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Effect of Zn and Fe concentrations on the fatty acid profile during germination of yellow quinoa (var. "Amarilla Maranganí") seeds

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ABSTRACT

Zinc (Zn) and iron (Fe) are essential micronutrients that participate in redox and enzymatic processes during germination, influencing lipid remodelling and antioxidant metabolism in seeds. Despite their importance, the combined effects of Fe and Zn supplementation on quinoa germination remain unclear. This study evaluated how $ZnSO_4$ and $FeSO_4$ affect the fatty acid composition, tocopherols, total phenolic content (TPC), and mineral profile of yellow "Amarilla Maranganí" quinoa. Seeds were germinated for 0, 24, and 48 h at 25 °C in solutions containing 0.00, 0.05, or 0.10 g L^{-1} $ZnSO_4$ and 0.00, 0.10, or 0.25 g L^{-1} $FeSO_4$. Germination exceeded 90% in all treatments, with slight radicle inhibition at the highest Fe concentration. Time significantly increased linoleic (18:2) and α-linolenic (18:3) acids and reduced palmitic acid (16:0), while $ZnSO_4$ produced small adjustments in unsaturated fractions. TPC and α-tocopherol rose markedly over time but were unaffected by mineral addition. Sprout Fe and Zn contents reflected applied levels, confirming effective uptake. Overall, germination time dominated biochemical changes; Fe/Zn priming enabled targeted mineral enrichment without impairing germination, offering a practical route to enhance the nutritional and functional value of quinoa sprouts for food and biofortification applications.

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KEYWORDS

quinoa, germination, minerals, fatty acids, pseudocereals, sprouts

1. INTRODUCTION

Quinoa (*Chenopodium quinoa* Willd.) is an Andean pseudocereal valued for its high-quality protein, dietary fibre, minerals, vitamins, and bioactive compounds, including a favourable lipid profile rich in unsaturated fatty acids and tocopherols (Navruz-Varli and Sanlier, 2016; Diaz-Valencia et al., 2018; Pachari Vera et al., 2019). Its gluten-free nature and versatility have driven its incorporation into a variety of functional foods.

Among the diverse quinoa varieties, the yellow "Amarilla Maranganí" has attracted attention for its distinctive seed composition, notably an elevated ω-6/ω-3 ratio and higher tocopherol levels compared to other Peruvian varieties (Pachari Vera et al., 2019). It also has higher riboflavin content than other quinoa cultivars (Granda et al., 2018).

Germination is known to enhance seed nutritional and bioactive profiles by increasing phenolic compounds and antioxidants, and modifying lipid fractions (Guardianelli et al., 2022; Al-Taher and Nemzer, 2023). Maldonado-Alvarado et al. (2023) showed that germination of "Amarilla Maranganí" for 4 days reduced phytic acid and enhanced mineral bioaccessibility. A 32–81% rise in both free and bound phenolics and flavonoids was observed after 48 h of quinoa germination (Lan et al., 2024). Moreover, mineral fortification during germination has proven effective in boosting Zn and Fe concentrations and their bioavailability in staples such as brown rice (Wei et al., 2012, 2013) and wheat (Naveen Kumar et al., 2019). Fe and Zn uptake during germination is transporter-mediated and buffered by chelation, with tight redox/hormonal control (Afzal et al., 2020). This regulatory context suggests that exogenous Fe/Zn can influence membrane remodelling and antioxidant responses in sprouts.

In quinoa, germination consistently elevates bioactive compounds across Andean varieties (Ramos-Pacheco et al., 2024, 2025). Cultivar-level differences in baseline composition and germination behaviour have been documented, including for "Amarilla Maranganí" (Manjarres-Hernández et al., 2024). Exogenous Zn supplied during seed treatment shows dose-dependent effects on early germination metrics in legumes (improvement at low doses and inhibition at higher doses), underscoring the importance of controlled levels (Choudhary and Khandelwal, 2020). Based on this background, we evaluated whether adding $ZnSO_4$ and $FeSO_4$ during short-term germination (24–48 h) modulates fatty acid composition, tocopherols, total phenolic content (TPC), and the mineral profile in "Amarilla Maranganí".

2. MATERIALS AND METHODS

2.1. Sample preparation

Seeds of "Amarilla Maranganí", grown by the Instituto Nacional de Investigación Agraria (INIA) in Cusco, Peru, were surface-sterilised with NaClO (Abderrahim et al., 2012), rinsed with water, and soaked for 3.5 h at room temperature in solutions containing $ZnSO_4$ (0, 0.05, 0.10 g L^{-1})

and $FeSO_4$ (0, 0.10, 0.25 g L^{-1}) (n = 3, 100 g seeds in 500 mL). Controls used water. The full treatment matrix is summarised in Table 1. After a distilled water rinse, seeds were germinated at 25 °C on moist blotting paper in Petri dishes (Wei et al., 2012, 2013).

