Research Article

Assessing the Effect of Mulching and Bio-fertilization and Nanoformulated NPK on Nutrients Profile of Soil and Plants of Three Olive (*Olea europaea* L.) Cultivars

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Abstract | Mulching, biofertilization and application of nanofertilizer have been promising eco-friendly strategies for sustainable crop production. This study was conducted to determine the effect of soil mulching, and fertilization with powdered aquatic weed *Ceratophyllum demersum* L. and nanoformulated NPK on the soil nutrients profile and biochemical constituents of six-month-old olive saplings of three olive cultivars viz; Arbequina, Ba'ashiqa, and Improved Nabali. Experimental design was split-plot RCBD with three factors and four replications per treatment. Results revealed that the Ba'ashiqa cultivar exhibited significantly higher soil NPK concentrations and leaf proline, phosphorus, and potassium contents than the other cultivars, whereas Arbequina showed the greatest chlorophyll concentration. Soil mulching significantly enhanced soil NPK status and increased leaf chlorophyll content. Moreover, a synergistic effect of the combined administration of *C. demersum* powder and nanoformulated NPK was observed on all mineral contents of soil and plant nutrients regardless of the cultivar or mulching treatment, suggesting their integrated incorporation in sustainable olive production in Iraq.

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Introduction

The olive (*Olea europaea* L.) is an evergreen subtropical tree species belonging to the Oleaceae family. It is one of the most important oilseed crops globally. Originating in the Mediterranean basin, it holds substantial economic, social, and environmental importance (Maesano *et al.*, 2021). Olive oil has a tremendous nutritional value with a wide range of medicinal, industrial and culinary uses (Çekiç, İ., and Oğan, 2025). About 2600 plus olive cultivars are being grown all over the world, with over 40 cultivars present in Iraq (Abdulrahem and Mohamed, 2024). Although olive cultivation in Iraq has not been considerable due to many socio-economic factors, country's olive oil production remained record high in 2025 contributing towards a milestone for Iraq's agriculture sector (IOC, 2025).

All plants including olive trees require essential nutrients for their optimal growth. Nitrogen supports protein synthesis and the formation of new tissues, phosphorus promotes root growth, bud formation, and energy transfer within the plants, and potassium aids in carbohydrate production, enhances disease resistance, and regulates metabolic activities (Jiaying *et al*., 2022). Agricultural soils in Iraq face several challenges, including low nutrient use efficiency, declining soil organic matter, multiple nutrient deficiencies, climate change, shrinking arable land, and limited water availability (Mahmud, 2021). Despite these challenges, achieving a sustainable agricultural growth rate of 4% is critical to ensuring food security (Salih and Kamall-Eldeen, 2021). Therefore, field application of advanced soil conservation strategies such as mulching and supplementing soil profiles with nanoformulated macro and micronutrients would be the need of the time in order to mitigate the soil deterioration and to enhance sustainability of agricultural soils (Bhaskar *et al*., 2023; Demo and Bogale, 2024; Irewale *et al*., 2025).

Mulching is a well-established soil conservation technique and among of the most effective practices promoting sustainable agriculture (El-Beltagi *et al*., 2022). It helps maintain soil physico-chemical stability by moderating temperature, reduces evaporation, preserves the soil moisture, suppresses weed emergence, limits pest proliferation, and stimulates the activity of beneficial soil fauna, thereby enhancing the crop growth and productivity (Prem *et al*., 2020; Kayusi *et al*., 2025). Moreover, mulching mitigates pesticide residues, minimizes soil erosion losses, reduces greenhouse gas emissions, and protects plants against drought stress (Demo and Bogale, 2024).

Nevertheless, supplementing agricultural soils with organic amendments such as by incorporating different plant materials is one of the environment-friendly strategies being focused to enhance the sustainable production (Matisic *et al*., 2024). *Ceratophyllum demersum* L. is a ubiquitous aquatic weed commonly known as hornwort or shambalan. It belongs to the family Ceratophyllaceae and is an important submerged, evergreen aquatic macrophyte plant. It has underwater roots, rigid olive-green branched stems with a coarse texture, and dense leaves (Masłyk *et al*., 2024). Its uncontrolled proliferation in rivers and irrigation canals impedes water flow, and annual removal imposes significant economic burdens (Datta, 2009). Therefore, transforming this abundant biomass into valuable organic fertilizers or growth media offers an environmentally sustainable solution. Such organic materials significantly enhance the water-holding capacity of soils. For instance, Al-Asafi *et al*. (2009) and Salih (2023) reported that powdered *C. demersum* used as a growth medium can retain water up to 4–6 times its weight and contains appreciable levels of nitrogen, potassium, calcium, and small amounts of phosphorus.

Moreover, nanotechnology facilitates precise nutrient delivery, improves nutrient-use efficiency, increases productivity, and promotes environmental safety (Qarachal and Alizadeh, 2025). Nano-fertilizers, as the latest innovation in mineral nutrient application, provide nutrients at significantly lower quantities than conventional chemical fertilizers, reducing environmental degradation while improving plant uptake efficiency (Demeke *et al*., 2025). Previous studies have demonstrated the effectiveness of nanoformulated NPK administration in enhancing soil health and plant growth characteristics of agricultural and horticultural crops (Sneharani and Kumar, 2021; Mhawesh and Mohsen, 2024; Marif *et al*., 2025).

