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Productivity and environmental performance influenced by ion interactions and site-specific responses to nutrient imbalances in decoupled aquaponics

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Decoupled aquaponics (DAPS) enables independent management of aquaculture and hydroponic subsystems and is increasingly considered a resource-efficient alternative to conventional hydroponics (HP). However, nutrient balancing under fixed electrical conductivity (EC) can be constrained by the ionic composition of recirculating aquaculture system (RAS) water, particularly when elevated Ca^{2+} and Na^{+} concentrations limit adjustment of essential macronutrients such as phosphorus (P) and potassium (K). This research investigated how controlled macronutrient-imbalances affect crop productivity and environmental performance in DAPS compared to hydroponics and single-loop coupled aquaponics (AP). Across three experiments with four lettuce cultivars, nutrient composition was strategically modified while maintaining constant EC (1.8–2.2 mS cm^{-1}), thereby separating osmotic effects from nutrient-specific responses. The effects on environmental performance following life cycle assessment was investigated based on the experimental results that allowed evaluation of how nutrient balancing, cultivar-specific productivity and regional production conditions in DAPS compared to AP and HP. For the experimental base, treatments included (i) a benchmark scenario with aligned nutrient profiles in HP and DAPS as well as regular AP, (ii) reduced P, and K supply in DAPS ($DAPS_L$), and (iii) induced P-limitation in hydroponics (HP_L). Under HP-aligned nutrient supply in the DAPS benchmark scenarios with full nutrient-profile in the nutrient solution, a biomass production level comparable to HP was achieved. On the the contrary, with the deficient nutrient regime in AP, a reduced growth was observed for all cultivars. Under nutrient constraint, ion interactions and EC limitations in $DAPS_L$ led to reduced macronutrient availability across all cultivars, while regular DAPS maintained higher biomass production and greater P accumulation compared to the P-limited benchmark HP_L, indicating system-level resilience beyond nominal nutrient concentration matching. A consecutive life cycle assessment (LCA) linked the experimentally determined yields and applied consumables (e.g., fertilizer, water, energy) directly to environmental performance per functional unit of 1 kg fresh lettuce. Environmental advantages of DAPS were conditional upon maintaining biomass under nutrient constraint, showing especially advantages in the impact categories fossil resource scarcity (FRS), mineral resource scarcity (MRS), fresh-water eutrophication (FEP), water consumption (WCO), and land use (ALU). Regional scenario analysis for controlled environment agriculture (CEA), temperate Central Europe (TCE) and Mediterranean Southern Europe (MSE) demonstrated that environmental performance is site- and location-specific, as variations in absolute energy and water demand substantially altered impact magnitudes despite constant crop productivity. These findings show that DAPS should not be regarded solely as hydroponics supplemented with fish water, but as a complex hybrid nutrient regime governed by ion interactions, system dynamics and cultivar-specific physiology. Environmental benefits depend on mechanistically informed nutrient management and regional production context. Future optimization requires integration of site-specific climate-scenario within a model-based digital twin frameworks to enable optimized site-specific production-system planning.

KEYWORDS

environmental footprints, hydroponics, LCA, lettuce, regional assessment

1 Introduction

Aquaponics is defined as an integrated multi-trophic, aquatic food production approach comprising at least a recirculating aquaculture system (RAS) and a connected hydroponic (HP) unit, whereby the water for culture is shared in some configuration between the 2 units (König et al., 2018). Advantages are synergetic effects with decrease in resource use per unit produce (Körner et al., 2017; Goddek and Vermeulen, 2018; Monsees et al., 2019; Tůmová et al., 2025). As the most simple coupled single loop aquaponic systems often fail in providing the necessary nutrients in amount and composition to the HP system (Goddek et al., 2019), significant amounts of crop produce in these systems are often of lower quality or a decreased yield. Whereas plants and fish are recirculated in one quasi-closed loop in conventional coupled aquaponics systems, decoupled multi-loop aquaponic systems (DAPS) comprise separate circuits, whose environmental parameters can be controlled independently (Kloas et al., 2015; Monsees et al., 2019). Compared to coupled aquaponic systems where the relative nutrient-poor water of the RAS water is directly used to irrigate the crop, within an additional water-loop in DAPS, the RAS-water is treated before entering the crop compartment: RAS-water is lifted to the desired nutrient composition of specific crops, usually to mimic known HP recipes. In the last years, DAPS systems were developed with great advantages (Goddek, 2017), such that in DAPS a high quality crop production comparable or superseding HP could be achieved (Goddek and Keesman, 2018). As such, while some scholars have reported an up to 35% yield increase in lettuce with DAPS (Delaide et al., 2016; Goddek and Keesman, 2018), others have solely observed a similar yield of DAPS and HP (Monsees et al., 2019).