2.2. Germination

Germination was carried out in the dark at 25 °C and 60% relative humidity (RH) for 24 or 48 h in an Inducell incubator (MMM Medcenter Einrichtungen, Germany). Germinated seeds were dried at 40 °C for 15 h in a Binder oven (Binder, Tuttlingen, Germany). This procedure was applied to each experimental unit and replicate.

2.2.1. Germination percentage. Germination percentage was determined on 100 seeds per treatment after 24 h at 25 °C (Table 1). Seeds were placed on filter paper moistened with 3 L distilled water in sterile Petri dishes, following Reyes-Pérez et al. (2013) (n = 3 per treatment).

2.2.2. Radicle length. Radicle length of 10 randomly selected germinated seeds was measured with a vernier caliper and reported in mm after 24 h at 25 °C.

2.3. Chemical analyses

2.3.1. Tocopherol analysis. Samples were oven-dried at 40 °C to <14% moisture (Abderrahim et al., 2012). Tocopherols were quantified by HPLC-FLD (Shimadzu 20-A, RF-20AXS, Kyoto, Japan) on a Supelcosil LC-18 column (25 cm × 4.6 mm, 5 µm) at 40 °C, with a mobile phase of acetonitrile/methanol/isopropanol/water (47.5:42.8:4.7:5 v/v) isocratic for 6 min, then ramped to 50:45:5:0 over 10 min and held to 30 min, followed by an acetonitrile wash and re-equilibration. Calibration used α-, β-, γ- and δ-tocopherol standards (Sigma-Aldrich) and detection at Ex/Em 290/330 nm. Analyses were performed in duplicate.

2.3.2. Total phenolic content (TPC). The total phenolic content (TPC) was determined following the method described by Singleton et al. (1999). Results were expressed as gallic acid equivalents (mg GAE/100 g sample, db). Analyses were performed in triplicate.

Table 1. Treatment matrix for $ZnSO_4$ and $FeSO_4$ priming during germination

$ZnSO_4$ (g L^{-1})	$FeSO_4$ (g L^{-1})	Soak time (h)	Germination time for assays (h)*
0.00	0.00	3.5	0, 24, 48
0.05	0.00	3.5	0, 24, 48
0.10	0.00	3.5	0, 24, 48
0.00	0.10	3.5	0, 24, 48
0.00	0.25	3.5	0, 24, 48
0.05	0.10	3.5	0, 24, 48
0.10	0.10	3.5	0, 24, 48
0.05	0.25	3.5	0, 24, 48
0.10	0.25	3.5	0, 24, 48

*Germination percentage and radicle length were evaluated at 24 h.

2.3.3. Lipid extraction. Lipids were extracted from dried quinoa shoots (4 g, ground) using hexane/isopropanol (3:2 v/v, 20 mL) at 40 °C for 60 min (Hara and Radin 1978). After centrifugation, the cake was washed four times with 7 mL of hexane/isopropanol solution. Combined supernatants were filtered (Whatman No. 1) and evaporated under N_2 at 40 °C. Total lipids (dry weight) were determined gravimetrically after constant-weight drying ($n = 2$).

2.3.4. Lipid profile. Fatty acid methyl esters (FAME) were prepared per International Olive Council (2017), with modifications: 20 mg oil was mixed with 2 mL hexane, shaken, then 0.2 mL 2 M methanolic KOH was added and vortexed for 30 s to induce transesterification. After phase separation, the upper layer (organic phase) was recovered for analysis. Samples (1 µL) were analysed by GC-FID (Shimadzu GC-14B, Kyoto, Japan; split 1:80 at 250 °C) on a Supelco SP-2330 column (30 m × 0.25 mm × 0.2 µm), with peaks identified by standards. Analyses were performed in duplicate ($n = 2$) on samples after 24 and 48 h germination and on ungerminated seeds. Results are expressed as fatty acid percentages for each fatty acid (palmitic (16:0), palmitoleic (16:1), stearic (18:0), oleic (18:1), linoleic (18:2), α-linolenic (18:3), eicosanoic acid (20:0), (Z)-11-eicosenoic acid (20:1 n-9), erucic acid (22:1 n-9)).