Therefore, this study aimed to investigate the effects of soil mulching, amendment of powdered aquatic plant *C. demersum* as an organic fertilizer, and administration of nanoformulated NPK fertilizers either alone or in interaction on soil fertility status and on the growth performance of three olive cultivars.

Materials and Methods

Research area

This research work was carried out in the farm area of the College of Agriculture, University of Diyala, during 2024 growing season. Experiment was laid out in an one-year-old saplings of three olive cultivars *i.e.*, Arbequina, Ba'ashiqa and Improved Napali.

Experimental layout

The objective was to determine the effect of soil mulching, the addition of *C. demersum* powder, nanofabricated NPK fertilizer, and their combination on improving soil properties and vegetative growth traits of these olive cultivars. A total of 96 saplings (32 saplings per cultivar), of uniform size and vigor, were planted on March 7, 2024, at a spacing of 4 m between plants. Each cultivar was divided into four replicates, with eight saplings per replicate. Standard orchard management practices were followed, including irrigation, fertilization, weeding, replanting where necessary, weed removal, and insect control as needed.

The experiment was laid out as a factorial trial in a split-plot arrangement within a randomized complete block design (RCBD) with three factors: i) first factor: olive cultivars—Arbequina, Ba'ashiqa, and Improved Nabali, ii) second factor: soil mulching at two levels—no mulch and mulch, and iii) third factor: fertilization at four levels—no fertilization (control), *C. demersum* powder, nanoformulated NPK fertilizer, and a combination of *C. demersum* powder + nanoformulated NPK. *C. demersum* powder was blended with farmyard manure @ 2:1 ratio (manure: plant powder), whereas nanoformulated NPK was applied as a foliar spray @1.0 mL L^{-1}. Mulching and fertilization treatments were randomly assigned to sub-plots. The interaction among the three factors resulted in 24 treatment combinations. Treatments were applied monthly for eight consecutive months from April to November, 2024.

Study parameters

Soil physico-chemical characteristics studied in this research work included total soil nitrogen (%) determined using a spectrophotometer according to Chapman *et al.* (1961), total soil phosphorus (%) determined spectrophotometrically at a wavelength of 882 nm (John, 1970) and total potassium in soil (%), determined using a flame photometer following Johnston *et al.* (1952). Plant nutritional traits assessed in this study included branch carbohydrate content (%) determined according to Joslyn (1970), leaf proline content (mmol g^{-1}) estimated according to Bates *et al.* (1973), total chlorophyll content in leaves (mg g^{-1}) determined according to Goodwin (1976) at wavelengths of 663 and 645 nm using a spectrophotometer, nitrogen, phosphorus, and potassium in leaves (%) determined using the same methods described above for soil analysis, and seedling height increase (cm), calculated as the difference between initial and final measurements from soil surface to top shoot.

Statistical analysis

The experiment layout was randomized complete block design (RCBD) with split-plot arrangement of three factors *i.e.,* olive cultivars, soil mulching and soil fertilization with nanoformulated NPK and *C. demersum* powder. The experimental data were analyzed using SAS (2003), and the treatment means were compared by Duncan's Multiple Range (DMR) test at standard level of probability ($\alpha - 0.05$) (Hasnain *et al.*, 2020).

Results and Discussion

Effect of cultivars, mulching and fertilization treatments on soil macro-nutrients status

Total soil nitrogen content

Results showed significant variations among olive cultivars regarding the effect of treatments soil nitrogen concentration (Table 1). Soil of Ba'ashiqa cultivar exhibited the highest nitrogen content (27.72%), followed by Improved Nabali (25.81%), while Arbequina showed the lowest (23.75%) soil nitrogen content. Moreover, soil mulching had a pronounced positive effect on soil nitrogen content, increasing it to 29.00% compared with only 22.52% in the no-mulch treatment. On the other hand, fertilization did not show a significant main effect on soil nitrogen levels. The highest nitrogen value (28.71%) was recorded in unfertilized control plots (Table 1).

Results of interaction treatments revealed that the cultivar × mulching interaction, Ba'ashiqa with mulching gave the highest nitrogen content (30.19%), while Arbequina without mulching recorded the lowest value (20.06%). In the cultivar × fertilization interaction, Ba'ashiqa without fertilization produced the highest nitrogen content (30.63%). Conversely, Arbequina with the application of nanoformulated NPK and *C. demersum* exhibited the lowest value (22.25%). As for the interaction between mulching and fertilization, it was noted that the interaction between soil mulching and no fertilization was superior with the highest value, reaching 31.33%, while the interaction between no mulching and the addition of nanoformulated NPK + *C. demersum* gave the lowest value of 19.25%. The three-way interaction showed that the Ba'ashiqa cultivar with mulching and no fertilization had the highest soil nitrogen content (33.00%), whereas the Arbequina cultivar without mulching and with nanoformulated NPK + *C. demersum* recorded the lowest value of 16.75% (Table 1).