In addition to ionic constraints, aquaponic nutrient solutions represent biologically active matrices in which transformation processes may influence nutrient speciation and temporal availability (Schmautz et al., 2017). Consequently, the critical challenge is not merely whether DAPS differs from conventional hydroponics or coupled aquaponics, but how ion composition, EC-related constraints and system dynamics interact to determine effective nutrient availability and crop productivity (Goddek et al., 2019; Yep and Zheng, 2019). Particularly under fixed electrical conductivity, elevated Ca^{2+} and Na^{+} concentrations originating from RAS-derived water may restrict the adjustment of essential macronutrients such as phosphorus (P) and potassium (K) (Monsees et al., 2019; Tellbüscher et al., 2025). Such structural ion constraints can result in nutrient imbalances that are not immediately apparent from total EC values, but may directly affect plant growth (Yang et al., 2024). However, the specific contribution of these macronutrient imbalances to yield formation in DAPS has rarely been experimentally investigated under controlled conditions. Beyond productivity, nevertheless, potential differences in nutrient dynamics expect to influence environmental performance of DAPS (Groenveld et al., 2019; Ghamkhar et al., 2022), that can investigated with life cycle assessment (LCA). Within LCA, environmental impact is related to a pre-defined target as certain amount of a product, changes in biomass formation directly modify impact intensities per unit of that product. LCA is increasingly applied to evaluate the environmental performance of controlled environment agriculture (CEA), including hydroponic- and aquaponic systems (Forchino et al., 2017; Graamans et al., 2018; Baganz et al., 2021; Ghamkhar et al., 2022).

Previous studies have highlighted the importance of energy demand, nutrient management, and system configuration as key drivers of environmental impacts (Torrellas et al., 2012; Graamans et al., 2018; Mousavi et al., 2023). In aquaponic systems, particular attention has been given to the potential for nutrient recycling and reduced fertilizer demand, although results remain highly dependent on system design and operational conditions (Körner et al., 2021). More recent work emphasizes the need for system-level comparisons under varying environmental and management scenarios, including the integration of dynamic modeling approaches (Körner et al., 2025). Moreover, together with nutrient management, also environmental impacts are governed by site- and location-specific production conditions, including regional energy structures and climate-dependent resource demand (Körner et al., 2021). It therefore remains unclear to what extent nutrient-driven yield responses in DAPS translate into environmental footprints across different climatic contexts and production environments.

To address these questions, we experimentally imposed controlled imbalances of P and K under constant EC conditions across three cultivation scenarios and four lettuce cultivars. Following LCA based on the experimental results allowed evaluation of how nutrient balancing, cultivar-specific productivity and regional production conditions jointly determine environmental performance in DAPS. The study therefore aims to disentangle whether reduced mineral fertilizer input in biologically active DAPS solutions can maintain hydroponic-level crop productivity while lowering environmental impacts across contrasting climatic production contexts. In this context, the present study contributes by combining experimental data with a comparative LCA framework to assess nutrient management strategies across hydroponic, aquaponic, and decoupled aquaponic systems across climatic regions.

2 Materials and methods

The overall study design combines multiple experiments with a subsequent life cycle assessment (LCA) to enable a consistent comparison of production systems under nutrient limitation. A schematic overview of the experimental setup and its integration into the LCA framework is provided in Figure 1. Three experiments under greenhouse and controlled environment conditions were performed to quantify system- and cultivar-specific productivity responses. These responses were used to derive relative scaling factors, which form the basis for the calculation of resource use per functional unit (1 kg fresh weight) in the LCA. The experimental components are described in detail below.