2.3.5. Elemental content. The elemental analysis of the samples was performed using ICP-MS (NexION 2000C, Perkin Elmer Inc., Connecticut, U.S.A.), according to the methodology described in Environmental Protection Agency (2007).

2.3.6. Statistical analysis. All analyses were conducted in R (R Core Team, 2024) via RStudio (Posit team, 2024) and are reported as mean ± SD. Germination percentage was evaluated by two-way ANOVA. Radicle length was modeled by generalized least squares (GLS), with competing variance structures compared by likelihood ratio tests (LRT). All other variables were analysed with linear mixed-effects models (LME), selecting between additive and full-interaction fixed-effect structures via LRT. Post hoc pairwise comparisons were adjusted by Tukey's method. Significance was set at $P < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Germination percentage and radicle length

Germination exceeded 90% across treatments (Fig. 1). Germination of all variants matched that of the control except at 0.10 g L^{-1} $FeSO_4$ (across $ZnSO_4$ levels) and at 0.05 g L^{-1} $ZnSO_4$ alone; radicle length declined at 0.10 and 0.25 g L^{-1} $FeSO_4$ except at 0.25 g L^{-1} $FeSO_4$ without $ZnSO_4$ and 0.10 g L^{-1} $ZnSO_4$ without $FeSO_4$. Wei et al. (2012, 2013) reported no loss of rice germination up to 0.25 and 0.15 g L^{-1} of $FeSO_4$ and $ZnSO_4$, respectively, while Naveen Kumar et al. (2019) noted negative effects on wheat radicle length at 3–15 mM NaFeEDTA.

These results are consistent with this trend. Dose-dependent Zn effects during seed treatment have been reported in legumes: ~100 ppm Zn improved germination and seedling vigour, whereas higher doses depressed growth, illustrating a narrow beneficial range for early seedlings (Choudhary and Khandelwal, 2020). Variety and handling differences also affect early quinoa performance, including faster hydration/germination behaviours documented for "Amarilla Marangani" (Manjarres-Hernández et al., 2024).

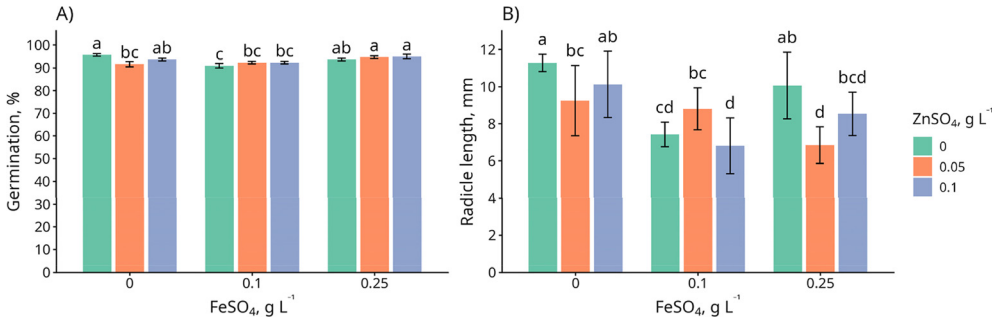

Fig. 1. Germination percentage (A; $n = 3$) and radicle length in mm (B; $n = 10$) of quinoa seeds soaked in solutions containing different concentrations of $FeSO_4$ and $ZnSO_4$. Different letters indicate significant differences (Tukey's HSD)

Because radicle growth proved sensitive to Fe dose and specific Fe × Zn combinations despite high germination, subsequent applications should measure Fe and verify vigour metrics before scale-up.

3.2. Total phenolic content

Figure 2 shows TPC values. The seed TPC exceeded three times the value previously reported (71.7 ± 5.5 mg GAE/100 g) by Alvarez-Jubete et al. (2010) for Bolivian quinoa. White (Goh and Lee, 2018) and red (Paucar-Menacho et al., 2018) Peruvian quinoa had lower TPC (108–137 mg GAE/100 g db), while Lan et al. (2024) found 500–600 mg GAE/100 g db in Chinese white quinoa.

After 48 h of germination, the TPC of the control was over seven times that reported by Alvarez-Jubete et al. (2010) for quinoa germinated at 10 °C for 82 h. The same authors reported 670 ± 12.3 mg GAE/100 g for buckwheat under those conditions. At 10 °C, Lan et al. (2024) observed a slight TPC drop during the first 24 h, then a plateau of 700–750 mg GAE/100 g db from 36 to 72 h. In contrast, Goh and Lee (2018) noted only modest increases at 25 °C: 122–124 mg GAE/100 g db at 24 h and 133–142 mg GAE/100 g^{-1} db at 48 h. After 42 and 72 h at 20 °C, Paucar-Menacho et al. (2018) reported red Peruvian quinoa TPC declining from 482.12–499.24 to 376.61 mg GAE/100 g, still below our values.