Table 1: *Effect of cultivar, soil mulching, nano-NPK addition, C. demersum, and their interactions on total nitrogen content in soil (%).*

Olive cultivars	Mulching	Fertilization				Cultivars × Mulching
		Control	C. demersum	NPK	C. demersum +NPK	
Arbequina	No mulching	24.75i	20.75k	19.00 l	16.75 m	20.06 F
	Mulching	29.25cd	26.75f	26.00 fg	27.75 e	27.44 C
Ba'ashiqa	No mulching	28.25e	25.75g	24.75 h	22.25 j	25.25 D
	Mulching	33.00a	30.00c	28.00 e	29.75 c	30.19 A
Improved Napali	No mulching	26.25fg	23.00ij	21.00 k	18.75 l	22.25 E
	Mulching	31.75b	28.75de	27.75 e	29.25 cd	29.38 B
						Cultivars
Cultivars × Fertilization	Arbequina	26.50d	23.75e	22.50 f	22.25 f	23.75 C
	Ba'ashiqa	30.63a	27.88c	26.38 d	26.00 d	27.72 A
	Improved napali	29.00b	25.88d	24.38 e	24.00 e	25.81 B
						Mulching
Mulching × Fertilization	No mulching	26.08d	23.17e	21.58 f	19.25 g	22.52 B
	Mulching	31.33a	28.50b	27.25 c	28.92 b	29.00 A
Fertilization		4.000C	6.625AB	6.833 A	5.792 B	

**Treatment means with similar letters do not differ significantly from each other (DMR @ α = 0.05).*

Table 2: *Effect of cultivar, soil mulching, nano-NPK addition, C. demersum, and their interactions on phosphorus content in soil (%).*

Olive cultivars	Mulching	Fertilization				Cultivars × mulching
		Control	C. demersum	NPK	C. demersum +NPK	
Arbequina	No mulching	6.625 d	6.475 e	6.300 f	6.175 g	6.394 D
	Mulching	6.950 b	6.900 bc	6.675 d	6.575 d	6.775 B
Ba'ashiqa	No mulching	6.800 c	6.825 c	6.625 d	6.400 f	6.644 C
	Mulching	7.125 a	7.000 b	6.825 c	6.625 d	6.894 A
Improved Napali	No mulching	6.400 ef	6.400 ef	6.300 f	6.175 g	6.319 E
	Mulching	6.975 b	6.675 d	6.450 e	6.300 f	6.600 C
						Cultivars
Cultivars × Fertilization	Arbequina	6.788 b	6.687 c	6.488 d	6.375 e	6.584 B
	Ba'ashiqa	6.963 a	6.913 a	6.725 bc	6.475 d	6.769 A
	Improved napali	6.688 c	6.538 d	6.375 e	6.238 f	6.459 C
						Mulching
Mulching × Fertilization	No mulching	6.608 cd	6.567 d	6.408 f	6.225 g	6.452 B
	Mulching	7.017 a	6.858 b	6.650 c	6.500 e	6.756 A
Fertilization		6.813A	6.713 B	6.529 C	6.363 D	

**Treatment means with similar letters do not differ significantly from each other (DMR @ α = 0.05).*

Total phosphorus content of soil

Results shown in Table 2 revealed a significant effect of different treatments on the three olive cultivars regarding soil phosphorus content. The Ba'ashiqa and Improved Nabali showed the highest (6.769%) and lowest (6.459%) phosphorus content, respectively. Soil mulching led to a notable increase in phosphorus content, reaching 6.756% as compared to no-mulch control treatment (6.452%). However, fertilization had no significant effect on soil phosphorus levels.

Table 3: *Effect of cultivar, soil mulching, nano-NPK addition, C. demersum, and their interactions on total potassium content in soil (%).*

Olive cultivars	Mulching	Fertilization				Cultivars × Mulching
		Control	C. demersum	NPK	C. demersum +NPK	
Arbequina	No mulching	79.25 fgh	77.00 jk	76.75 jk	74.00 l	76.75 D
	Mulching	81.75 bc	79.25 fgh	77.25 ij	75.00 l	78.31 C
Ba'ashiqa	No mulching	81.25 bcd	79.75 efg	80.25 def	77.25 ij	79.63 B
	Mulching	85.00 a	82.25 b	80.75 cde	78.25 hi	81.56 A
Improved Napali	No mulching	77.25 ij	74.75 l	74.75 l	71.75 m	74.63 E
	Mulching	79.00 gh	76.00 k	74.75 l	71.00 m	75.00 E
						Cultivars
Cultivars × Fertilization	Arbequina	80.50 b	78.13 c	77.00 d	74.50 f	77.53 B
	Ba'ashiqa	83.13 a	81.00 b	80.50 b	77.75 c	80.59 A
	Improved Napali	78.13 c	77.00 e	74.38 f	71.38 g	74.81 C
						Mulching
Mulching × Fertilization	No mulching	79.25 b	77.17c	77.25c	74.33 d	77.00 B
	Mulching	81.92 a	79.17b	77.33 c	74.75 d	78.29 A
Fertilization		80.58 A	78.17B	77.29C	74.54 D	

**Treatment means with similar letters do not differ significantly from each other (DMR @ α = 0.05).*

The two-way interaction between cultivar and mulching showed that Ba'ashiqa with mulching and Improved Nabali without mulching exhibited the highest (6.894%) and lowest (6.319%) phosphorus content, respectively. In the cultivar × fertilization interaction, Ba'ashiqa without fertilization recorded the highest phosphorus level (6.963%) and Improved Nabali with nanoformulated NPK + *C. demersum* application showed the lowest phosphorus value (6.238%). For the mulching × fertilization interactions, the combination of mulching and no fertilization resulted in the highest phosphorus content (7.017%), while no mulching with nanoformulated NPK + *C. demersum* recorded the lowest value (6.225%). The three-way interaction results showed that the Ba'ashiqa cultivar combined with soil mulching and no fertilization yielded the highest value at 7.125%. The interaction of the Arbequina cultivar with no mulching and the addition of NPK + *C. demersum* gave the lowest value of 6.175% (Table 2).