2.1 Experimental set-up

The three experiments were conducted at the Leibniz-Institute of Vegetable and Ornamental Crops (Grossbeeren, Germany; LAT 52.35, LON 13.31). In all three experiments (Table 1), the same four lettuce cultivars were cultivated in three nutrient solutions used as treatments with standard hydroponics solution (HP), regular coupled one-loop aquaponics solution (AP), and decoupled aquaponics solution (DAPS). Exp. 1 was conducted as baseline comparison between HP,

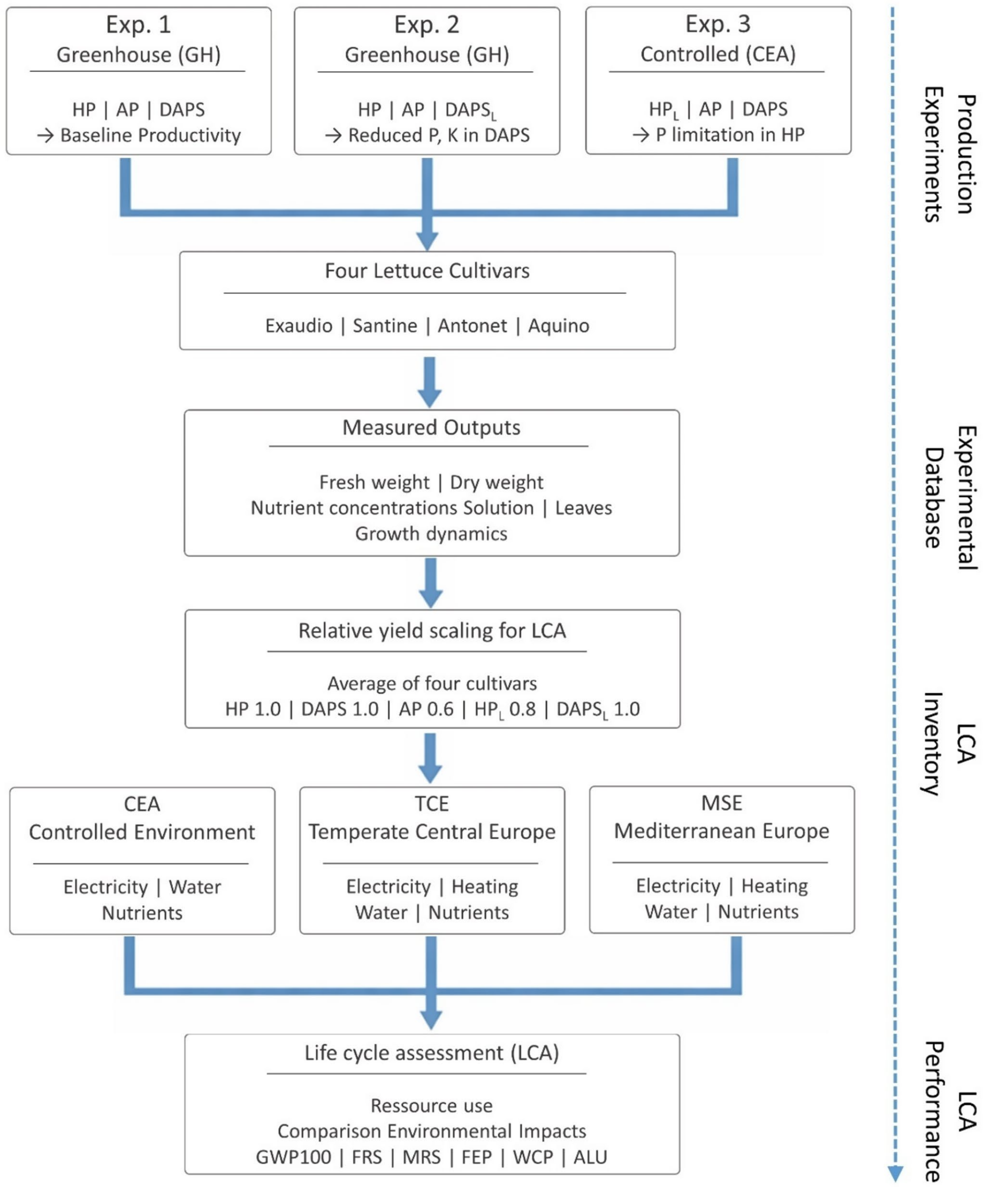

FIGURE 1
Schematic overview of the experimental design and its integration into the site-specific life cycle assessment (LCA). Three experiments were conducted in greenhouse and controlled-environment systems using four lettuce cultivars ('Exaudio', 'Santine', 'Antonet', 'Aquino'). Experimentally observed productivity responses were used for relative scaling of resource use per functional unit (1 kg fresh weight), which was then evaluated in three site-specific LCA scenarios: controlled environment agriculture (CEA), temperate Central Europe (TCE), and Mediterranean Southern Europe (MSE).

TABLE 1 Overview of the three experiments, Exp. 1, Exp. 2, Exp. 3.