LME modelling showed germination time had a strong, significant effect on TPC ($P < 0.001$). Paucar-Menacho et al. (2018) also reported time as the dominant factor, with a non-significant time–temperature interaction, but our TPC increase was more pronounced at similar temperatures. Neither $ZnSO_4$ nor $FeSO_4$, alone or in interaction, significantly affected TPC ($P > 0.5$). Samples at 48 h had the highest TPC levels. The strong time effect observed here agrees with the findings of Ramos-Pacheco et al. (2025), who reported that germination increased phenolic compounds in Andean quinoa varieties (including "Amarilla Marangani") and boosted antioxidant capacity. Similar trends were observed in Ramos-Pacheco et al. (2024), where phenolics and flavonoids rose sharply after germination, attributed to activation of biosynthetic pathways. These findings support the time-driven TPC increase observed in this study.

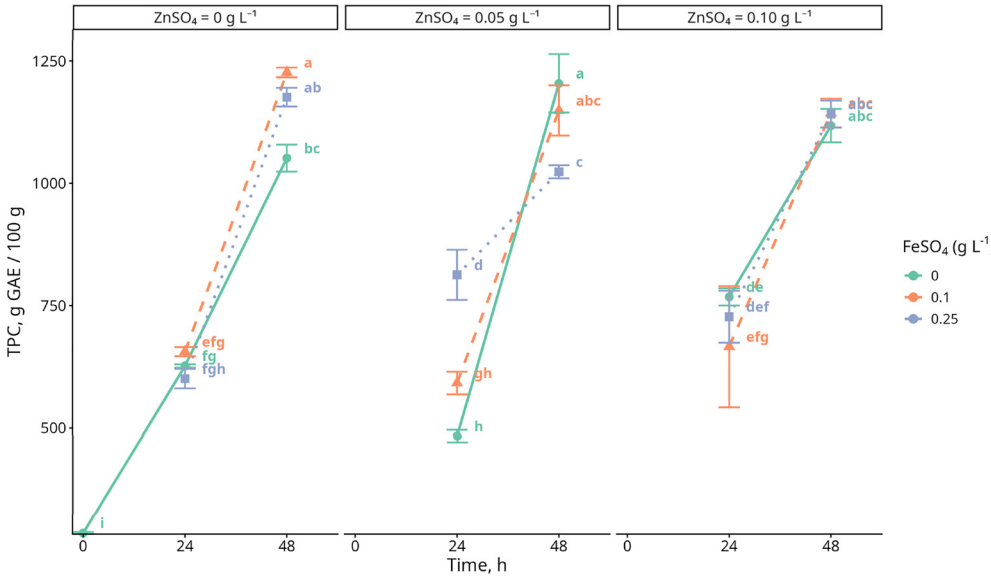

Fig. 2. Total phenolic content (TPC; g gallic acid equivalents (GAE)/100 g) of quinoa shoots ($n = 3$) obtained from seeds germinated for different times in solutions containing different concentrations of $FeSO_4$ and $ZnSO_4$.
Different letters indicate significant differences (Tukey's HSD)

Within 24–48 h at 25 °C, germination time (not mineral dosing) governs TPC, allowing Fe/Zn enrichment to be implemented without a phenolic trade-off.

3.3. Lipid profile

Initial fatty acid concentrations in quinoa seeds were: palmitic 10.29 ± 0.11%, palmitoleic 0.12 ± 0.00%, stearic 0.65 ± 0.01%, oleic 18.35 ± 0.08%, linoleic 51.86 ± 0.10%, α-linolenic 10.02 ± 0.05%, eicosanoic 0.10 ± 0.01%, eicosenoic 1.24 ± 0.03%, and erucic 1.30 ± 0.02%. These values were similar to those reported previously for the same cultivar (Pachari Vera et al., 2019).

Fatty acid profiles across treatments are presented in Table 2. Whereas Pachari Vera et al. (2019) noted slight increases in palmitic, linoleic, and linolenic acids over 24–48 h (at 25 °C) with modest declines in oleic, eicosenoic (20:1), and erucic (22:1) acids, our data showed a small decrease in palmitic acid: unchanged at 24 h, but significantly lower under the highest $ZnSO_4$ + $FeSO_4$ treatment at 48 h. Mixed-effects modelling identified time as the only significant predictor for palmitic acid ($P < 0.001$), with palmitoleic and stearic acids remaining stable ($P > 0.05$).