Total potassium content of soil

A similar trend of significance had been recorded in case of soil potassium contents. Ba'ashiqa and Improved Nabali exhibited the highest (80.59%) and lowest (77.53%) value of soil potassium content, respectively (Table 3). The results also showed an increase in soil potassium content under soil mulching, reaching 78.29%, whereas the no-mulch treatment showed the lowest value (77.00%) of potassium. Fertilization, however, did not result in significant changes in potassium content.

The effect of interaction between cultivars and mulching demonstrated that cultivar Ba'ashiqa and soil mulching were superior with the highest content of potassium in the soil (81.56%), while the interaction between the cultivar Improved Nabali and no mulching showed the lowest content (74.63%). In the cultivar × fertilization interaction, Ba'ashiqa in the control treatment gave the highest potassium content (83.13%), while Improved Nabali with nanoformulated NPK + *C. demersum* recorded the lowest value (71.38%). The mulching × fertilization interaction showed that mulching combined with no fertilization exhibited the highest soil potassium content (81.92%), whereas no mulching with nanoformulated NPK + *C. demersum* yielded the lowest (74.33%). Moreover, Ba'ashiqa with mulching and no fertilization gave the highest soil potassium level (85.00%), while the treatment Improved Nabali cultivar, soil mulching and adding NPK + *C. demersum* exhibited the lowest value (71.00%) of soil potassium content (Table 3).

Effect of treatments on plant nutritional profile

Total carbohydrate content of olive branches

Results had showed that neither the olive cultivars

Table 4: *Effect of cultivar, soil mulching, nano-NPK addition, C. demersum, and their interactions on total carbohydrate content in branches (%).*

Olive cultivars	Mulching	Fertilization				Cultivars × Mulching
		Control	C. demersum	NPK	C. demersum +NPK	
Arbequina	No mulching	3.513 e	4.523 cd	4.550 cd	5.730 a	4.579 AB
	Mulching	3.603 e	4.625 cd	4.615 cd	5.795 a	4.659 AB
Ba'ashiqa	No mulching	3.588 e	4.655 cd	4.690 cd	5.840 a	4.693 A
	Mulching	3.683 e	4.770 c	4.700 cd	5.290 b	4.611 AB
Improved Napali	No mulching	3.540 e	4.375 d	4.513 cd	5.665 a	4.523 B
	Mulching	3.435 e	4.570 cd	4.583 cd	5.730 a	4.577 AB
						Cultivars
Cultivars × Fertilization	Arbequina	3.558 d	4.574 bc	4.583 bc	5.763 a	4.619 A
	Ba'ashiqa	3.635 d	4.713 b	4.695 b	5.565 a	4.652 A
	Improved Napali	3.488 d	4.473 c	4.548 bc	5.693 a	4.550 A
						Mulching
Mulching × Fertilization	No mulching	3.547 c	4.518 b	4.584 b	5.745 a	4.598 A
	Mulching	3.573 c	4.655 b	4.633 b	5.602 a	4.616 A
Fertilization		3.560 C	4.586 B	4.608 B	5.673 A	

**Treatment means with similar letters do not differ significantly from each other (DMR @ α = 0.05).*

nor soil mulching alone had a significant effect on the carbohydrate content of olive tree branches (Table 4). However, all fertilization treatments had a significant influence. The combined application of nanoformulated NPK + *C. demersum* exhibited the highest value (5.673%) of carbohydrate content of branches, followed by nanoformulated NPK alone (4.608%). This was closely followed, without a significant difference, by *C. demersum* alone (4.586%), while the lowest carbohydrate content (3.560%) of branches was recorded in the control treatment without any fertilization (Table 4).

For two-way interactions, the Ba'ashiqa cultivar without mulching showed the highest carbohydrate content (4.693%), whereas Improved Nabali without mulching showed the lowest value (4.523%). In the cultivar × fertilization interaction, Arbequina with nanoformulated NPK + *C. demersum* achieved the highest content 5.763%), while Improved Nabali without fertilization recorded the lowest at 3.488%. The mulching × fertilization interaction indicated that the combination of no mulching with nanoformulated NPK + *C. demersum* resulted in the highest carbohydrate content (5.745%), while no mulching without fertilization produced the lowest value of carbohydrate content (3.547%). Moreover, Ba'ashiqa without mulching and with nanoformulated NPK + *C. demersum* application achieved the highest value of branch carbohydrate content (5.840%).