Experiment	Exp. 1	Exp. 2	Exp. 3
Facility	Greenhouse	Greenhouse	Climate Chamber
Length cultivation, days	21	28	28
Cultivation Period, DoY	43–64	227–254	9–27
Weight Measurements, DaT	0, 8, 15, 21	0, 3, 7, 10, 14, 17, 21, 24, 28	0, 7, 14, 21, 28
Statistical Replications, n	4	4	3
Nutrient Treatment	Regular level, benchmark (HP, AP, DAPS)	P, K -deficiency in DAPS ($DAPS_L$)	P deficiency in hydroponics (HP_L)

AP; and DAPS, while in Exp. 2 and Exp. 3 nutrient deficient regimes of DAPS ($DAPS_L$) or HP (HP_L) were conducted (Table 1).

Thus, the study consisted of three separate experiments with different treatment combinations (cf. Figure 1): Exp. 1 (greenhouse) with HP, AP and DAPS; Exp. 2 (greenhouse) with HP, AP and $DAPS_L$; Exp. 3 (controlled environment) with HP_L, AP and DAPS. A nutrient film technique (NFT) system was used in all experiments.

In each of the three experiments seed of four different leafy lettuce cultivars (*Lactuca sativa*) ('Satine', 'Exaudio', 'Antonet' and 'Aquino'; all Rijk Zwaan, De Lier, Netherlands) were sown in rockwool cubes (Grodan, The Netherlands) of 5 cm^3 and germinated on trays in sand for 21 days in a climate-controlled greenhouse at 20 °C and at 90% relative humidity. After germination, the plants were kept in the same greenhouse for 12 days and watered with a standard hydroponic nutrient solution for lettuce at EC 1.8 ms m^{-1} (Sonneveld and Straver, 1994). After this period, the plants were placed in hydroponic gutters in a greenhouse compartment (Exp. 1, Exp. 2) or in climate-controlled chambers (Exp. 3). Because not all treatments were tested in all facilities, productivity differences were incorporated in the environmental assessment via relative normalization rather than direct cross-experimental comparison.

2.1.1 Experiment 1 and 2

Experiments 1 and 2 were conducted in a climate-controlled greenhouse compartment (controlled by RAM, Herrsching, Germany) equipped with pipe heating, passive roof ventilation, and energy-saving thermal screens deployed during night-time when required.

Within the compartment, 12 hydroponic gutters (4 m length each) were installed and arranged in four spatial blocks. Each block consisted of three adjacent gutters positioned 30 cm apart, with 90 cm spacing between blocks. The experimental design followed a randomized complete block design with four blocks. Within each block, the three basic treatments (HP and AP in both; and DAPS in Exp. 1) or the nutrient deficient treatment in Exp. 2 ($DAPS_L$) were randomly assigned to one of the three gutters. Each experiment had exactly three treatments. Each gutter was hydraulically independent and equipped with its own recirculation system, thereby representing one experimental unit. Consequently, each treatment was replicated four times ($n = 4$).

At 33 days after sowing (see Table 1), 48 uniform seedlings per cultivar were selected and transferred to the gutters. Within each gutter, four cultivars were grown simultaneously, with four plants per cultivar positioned at 22 cm spacing, including two border plants resulting in 18 plants per gutter. Individual plants were considered observational units, whereas the independent recirculating gutter represented the statistical replicate. Plants were cultivated for 21 days (Exp. 1) or 28 days (Exp. 2). The greenhouse climate was maintained at 18/20 °C (day/night) and 85% relative humidity. Photoperiod was set to 16 h (06:00–22:00). Nutrient solutions were supplied at 30-min intervals for 10 min using independent pump systems (Gardena, Germany) for each gutter. For growth curve analysis, two plants per gutter were repeatedly measured non-destructively throughout the cultivation period. Destructive measurements were conducted at the end of the experiment.

2.1.2 Experiment 3

Experiment 3 was conducted in three walk-in climate chambers (York, 2013; 240 × 385 cm, 220 cm height) equipped with metal halide lamps (MT400/DL/BUD; maximum 650 µmol m^{-2} s^{-1} PPFD). One third of the lamps were switched off, resulting in mean light intensities of 411, 433 and 398 µmol m^{-2} s^{-1} at canopy level in the three chambers, respectively, corresponding to an inter-chamber variation of less than 5%. All chambers were equipped with automated control of temperature and relative humidity.