Oleic acid peaked in low-Zn treatments at 24 and 48 h. Three-way interactions for oleic and stearic acids were not significant ($P > 0.05$); additive models indicated $ZnSO_4$ effects on both ($P < 0.05$) and a negative time effect for oleic acid ($P < 0.01$), while $FeSO_4$ had no impact. Linoleic acid contents rose in all treatments by 48 h, driven by time ($P < 0.001$) and enhanced by a $ZnSO_4$ × time interaction ($P < 0.0415$), with no main effects of $ZnSO_4$ or $FeSO_4$. α-Linolenic

Table 2. Lipid profile (fatty acid composition, % of total fatty acids) of oils extracted from dried quinoa shoots ($n = 2$) obtained from seeds germinated for different times in solutions containing different concentrations of $FeSO_4$ and $ZnSO_4$

Fatty acid	Time (h)	$FeSO_4$ = 0.00 mM			$FeSO_4$ = 0.10 mM			$FeSO_4$ = 0.25 mM		
		$ZnSO_4$ = 0.00	$ZnSO_4$ = 0.05	$ZnSO_4$ = 0.10	$ZnSO_4$ = 0.00	$ZnSO_4$ = 0.05	$ZnSO_4$ = 0.10	$ZnSO_4$ = 0.00	$ZnSO_4$ = 0.05	$ZnSO_4$ = 0.10
Palmitic	24	11.05 ± 0.20a	11.01 ± 0.14a	10.71 ± 0.20a	12.08 ± 1.11a	10.82 ± 0.22a	10.92 ± 0.12a	11.17 ± 0.69a	10.87 ± 0.03a	10.81 ± 0.16a
	48	9.89 ± 0.23a	9.67 ± 0.01ab	9.70 ± 0.09ab	9.89 ± 0.16a	9.47 ± 0.23ab	9.48 ± 0.02ab	9.90 ± 0.17a	9.52 ± 0.01ab	9.32 ± 0.00b
Palmitoleic	24	0.11 ± 0.00a	0.09 ± 0.01a	0.11 ± 0.00a	0.11 ± 0.00a	0.09 ± 0.02a	0.10 ± 0.00a	0.10 ± 0.00a	0.10 ± 0.00a	0.10 ± 0.00a
	48	0.12 ± 0.01ab	0.09 ± 0.01a	0.09 ± 0.01ab	0.10 ± 0.02ab	0.11 ± 0.01ab	0.10 ± 0.00ab	0.10 ± 0.00ab	0.13 ± 0.01b	0.10 ± 0.00ab
Stearic	24	0.66 ± 0.01a	0.66 ± 0.00a	0.64 ± 0.02a	0.67 ± 0.01a	0.67 ± 0.00a	0.65 ± 0.00a	0.66 ± 0.00a	0.66 ± 0.00a	0.45 ± 0.29a
	48	0.69 ± 0.01a	0.67 ± 0.01a	0.67 ± 0.01a	0.68 ± 0.02a	0.68 ± 0.00a	0.66 ± 0.01a	0.68 ± 0.00a	0.67 ± 0.01a	0.66 ± 0.00a
Oleic	24	17.84 ± 0.05bcd	18.09 ± 0.01abc	17.62 ± 0.29d	18.47 ± 0.07a	18.09 ± 0.08abc	17.71 ± 0.09bd	18.22 ± 0.10ac	18.03 ± 0.01abcd	17.92 ± 0.04bcd
	48	18.06 ± 0.03bc	17.60 ± 0.07abc	17.74 ± 0.06abc	17.60 ± 0.11abc	17.27 ± 0.24ab	17.24 ± 0.09a	18.40 ± 0.54c	17.21 ± 0.05a	17.29 ± 0.00ab
Linoleic	24	51.59 ± 0.32a	52.09 ± 0.02a	51.36 ± 0.87a	52.09 ± 0.10a	51.77 ± 0.33a	51.86 ± 0.18a	52.10 ± 0.06a	51.92 ± 0.04a	51.92 ± 0.12a
	48	52.71 ± 0.05e	53.31 ± 0.05abc	53.13 ± 0.01a	53.49 ± 0.01abcd	53.66 ± 0.14bd	53.54 ± 0.20bcd	53.26 ± 0.13ac	53.81 ± 0.07d	53.49 ± 0.00abcd
α-linoenic	24	9.75 ± 0.16a	9.88 ± 0.03a	9.75 ± 0.22a	9.65 ± 0.02a	9.76 ± 0.06a	9.86 ± 0.03a	9.61 ± 0.02a	9.84 ± 0.01a	9.95 ± 0.02a
	48	10.48 ± 0.01b	10.77 ± 0.04a	10.56 ± 0.02b	10.72 ± 0.02a	11.05 ± 0.03c	10.88 ± 0.03d	10.54 ± 0.02b	11.07 ± 0.05c	10.96 ± 0.00cd
Eicosenoic	24	0.34 ± 0.03a	0.32 ± 0.01a	0.31 ± 0.01a	0.30 ± 0.05a	0.33 ± 0.02a	0.32 ± 0.00a	0.32 ± 0.04a	0.33 ± 0.00a	0.33 ± 0.00a
	48	0.33 ± 0.02a	0.32 ± 0.01a	0.31 ± 0.01a	0.32 ± 0.00a	0.32 ± 0.01a	0.33 ± 0.00a	0.32 ± 0.01a	0.32 ± 0.01a	0.32 ± 0.00a
Gondoic	24	1.22 ± 0.06a	1.18 ± 0.01a	1.18 ± 0.03a	1.07 ± 0.14a	1.23 ± 0.06a	1.20 ± 0.00a	1.16 ± 0.08a	1.21 ± 0.00a	1.23 ± 0.01a
	48	1.19 ± 0.02a	1.18 ± 0.03a	1.17 ± 0.02a	1.15 ± 0.00a	1.18 ± 0.02a	1.22 ± 0.01a	1.15 ± 0.05a	1.17 ± 0.04a	1.23 ± 0.00a
Erucic (22:1 n-9)	24	1.26 ± 0.12a	1.15 ± 0.00a	1.18 ± 0.04a	0.97 ± 0.22a	1.24 ± 0.15a	1.29 ± 0.00a	1.11 ± 0.11a	1.20 ± 0.01a	1.25 ± 0.02a
	48	1.16 ± 0.01a	1.14 ± 0.03a	1.14 ± 0.04a	1.13 ± 0.01a	1.13 ± 0.01a	1.21 ± 0.09a	1.06 ± 0.08a	1.09 ± 0.01a	1.21 ± 0.00a

