better leaf nutriment level (especially N, Mg and P) allows activation of chlorophyll biosynthetic activity and electron transport chain enough to control their activities especially for more carbon assimilation and primary productivity. This positive correlation in Rubisco performance and yield explains the significance of this enzyme in carbon assimilation; an improved effectiveness of Rubisco will lead directly to more carbon being channelled into organic molecules that are necessary for expansion of tissues and for filling up or developing fruit. The increase in SOD activity therefore represents not only an efficient defensive response at the level of potential oxidative stress but also the cell's capability to retain fee chloroplasts and proteins, especially when fruits are rapidly developing or factors that affect environmental conditions have changed (Lavic *et al.*, 2023).

The clustering groups formed in the dendrogram also provide additional evidences that plant responses to treatments are not isolated events that occurs independently for specific O species, but occur within a network of integrated responses in which phosphate and organic fertilization, synergistically interact with each other toward enhancing photosynthetic efficiency, antioxidant defences and ultimately fruit quality. This is in agreement with the hypothesis that coincidental enhancement of both photosynthesis and antioxidative systems, as a consequence of integrated nutrient management, might offer useful strategies to optimize the efficiency use of agricultural resources and may also have value for improving competitive ability in crop production system. Finally, the high correlation levels among traits found here are consistent with a reflection on plant physiology: an enhancement in one primary function (nutritional, defensive, productive), is mirrored by improvements of other ones. This process of integration gives an apple orchard under high fertilization strategies the capacity to withstand environmental stress.

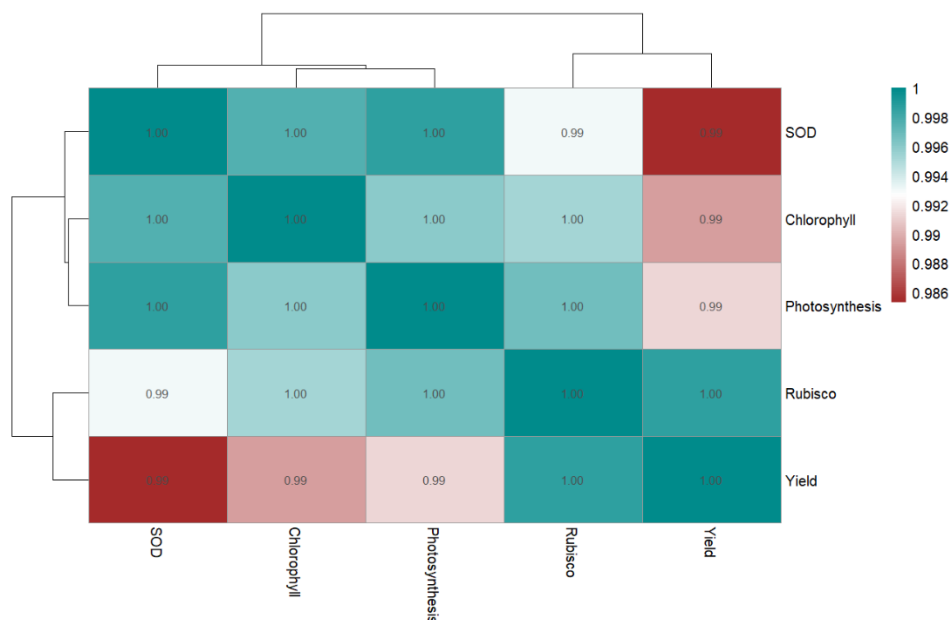


Figure 5. Clustered correlation heatmaps of Pearson's correlation between the physiological and yield-related traits in apple leaves across diverse fertilization treatments. Values indicate the strength and direction of the Pearson's correlation (r) between traits; row/column color intensity reflect r value, clustering in rows/columns is applied hierarchically to traits with similar patterns. High positive correlations were identified between all traits monitored, suggesting strong physiological interaction and possible co-regulation under integrated fertilization management.

CONCLUSION

Results of this study can effectively serve as concrete evidence that an integrated management plan including organic and phosphate fertilization is a good strategy for improving physiological characteristics, yield, and fruit quality in the apple orchard under semiarid conditions. The addition of organic and phosphate fertilizers at the highest rates stimulated the most significant improvements in all measured plant physiological indicators, such as leaf chlorophyll content, net photosynthetic rate, activities of Rubisco and SOD enzymes, as well as significant increases in leaf nitrogen, phosphorus and potassium concentrations compared with that from the control plant without application. These physiological changes were directly correlated with agronomic and quality traits because total fruit yield, the number of fruits and the average fruit weight significantly increased due to drastic improvements in fruit diameter, length, firmness and soluble solids concentration. These findings underscore the need to implement balanced nutrition coupled with organic and mineral based fertilizers in order to improve productivity and fruit quality in (marginal) water-insecure conditions. Based on these results, application of combined fertilization regimes with organic and phosphate-based for obtaining good production is highly recommended in apple orchards grown under semi-arid conditions for a sustainable product and profitable purpose. Additionally, long-term investigations are needed to determine the potential accumulative

impact of these practices on soil characteristics and nutrient dynamics as well as sustainability of orchard system under varying environmental conditions.

Conflict of interest

The authors declare no conflicts of interest associated with this manuscript.

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