The experiment followed a randomized complete block design with climate chamber as block factor. Each chamber contained three hydroponic gutters (4 m length), and each gutter represented one independent recirculating unit assigned to one of the three treatments: hydroponics (HP), aquaponics (AP), or decoupled aquaponics (DAPS). Thus, each treatment was replicated once per chamber, resulting in $n = 3$ independent experimental units per treatment. Within each gutter, four lettuce cultivars were grown simultaneously. For each cultivar, four plants were positioned at 22 cm spacing, including two border plants resulting in 18 plants per gutter. Individual plants were considered observational units, while the recirculating gutter system represented the statistical replicate.

At January 9th, 36 uniform seedlings per cultivar were selected and transferred to the gutters. Plants were cultivated for 28 days. Climate conditions were maintained at 18/20 °C (day/night) and 85% relative humidity. Photoperiod was set to 18 h (04:00–22:00). Nutrient solutions were supplied at 30-min intervals for 10 min using independent pump systems (Gardena, Germany) for each gutter. Water demand was predefined by simulation using a aquaponics system model (Goddek and Körner, 2019), resulting in a maximum water consumption of approximately 4 L m^{-2} day^{-1}.

2.2 Nutrient solution

The aquaculture-derived water used for the aquaponics treatment (AP) and as the basis for decoupled aquaponics (DAPS) originated from a recirculating aquaculture system (RAS) stocked with Nile tilapia (mean stocking density 67 kg m^{-3}) at the Leibniz-Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany. Fish husbandry complied with German animal welfare legislation (permit ZH 114). RAS water was collected weekly (1.0 m^3), transported 37 km to the plant production site at IGZ, and stored prior to use. Residual water from the previous week was discarded to avoid uncontrolled nutrient carryover.

In each experiment, three independent nutrient reservoirs were maintained corresponding to hydroponics (HP), aquaponics (AP), and decoupled aquaponics (DAPS). Tap water from the public supply served as the source for HP, whereas RAS water was used directly for AP and as the base solution for DAPS. HP and DAPS nutrient solutions were prepared weekly in 250 L mixing tanks following the standard lettuce recipe of Sonneveld and Straver (1994). Nutrient solutions were prepared initially to concentrated A and B solutions as done in practice using standard commercially available mineral fertilizers (i.e., from Yara Terra, Haifa, Van Iperen, Merck, EpsoTop, Roth) for the macronutriets N, P, K, Ca, Mg, S with a mix of $Ca(NO_3)_2$, KNO_3, NH_4NO_3, KH_2PO_4, $Mg(NO_3)_2$, K_2SO_4, $MgSO_4$, $Ca(SO_4)_2$ and the required micronutrients Fe, Mn, Zn, B, Cu, Mo. To achieve the target ion concentrations (listed in Table 2) compositions were calculated based on the target ion concentrations supported by in-house calculation routines. No dedicated fertigation software was used. However, due to the use of standard fertilizer salts, individual ion adjustments were not fully independent. Overall solution stability was tried to take care for by selecting suitable mixes of the above listed chemical compositions.

In AP, RAS water was applied without nutrient supplementation. DAPS nutrient composition was adjusted depending on the experimental objective: (i) alignment with the standard hydroponic recipe (benchmark), (ii) controlled reduction of selected macronutrients (P, K), or (iii) restoration of full hydroponic nutrient levels under conditions of induced phosphorus limitation in HP (i.e., HPL). The existing solution was regularly replenished (topped up) to compensate for plant uptake and water losses. Electrical conductivity (EC) and pH were monitored daily (calibrated multimeter, HQ40d, Hach Lange GmbH, Germany) and pH was adjusted as required to maintain target conditions at EC 1.8 – 2.2 dS m^{-1} and pH 5.5–6.5 by manual adjustment with nitric acid (HNO_3) or potassium hydroxide (KOH). All source waters and prepared nutrient solutions were analysed weekly for complete macro- and micronutrient composition at the IGB laboratory. Nutrient solutions were maintained at ambient greenhouse temperature and continuously aerated.

2.3 Non-destructive growth monitoring

For non-destructive monitoring of chlorophyll content a portable, hand-held spectrophotometer device (Pigment Analyzer PA-1101, CP, Falkensee, Germany) equipped with photodiode arrays was applied to record the leaf spectra in the UV and visible wavelength range from 190 to 720 nm (MMS1 UV/ VIS, Carl Zeiss, Jena, Germany) or in the visible and near infrared range from 320 to 1,120 nm (MMS1 NIR enh., Carl Zeiss, Germany), providing a spectral resolution of 2.2 nm. An integrated light cup equipped with light-emitting diodes, capturing the entire wavelength range recorded, served as the light source. Spectralon (20% certified, Labsphere Ltd., North Sutton, United States) was used as the white reference for the calibration. The leaf raw spectra were used to calculate the indices (Kläring and Zude, 2009).