Different letters in the row indicate significant differences (Tukey's HSD).

acid also increased solely with time ($P < 0.001$); the time × $FeSO_4$ term was borderline ($P = 0.059$). Longer-chain acids (20:0, 20:1, 22:1) showed no clear main or interaction effects ($P > 0.08$).

These findings are in line with the general rise in polyunsaturates during cereal germination (Al-Taher and Nemzer, 2023) and with the time-linked increases in linoleic and α-linolenic acids in quinoa sprouts (Guardianelli et al., 2022). Overall, germination time is the principal determinant of fatty acid shifts, with $ZnSO_4$ providing only minor tuning; reported quinoa studies likewise describe reserve mobilisation during sprouting (Ramos-Pacheco et al., 2024, 2025) and cultivar-dependent behaviour in Andean materials (Manjarres-Hernández et al., 2024).

Because PUFA enrichment was time-linked, and mineral priming did not significantly perturb lipid quality over this window; time should be the primary process lever for lipid targets.

3.4. Tocopherols

Tocopherol concentrations (Fig. 3) increased only in the control (no $FeSO_4$ or $ZnSO_4$). Of the tocopherols, only α-tocopherol rose significantly with germination time ($P = 0.002$), consistent with increases in red and black quinoa cultivars (Pachari Vera et al., 2019) and in the "Real" variety up to 72 h (Carciochi et al., 2016). Levels of β+γ- and δ-tocopherol were unaffected by $FeSO_4$, $ZnSO_4$, or their interaction (all $P > 0.08$), similar to the stable γ/δ-tocopherol profiles reported by Pachari Vera et al. (2019). Carciochi et al. (2016) reported that α-tocopherol increased during quinoa germination, and baseline tocopherol levels differ among Peruvian cultivars, including "Amarilla Marangani" (Pachari Vera et al., 2019). Our 24–48 h increase in α-tocopherol and the limited effects of $FeSO_4$/$ZnSO_4$ are therefore consistent with time-driven changes under these conditions.

Because α-tocopherol was time-responsive and Fe/Zn had no detectable effect in this range; optimisation should prioritise germination time rather than salt dose.