Leaf proline content

Results indicated that the Ba'ashiqa and Improved Nabali cultivar had the highest (3.400 mmol g^{-1}) and lowest (3.205 mmol g^{-1}) leaf proline content, respectively. Soil mulching had no significant effect on leaf proline content. In contrast, fertilization treatments had a pronounced effect, with the combined application of nanoformulated NPK + *C. demersum* giving the highest value of 5.398 mmol g^{-1}. The lowest leaf proline content (1.557 mmol g^{-1}) was observed in case of unfertilized control. In interaction treatments, Ba'ashiqa with mulching yielded the highest value (3.480 mmol g^{-1}), while Improved Nabali without mulching recorded the lowest value (3.125 mmol g^{-1}) of leaf proline content. In the cultivar × fertilization interaction, Arbequina with nanoformulated NPK + *C. demersum* achieved the highest value (5.470 mmol g^{-1}), whereas Improved Nabali without fertilization recorded the lowest (1.506 mmol g^{-1}). The mulching combined with nanoformulated NPK + *C. demersum* application resulted in the highest leaf proline content (5.421 mmol g^{-1}), while no mulching with no fertilization recorded the lowest (1.500 mmol g^{-1}). Three-way interaction of Arbequina without mulching and with

Table 5: *Effect of cultivar, soil mulching, nano-NPK addition, C. demersum, and their interactions on leaf proline content (mmol g^{-1} dry weight).*

Olive cultivars	Mulching	Fertilization				Cultivars × Mulching
		Control	C. demersum	NPK	C. demersum +NPK	
Arbequina	No mulching	1.49 e	2.82 b-e	3.13 bcd	5.53 a	3.24 A
	Mulching	1.64 cde	3.13 bcd	3.27 b	5.41 a	3.36 A
Ba'ashiqa	No mulching	1.57 de	3.10 bcd	3.26 b	5.35 a	3.32 A
	Mulching	1.63 cde	3.21 b	5.24 b	5.50 a	3.48 A
Improved Napali	No mulching	1.44 e	2.76 b-e	3.06 bcd	5.24 a	3.13 A
	Mulching	1.58 de	3.04 bcd	3.17 bc	5.35 a	3.29 A
						Cultivars
Cultivars × Fertilization	Arbequina	1.57 c	2.97 b	3.20 b	5.47 a	3.30 AB
	Ba'ashiqa	1.60 c	3.16 b	3.42 b	5.43 a	3.40 A
	Improved napali	1.51 c	2.90 b	3.12 b	5.30 a	3.21 B
						Mulching
Mulching × Fertilization	No mulching	1.50 c	2.89 b	3.15 b	5.37 a	3.23 A
	Mulching	1.61 c	3.13 b	3.34 b	5.42 a	3.38 A
Fertilization		1.56 C	3.01 B	3.25 B	5.40 A	

**Treatment means with similar letters do not differ significantly from each other (DMR @ α = 0.05).*

Table 6: *Effect of cultivar, soil mulching, nano-NPK addition, C. demersum, and their interactions on leaf chlorophyll content (mg g^{-1} fresh weight).*

Olive cultivars	Mulching	Fertilization				Cultivars × Mulching
		Control	C. demersum	NPK	C. demersum +NPK	
Arbequina	No mulching	19.10 g	41.10 ef	69.33 ab	56.25 dc	46.44 B
	Mulching	30.09 f	63.10 bc	68.24 ab	79.03 a	60.11 A
Ba'ashiqa	No mulching	9.96 g	11.96 g	12.12 g	13.97 g	12.00 D
	Mulching	11.86 g	13.56 g	19.10 g	13.50 g	13.72 D
Improved napali	No mulching	31.99 f	36.02 ef	35.71 ef	40.69 ef	36.10 C
	Mulching	34.35 f	41.07 ef	38.42 ef	47.38 de	40.30 C
						Cultivars
Cultivars × fertilization	Arbequina	24.60 e	52.10 b	68.78 a	67.64 a	53.28 A
	Ba'ashiqa	10.91 f	12.76 f	14.04 f	13.73 f	12.86 C
	Improved napali	33.17 d	38.55 dc	37.07 dc	44.03 c	38.20 B
						Mulching
Mulching × fertilization	No mulching	20.35 d	36.97 c	39.05 b	36.97 b	31.52 B
	Mulching	25.43 dc	39.24 b	40.87 ab	46.64 a	38.05 A
Fertilization		22.89 C	34.47 B	39.96 A	41.80 A	

**Treatment means with similar letters do not differ significantly from each other (DMR @ α = 0.05).*

nanoformulated NPK + *C. demersum* application exhibited the highest value (5.530 mmol g^{-1}), while Improved Nabali without mulching and without fertilization recorded the lowest value at 1.438 mmol g^{-1} (Table 5).

Total chlorophyll concentration

Data regarding leaf chlorophyll content showed that the Arbequina cultivar had the highest leaf chlorophyll content (53.28 mg g^{-1}), followed by Improved Nabali with a significantly lower value of 38.20 mg g^{-1}. The Ba'ashiqa cultivar recorded the lowest chlorophyll content at 12.86 mg g^{-1}. Soil mulching significantly increased chlorophyll content to 38.05 mg g^{-1} as compared to 31.52 mg g^{-1} in the no-mulch treatment. Fertilization treatments also had a clear positive effect. The highest chlorophyll content (41.80 mg g^{-1}) was recorded for the combined application of nanoformulated NPK + *C. demersum*, followed closely and without significant difference by nanoformulated NPK alone at 39.96 mg g^{-1}. Application of *C. demersum* alone yielded 34.47 mg g^{-1}, while the lowest value (22.89 mg g^{-1}) of leaf chlorophyll content was exhibited in the control treatment (no fertilization).