2.4 Plant nutrient and chlorophyll analysis

Destructive measurements were done where 4 individual plants in each repetition were destructively measured. Fresh weight of both roots and shoot, and leaf area (LI-COR 3100, LI-COR Bioscience) was measured for all plants. The fresh shoot material of the four plants of each repetition was used differently: One plant (plant 1) was used for dry weight estimations (oven for 24 h at 103 °C); from one plant (plant 2) three 2^{nd} range leaves were removed and used for measurement of chlorophyll a, b content, and total carotinoid levels (UV–VIS Spectroscopy) as used (Cammarisano and Körner, 2022), and from two plants (plants 3 and 4) three 2^{nd} range leaves were used to analyze P, K, Ca, S content (Inductively Coupled Plasma, ICP-OES) and total N, C and their ratio (Element Analysis).

2.5 Statistical analysis

For all data and statistical analysis the mathematical software package Matlab (Mathworks, Nattick, USA) was used. Significance on experimental data differences was statistical analysed with analysis of variance (ANOVA) and the following post-hoc test applying Student' t-test, using the statistical methods 'anovan' and 'multcomp'. Statistical significance was assessed at $\alpha = 0.05$. Samples were tested on normal distribution with Kolmogorov–Smirnov; for growth data in time the 'fit' module was used with nonlinear least squares fitting on a logistic growth curve, i.e., $[y = a/(1 + \exp(-b(x-c)))]$.

TABLE 2 Nutrient-related inventory inputs (N, P, K, Mg, Ca, S, Fe) in mg L^{-1} used in the consequential LCA per functional unit of 1 kg fresh lettuce.

	Concentration (mg L^{-1})			Additional Supply (mg L^{-1})			
Nutrients	Target	RAS water	HP	AP	DAPS	$DAPS_L$	HP_L
NO_3-N	200	120	200	0	80	80	200
NO_4-N	8.0	0	8.0	0	8	8	8.0
P	30	16	30	0	14	**0**	**4**
K	330	7	330	0	223	**0**	330
Mg	18	15	18	0	3	3	18
Ca	138	125	138	0	13	13	138
S	36	65	36	0	0	0	36
Fe	2.24	0.02	2.24	0	2.22	2.22	2.24

These values represent LCA inventory assumptions. Experimental nutrient compositions are reported separately in Tables 5, 6. Values written in bold indicate the active treatment.

2.6 Environmental assessment

A consequential Life Cycle Assessment (LCA) (Ekvall and Weidema, 2004) was carried out to compare environmental impacts of the three production systems. For that, experimental data on crop yield, consumption of consumables as nutrients and water were taken from Exp. 1–3. The methodological LCA framework follows ISO 14040/44 and builds on the approach established by Körner et al. (2021), adapted for prospective system redesign and nutrient reuse scenarios. The system boundary was defined as cradle-to-gate with consequential system expansion (Lund et al., 2010) as illustrated in Figure 2, including all upstream processes related to the provision of materials (fertilizers, energy, substrates), greenhouse infrastructure and its operation (climate control, fertigation, irrigation), but excluding post-harvest handling. Background processes were modeled using the Ecoinvent database (version 3.7). The consequential modeling approach included the effect of nutrient reuse within the aquaponics systems as performed earlier (Körner et al., 2025), and system expansion was applied substituting allocation, i.e., the saved production and avoided fertilizer input was credited to the crop. As such, the consequential LCA approach was applied to all scenarios, while system expansion was used to account for substitution of mineral fertilizers in AP and DAPS, where nutrients derived from aquaculture replace external inputs. In HP, no substitution occurs, and therefore system expansion was not applied. Explicit wastewater treatment processes were not modeled; instead, system-level discharge assumptions were applied consistently across scenarios.