3.5. Elemental content

Figure 4 presents elemental contents (Ca, Fe, Mg, P, Zn). Control Ca exceeded the range reported (69–118 mg/100 g) by Diaz-Valencia et al. (2018); Fe, Mg, and Zn were within their ranges, and P was lower. P exhibited a $ZnSO_4$ × $FeSO_4$ × time interaction ($P = 0.018$) and a $ZnSO_4$ main effect ($P = 0.004$), indicating that the impact of $ZnSO_4$ on P varies with the concentration of $FeSO_4$ and time. Mg varied only *via* the three-way interaction ($P = 0.028$). Ca was unaffected by treatments or time (all $P > 0.1$), though the full-interaction model fit better than the additive model (LRT $P = 0.003$). Fe rose with $FeSO_4$ ($P < 0.001$); neither $ZnSO_4$ nor time had a significant effect. Zn increased with $ZnSO_4$ ($P < 0.001$) and marginally declined over time ($P = 0.053$). In contrast, Maldonado-Alvarado et al. (2023) observed time-driven Fe and Zn increases in quinoa sprouts at lower temperature (20 °C) over 4–7 days. Micronutrient uptake, distribution, and storage in plants are tightly regulated to maintain metal homeostasis (Afzal et al., 2020). The observed increases in Fe and Zn with supplementation, along with relatively small short-term changes in other minerals, are consistent with regulated uptake during early germination. In this study, Fe and Zn in sprouts increased with their solution concentrations over 24–48 h, indicating that short germination can achieve mineral enrichment.

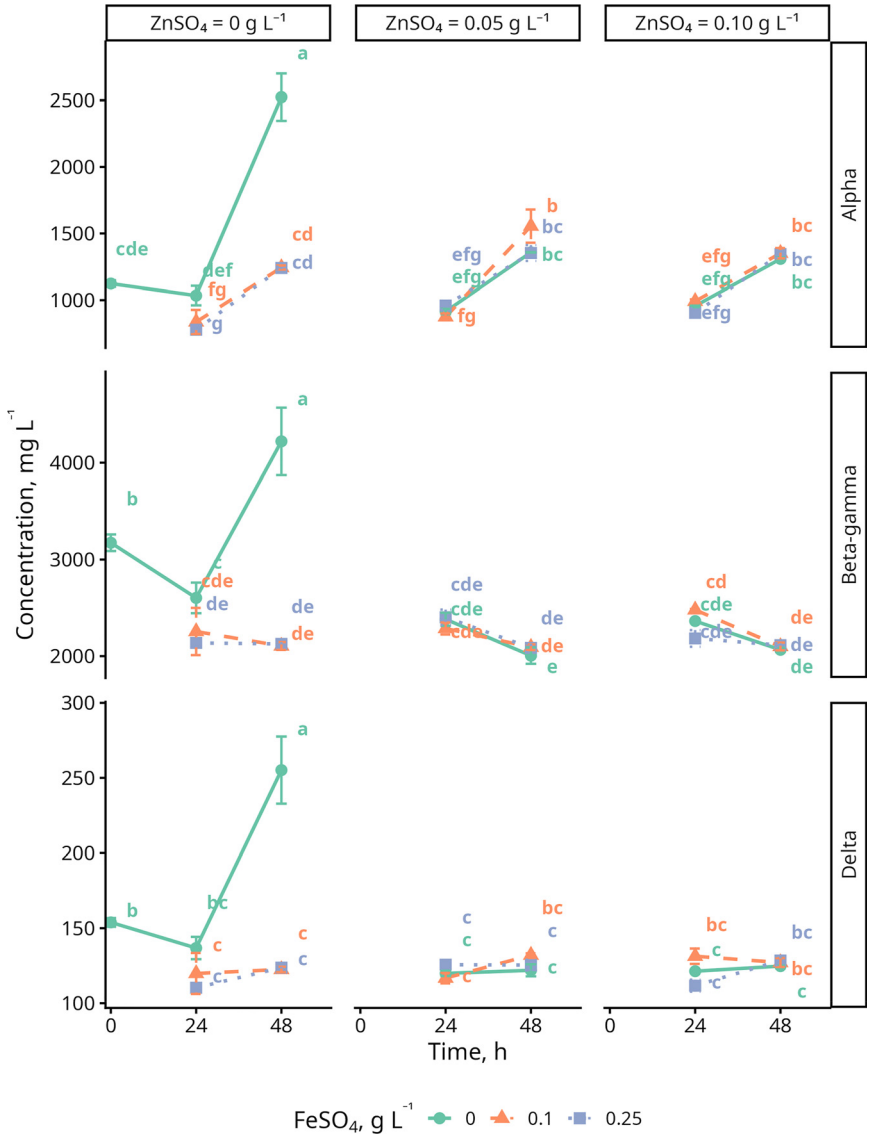

Fig. 3. Tocopherol concentration (mg L^{-1}) in quinoa shoots (n = 2) obtained from seeds germinated for different times in solutions containing different concentrations of $FeSO_4$ and $ZnSO_4$. Different letters indicate significant differences (Tukey's HSD)