In the cultivar × mulching interaction, Arbequina with mulching gave the highest chlorophyll content (60.11 mg g^{-1}), whereas Ba'ashiqa without mulching had the lowest (12.00 mg g^{-1}). The cultivar × fertilization interaction revealed that Arbequina with nanoformulated NPK achieved the highest value (68.78 mg g^{-1}), while Ba'ashiqa without fertilization recorded the lowest (10.91 mg g^{-1}). For the mulching × fertilization interaction, the highest value (46.64 mg g^{-1}) was obtained with mulching combined with nanoformulated NPK + *C. demersum*, while the lowest (20.35 mg g^{-1}) occurred in no mulching and no fertilization. The three-way interaction results indicate that the Arbequina cultivar with mulching and nano-NPK + *C. demersum* achieved the highest chlorophyll content at 79.03 mg g^{-1}, whereas the interaction between the Ba'ashiqa cultivar with no mulching and no fertilization recorded the lowest value at 9.96 mg g^{-1} (Table 6).

Leaf nitrogen content

There were no significant differences among the olive cultivars in leaf nitrogen content. However, mulching led a slight but significant increase, with mulched plants recording 1.601% leaf nitrogen content as compared to 1.547% recorded in the no-mulch treatment. The combined application of nanoformulated NPK + *C. demersum* gave the highest leaf nitrogen content (1.676%), while, the lowest leaf nitrogen content (1.392%) was observed in the unfertilized control treatment (Table 7). Moreover, Improved Nabali with mulching exhibited the highest leaf nitrogen value (1.605%), while the same cultivar without mulching had the lowest (1.523%). Similarly, Improved Nabali with nanoformulated NPK + *C. demersum* achieved the highest nitrogen content (1.700%), whereas the same cultivar without fertilization recorded the lowest (1.320%). Mulching combined with nanoformulated NPK + *C. demersum* application resulted in the highest value (1.701%), while no mulching without fertilization gave the lowest (1.343%). The combination of Improved Nabali × mulching × nanoformulated NPK + *C. demersum* yielded the highest nitrogen content in

Table 7: *Effect of cultivar, soil mulching, nano-NPK addition, C. demersum, and their interactions on leaf nitrogen content (%).*

Olive cultivars	Mulching	Fertilization				Cultivars × Mulching
		Control	C. demersum	NPK	C. demersum +NPK	
Arbequina	No mulching	1.383 e	1.595 c	1.588 c	1.633 bc	1.549 BC
	Mulching	1.485 d	1.623 bc	1.615 bc	1.670 abc	1.598 A
Ba'ashiqa	No mulching	1.403 de	1.613 bc	1.608 bc	1.653 abc	1.569 AB
	Mulching	1.440 de	1.638 abc	1.625 bc	1.703 ab	1.601 A
Improved napali	No mulching	1.243 f	1.600 c	1.578 c	1.670 abc	1.523 C
	Mulching	1.398 de	1.645 abc	1.648 abc	1.730 a	1.605 A
						Cultivars
Cultivars × fertilization	Arbequina	1.434 d	1.609 c	1.601 c	1.651 abc	1.574 A
	Ba'ashiqa	1.421 d	1.651 bc	1.616 bc	1.678 ab	1.585 A
	Improved Napali	1.320 e	1.623 bc	1.613 c	1.70 a	1.564 A
						Mulching
Mulching × Fertilization	No mulching	1.343 e	1.603 bc	1.591 c	1.652 b	1.547 B
	Mulching	1.441 d	1.652 bc	1.629 bc	1.701 a	1.601 A
Fertilization		1.392 C	1.619 B	1.610 B	1.676 A	

**Treatment means with similar letters do not differ significantly from each other (DMR @ α = 0.05).*

leaves (1.730%), while interaction of Improved Nabali without mulching and without fertilization recorded the lowest value at 1.243% (Table 7).

Leaf phosphorus and potassium concentration

A similar trend was recorded in case of leaf phosphorus and potassium contents. Olive cultivar Ba'ashiqa and Improved Nabali exhibited the highest phosphorus and potassium content *i.e.* 0.409 and 1.627%, respectively, and lowest (0.368 and 1.548%, respectively (Table 8 and Table 9). Mulching significantly increased phosphorus and potassium contents to 0.409% and 1.106% as compared to 0.368% and 1.570% in the no-mulch treatment, respectively.

Table 8: *Effect of cultivar, soil mulching, nano-NPK addition, C. demersum, and their interactions on leaf phosphorus content (%).*

Olive cultivars	**Mulching**	**Fertilization**				**Cultivars × Mulching**
		Control	C. demersum	NPK	C. demersum +NPK	
Arbequina	No mulching	0.278 m	0.338 i	0.363 h	0.490 d	0.367 D
	Mulching	0.308 jk	0.380 g	0.388 g	0.560 b	0.409 B
Ba'ashiqa	No mulching	0.290 l	0.360 h	0.383 g	0.523 c	0.389 C
	Mulching	0.313 j	0.418 f	0.410 f	0.580 a	0.430 A
Improved Napali	No mulching	0.263 n	0.308 jk	0.340 i	0.478 e	0.347 E
	Mulching	0.298 kl	0.360 h	0.368 h	0.528 d	0.388 C
						Cultivars
Cultivars × Fertilization	Arbequina	0.293 I	0.359 f	0.375 e	0.525 b	0.388 B
	Ba'ashiqa	0.301 h	0.389 d	0.396 d	0.551 a	0.409 A
	Improved napali	0.280 J	0.354 g	0.354 f	0.503 c	0.368 C
						Mulching
Mulching × Fertilization	No mulching	0.277 g	0.335 e	0.362 d	0.497 b	0.368 B
	Mulching	0.306 f	0.385 c	0.388 c	0.556 a	0.409 A
Fertilization		0.291D	0.360 C	0.375 B	0.526 A	