The LCA was designed as a comparative assessment between production systems and therefore uses a harmonized modeling approach focusing on relative differences in resource use per functional unit. To ensure comparability across experiments, a relative normalization approach was applied. Hydroponic yield from Exp. 1 served as the reference (factor = 1.0), while treatment-specific productivity deviations observed in Exp. 2 ($DAPS_L$) and Exp. 3 (HP_L) were expressed as relative factors. Specifically, relative production values of 1.0, 0.6, 1.0, 1.0 and 0.8 were used for HP, AP, DAPS, $DAPS_L$ and HP_L, respectively (cf. Table 3). These factors were used to scale resource inputs (nutrients, energy, water) to the functional unit of 1 kg fresh lettuce, ensuring that differences in productivity were consistently reflected in consumables per unit output.

Life cycle inventories were compiled using simulation outputs combined with background data from Ecoinvent (version 3.7), adjusted for regional energy mixes and fertilizer production. The foreground life cycle inventory is provided in Table 4 (energy and water inputs). All values are expressed per functional unit of 1 kg fresh lettuce after normalization based on relative yield difference. As no significant differences in biomass production between cultivars were observed (cf. Results), productivity values were averaged across cultivars for the LCA.

Emissions from fertilizer use (e.g., leaching, volatilization, N_2O) were estimated based on standard emission factors and for hydroponics as reported by Karlowsky et al. (2021). As fertilizer for HP and as supplement for DAPS (N, P, K, Mg, Ca, S, Fe) were used (for concentration see Table 2). N was modeled as global nitrogen fertilizer, P as global P_2O_5 fertilizer, K as potassium sulfate as global K_2O, all taken from the Ecoinvent database (version 3.7; cf. Supplementary Table S1). The software environment SimaPro (Craft, Release 10.2, PRé) was used for calculations. The functional unit was defined as 1 kg of marketable fresh lettuce at production site (gate). Impact assessment was conducted using the ReCiPe 2016 Midpoint (H) method (Huijbregts et al., 2017), including: Global Warming Potential for a time-frame of 100 years (GWP_{100}), fossil resource scarcity (FRS), mineral resource scarcity (MRS), fresh-water eutrophication (FEP), water consumption (WCO), and land use (ALU).

2.7 Assessment of site- and system specific production

Assessment of site- and system specific production was done for theoretical scenarios of production system - location combinations.

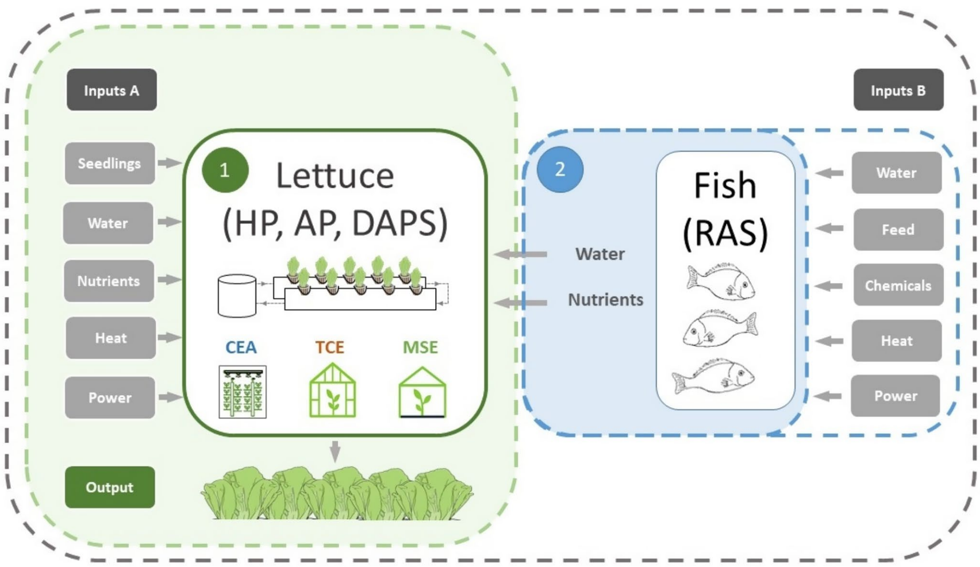

FIGURE 2
System boundary of the cradle-to-gate life cycle assessment for the combined production system with receiver-system hydroponics (HP; 1) and the system-expansion with the donor-system recirculating aquaculture system (RAS; 2) providing water and nutrients (used as avoided within system 1). The system includes resource inputs to the RAS system (A; water, fish feed, chemicals, heat, power) and to the HP system (water, heat, power, nutrients), crop production and nutrient reuse flows, with outputs expressed per functional unit of 1 kg fresh lettuce.