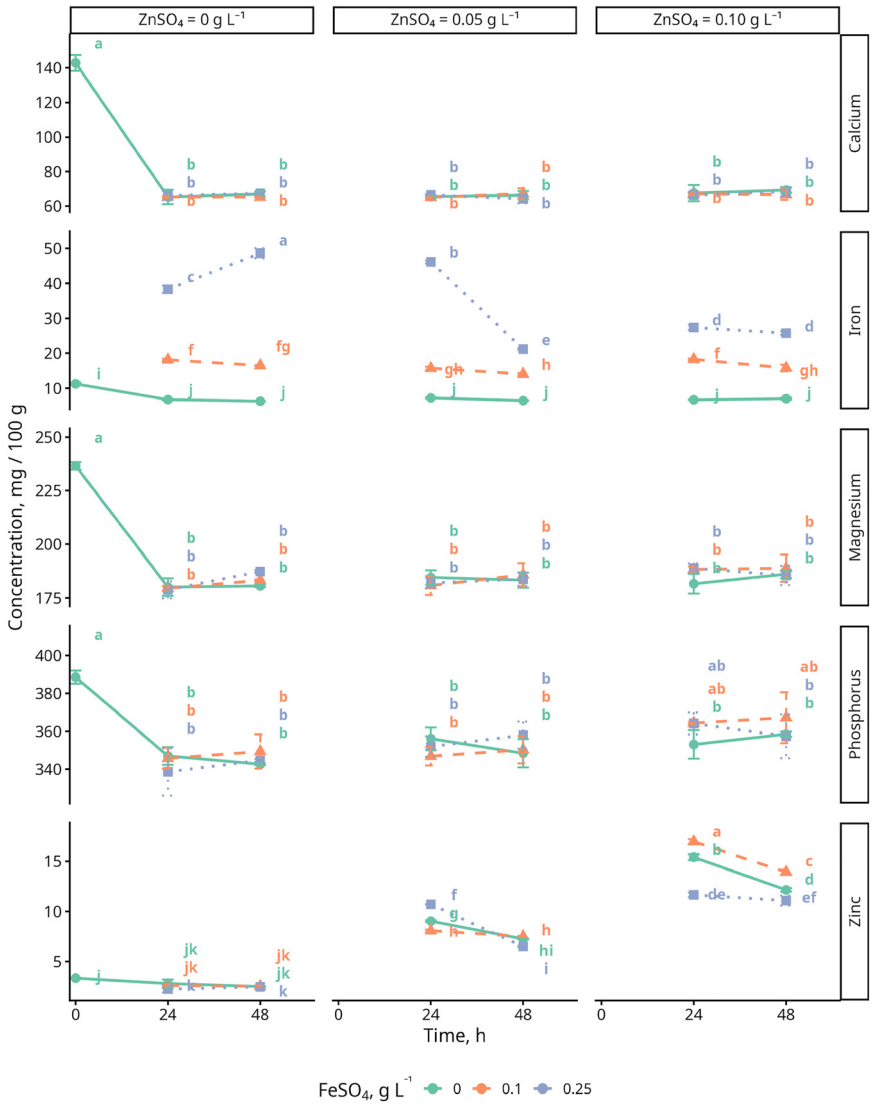

Fig. 4. Elemental content (mg/100 g) of quinoa shoots ($n = 2$) obtained from seeds germinated for different times in solutions containing different concentrations of $FeSO_4$ and $ZnSO_4$. Different letters indicate significant differences (Tukey's HSD)

4. CONCLUSIONS

Germination of "Amarilla Maranganí" quinoa seeds at 25 °C maintained >90% viability, with only a modest reduction in radicle length at the highest $FeSO_4$ level. Across 24–48 h, time (not mineral dose) primarily increased total phenolics and α-tocopherol and shifted lipids toward

higher 18:2 and 18:3, while $ZnSO_4$ produced only minor adjustments and $FeSO_4$ showed no consistent effects on the fatty-acid profile. These outcomes indicate that germination time can be used to optimise antioxidant and PUFA metrics, whereas Fe/Zn solutions enable rapid mineral enrichment of sprouts or sprouted flours without compromising biochemical quality. Because the models detected significant $ZnSO_4 \times FeSO_4 \times$ time terms for P and for Mg, macro-minerals should be verified when specific claims are intended. Future work should examine oxidative stability, sensory attributes, and Fe/Zn bioaccessibility in finished products.

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