**Treatment means with similar letters do not differ significantly from each other (DMR @ α = 0.05).*

Table 9: *Effect of cultivar, soil mulching, nano-NPK addition, C. demersum, and their interactions on leaf phosphorus content (%).*

Olive cultivars	**Mulching**	**Fertilization**				**Cultivars × Mulching**
		Control	C. demersum	NPK	C. demersum +NPK	
Arbequina	No mulching	1.373 o	1.533 jk	1.555 i	1.788 d	1.562 D
	Mulching	1.395 n	1.578 h	1.603 fg	1.840 c	1.604 C
Ba'ashiqa	No mulching	1.415 m	1.588 gh	1.590 gh	1.860 b	1.613 B
	Mulching	1.445 l	1.595 gh	1.620 f	1.900 a	1.640 A
Improved napali	No mulching	1.340 p	1.518 k	1.528 jk	1.753 e	1.534 E
	Mulching	1.365 o	1.538 ij	1.540 ij	1.800 d	1.561 D
						Cultivars
Cultivars × fertilization	Arbequina	1.384 j	1.555 g	1.579 f	1.814 b	1.583 B
	Ba'ashiqa	1.430 i	1.591 e	1.605 d	1.880 a	1.627 A
	Improved napali	1.353 k	1.528 h	1.534 h	1.776 c	1.548 C
						Mulching
Mulching × fertilization	No mulching	1.376 h	1.546 f	1.558 e	1.800 b	1.570 B
	Mulching	1.402 g	1.570 d	1.588 c	1.847 a	1.601 A
Fertilization		1.389 D	1.558 C	1.573 B	1.823 A	

**Treatment means with similar letters do not differ significantly from each other (DMR @ α = 0.05).*

In both cases, fertilization had a pronounced effect, with the combined application of nanoformulated NPK + *C. demersum* producing the highest value of phosphorous (0.526%) and potassium (1.823%), while the lowest phosphorus (0.291%) and potassium (1.389%) contents were recorded in the unfertilized control. Similarly, regarding the interaction of cultivar × mulching, the highest phosphorus (0.430%) and potassium (1.640%) contents of leaves were recorded for Ba'ashiqa with mulching, while the interaction of Ba'ashiqa with nanoformulated NPK + *C. demersum* showed the highest values of leaf phosphorus (0.551%) and potassium (1.880%) contents. Similarly, mulching combined with nanoformulated NPK + *C. demersum* resulted in the highest phosphorus (0.556%) and potassium (1.847%) contents. The three-way interaction of Ba'ashiqa cultivar with mulching and nanoformulated NPK + *C. demersum* application exhibited the highest leaf phosphorus (0.580%) and potassium (1.900%) contents, while the lowest values are recorded for Improved Nabali without mulching and without fertilization (Table 8 and Table 9). The he in line with sustainable agriculture principles—thereby converting an environmental problem into a valuable resource. Additionally, it seeks to evaluate the effects of and its combination with *C. demersum* powder on improving soil properties and the growth performance of three olive cultivars.

This field experiment aimed to determine the impact of soil mulching and application of powdered aquatic plant *C. demersum* as an organic fertilizer, and nanoformulated NPK fertilizers either alone or in interaction on soil fertility status and on the mineral or nutrients profiles of three olive cultivars.

Effect of cultivars, mulching and fertilization treatments on soil macro-nutrients status

The results regarding the effect of mulching, *C demersum* powder mixing and nano-formulated NPK administration on the soil nutrients status of three olive cultivars suggest that the interaction or combined application of these factors had a significant impact on the soil macronutrient profiles. The Ba'ashiqa cultivar exhibited the highest level of nitrogen, phosphorus and potassium in the soil. This may be caused by the limited reduction or underlying genetic factors for available edaphic nutrients, as each olive cultivar would have a unique genetic ability and potential to utilize available soil nutrients (Roussos *et al*., 2017), and how these plant cultivars interact with the surrounding environmental conditions (Gargouri *et al*., 2006; Carella *et al*., 2022).

The role of soil mulching in increasing the soil fertility and nutritional retention can be attributed to the ability to reduce soil compaction, prevent erosion and improve the soil structure strengthening aggregation in clay soils and increase nutritional-holding capacity of sandy soil (Ngosong *et al*., 2019). Mulching also enhances soil micro-organisms activity resulting in higher nutrient availability (Yadav *et al*., 2024). By acting as a protective layer, mulching reduces nutrients and reduces the runoff of surface by reducing water movement and conserving the nutrients into the root zone. Also, mulching improves conditions for soil microorganisms which are useful in nutrient cycling, bioavailability of soil nutrients and their absorption by plants (Wang *et al*., 2020; Bandyopadhyay and Mukhopadhyay, 2021; Liang *et al*., 2025).

Effect of cultivars, mulching and fertilization treatments on nutrient profiles of plants

The results showed cultivar Ba'ashiqa and application of mulching and combined application of nanoformulated NPK and *C. demersum* had significantly enhanced the nutritional or mineral profile of branches and leaves of olive saplings. The results showed a synergistic effect of combined nanoformulated NPK and *C. demersum* application substantially all mineral contents of olive branches, regardless of cultivar or mulching treatment. Soil mulching significantly increased proline, chlorophyll, nitrogen, potassium, and phosphorus contents as compared to control (no-mulch) treatment. This would be likely due to the role of mulching in moderating soil temperature, maintaining soil moisture, in conserving soil moisture, reducing nutrient leaching, and enhancing phosphorus solubility in the root zone and improving nutrient availability for chlorophyll synthesis (Liang *et al*., 2025).

The results showed that the cultivars and their interactions with the study factors had a significant impact on the mineral profiles of soils and olive plants. Ba'ashiqa cultivar outperformed the other two cultivars in leaf element content, which included proline, phosphorus, and potassium, while the Arbequina cultivar outperformed in leaf chlorophyll content. The responsiveness of the different cultivars to the applied nanoformulated and bio-fertilizers may be related to their genetic make-up and varietal characters as each cultivar is characterized by unique combinations of gene types that differ in degree and type of interaction with surrounding conditions (Therios, 2009). These findings are line with the results of some previous studies by Roussos *et al*. (2017), Falih *et al*. (2018) and Abdulrahem and Mohamed (2024).

The increased values of leaf chlorophyll and NPK content due to the mulching could be attributed to the protective aspect of the mulch for preventing leaching nutrients away from root zone, which made more nutrient available for plants. It is also used to reduce nitrate leaching, stabilize the N pool, and enhance soil biological activity (Stratton and Rechcigl 2020). Mulching also increases transpiration efficiency by reducing evaporation (this improves water and nutrient transport). The resulting increase in soil temperature and moisture further stimulates root growth, thereby supporting plant growth and development (Yadav *et al*., 2024).

The results also revealed a significant effect of *C. demersum* fertilization compared with the control, indicating its positive influence on the chemical properties of olive leaves. This enhancement likely stems from its role in boosting photosynthetic activity through increased chlorophyll levels which in turn enhances carbohydrate production (Sachet *et al*., 2021; Aboohana *et al*., 2022). These carbohydrates are used for various physiological processes, tissue formation, and are stored in the branches for use during the following growing season. The improvement in leaf nutrient content under *C. demersum* treatment may be attributed to the naturally high nutrient content of aquatic plants, particularly *C. demersum*, which absorbs large quantities of nutrients from the water it inhabits. This nutrient-rich biomass—especially in carbon and nitrogen—remains readily available for plant root uptake (Al-Miyahi, 2013).

Data regarding plant mineral profiles showed that the application of nano-formulated nitrogen, phosphorus, and potassium fertilizers (NPK) significantly improved the vegetative growth traits of olive saplings compared with the unfertilized control. This effect can be linked to the roles of nitrogen, phosphorus, and potassium in enhancing nutrient distribution, solubilization, and availability to plants, thereby stimulating photosynthesis (Tanou *et al*., 2017). Similarly, the role of nitrogen is to increase the effectiveness of photosynthesis in combination with phosphorus. Nitrogen also stimulates the production of auxin, which encourages cell division and cell elongation, in addition to the role of potassium, which controls the process of opening and closing stomata through osmotic regulation of plant cells (Faker and Obaid, 2020). In addition, nanotechnology provides opportunities to use nanomaterials as carriers for fertilizers or for controlled- release delivery system, leading to the development of "smart fertilizer" that increases the use of nutrients. These conclusions fit those reported by Ghosh *et al*. (2023), Aljubori *et al*. (2024) and Gupta *et al*. (2025).

Conclusions and Recommendations

This study concludes that the combined application soil mulching and fertilization - especially the combined application of powdered *C. demersum* and nano-formulated NPK -enhanced the fertility status of soils and mineral profiles of branches and leaves of different olive cultivars. Ba'ashiqa cultivar outperformed the others in retaining higher nutrient contents in both soil and leaves, while Arbequina excelled in chlorophyll accumulation. Mulching played an important role in increasing the soil fertility and nutrient retention within the plant tissues, while *C. demersum* amendment promoted photosynthetic activity and carbohydrate accumulation. The nanoformulated NPK application enhanced the nutrients availability and uptake, confirming its potential as an efficient and eco-friendly fertilization approach. Integration of mulching with organic nano-fertilization provides a promising approach to the growth of olives under sustainable agricultural practices and improvement of soil health. These findings can guide farmers and researchers in optimizing fertilization and soil management for sustainable olive production in Iraq. The consistency between the soil and leaf nutrient improvement confirms the synergistic role of nanoformulated and organic amendments of soil combined with mulching strategy.

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Novelty Statement

This field study demonstrated clearly the positive and synergistic role of mulching along with administration of aquatic weed *C. demersum* powder as organic fertilizer and nanoformulated NPK in enhancing the mineral and nutrient profiles of both soil and olive plants, advocating their integrated incorporation in sustainable olive production in Iraq.

Author's Contribution

Zahraa Ali Hussain: Wrote the manuscript, performed data analysis and laboratory work.
Zeina Sami Rashid: Edited the final version of manuscript and supervision of the project.

Generative AI or AI assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors have no conflict of interest.

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