TABLE 3 Percentage difference of crop fresh production weight between the five production systems (HP, HP_L, DAPS, $DAPS_L$, AP) in four lettuce cultivars, between (i) decoupled aquaponics and hydroponics (DAPS/HP; Exp. 1); (ii) nutrient-limited DAPS and hydroponics ($DAPS_L$/HP; Exp. 2); (iii) P-limited hydroponics and DAPS (HP_L/DAPS; Exp. 3); and (iv) single-loop aquaponics and hydroponics (AP/HP; Exps. 1, 2); and fractions as implemented in the LCA.

Cultivar	DAPS/HP, %	$DAPS_L$/HP, %	HP_L/DAPS, %	AP/HP, %	
	Exp. 1	Exp. 2	Exp. 3	Exp. 1	Exp. 2
Exaudio	10.2	11.6	21.7	23.8	64.3
Santine	3.0	−0.1	19.6	5.5	62.9
Antonet	−13.8	4.3	15.8	19.1	55.9
Aquino	−1.5	−9.8	20.9	28.9	68.8
Mean	−0.5	1.5	19.4	19.3	63.0
Fraction	DAPS/HP: 1.00	$DAPS_L$/HP: 0.99	HP_L/HP: 0.80	AP/HP: 0.59	

As such, LCA-simulations were performed for three climatic - system contexts: (i) controlled environment indoor farming (CEA), (ii) temperate Central European greenhouse production (TCE), and (iii) Mediterranean Southern European greenhouse production (MSE) (see Table 4). For each treatment, experimentally determined yields were used as fixed input parameters across the three regional scenarios.

These regional and system specific differences were implemented by adapting both background processes (e.g., electricity mix) and absolute resource demands (e.g., heating energy and irrigation water) according to climate-specific production requirements (Table 4; Supplementary Table S1). The operational assumptions for the three scenarios (CEA, TCE, MSE) are consistent with ranges reported in previous LCA studies of lettuce production in hydroponics and aquaponics across regions and production systems (Graamans et al., 2018; Körner et al., 2021; Martin et al., 2024; Pinho et al., 2024; Körner et al., 2025). Values used in this study represent simplified but realistic scenarios and were selected to enable a consistent comparison of production systems rather than to represent a specific production site.

For each treatment, experimentally observed productivity was used as the biological reference and was kept constant across the regional LCA scenarios (CEA, TCE and MSE). In contrast, regional differences were implemented by adjusting background processes and operational resource demands, particularly electricity, heating and irrigation water use, according to the respective production environment. Thus, the regional comparison does not predict environment-specific yield, but evaluates how identical experimentally observed treatment performance translates into environmental impacts under contrasting resource-demand structures. For that, resource demand assumptions were derived from previously published system analyses or literature (Eaton et al., 2023; Graamans et al., 2018; Körner et al., 2021; Pinho et al., 2024; Körner et al., 2025), while productivity was transferred as absolute yield between environments. Instead, experimentally observed relative productivity responses were used as scaling factors to derive resource demand per functional unit. This ensures that differences in biomass production are consistently represented without assuming identical absolute yields across greenhouse and controlled environment systems. For that, absolute heating and irrigation demands were parameterised based on previously modeled site-specific production scenarios (Körner et al., 2021; Körner et al., 2025).

3 Results

3.1 Nutrient composition of irrigation solutions

The experimentally measured nutrient composition of the irrigation solutions is reported in Tables 5, 6, whereas Table 2 summarizes the simplified nutrient input data used for the LCA inventory. In the benchmark scenario with regular nutrient levels as expected for HP, AP and DAPS (Exp. 1), the nutrient composition of DAPS closely matched the target hydroponic (HP) recipe (Figure 3). Minor deviations were observed for few nutrients, whereas nitrogen concentrations (NO_3^--N, NH_4^+-N) were comparable between DAPS and HP. As expected, the AP solution showed lower overall macronutrient concentrations.

In Experiment 2 ($DAPS_L$), concentrations of K and P in DAPS were substantially reduced compared to HP (Figure 4). Elevated Ca and Na concentrations originating from the RAS water constrained adjustment of the nutrient profile under the fixed EC condition.

In Experiment 3 (HP_L), phosphorus concentration in HP decreased to approximately 25% of the standard level after 7 days of recirculation (Table 5). Continued cultivation resulted in near-complete depletion of available P in HP_L (Table 6), whereas P concentrations in DAPS decreased over time but remained above depletion levels. Despite these differences in nutrient composition, overall nutrient removal rates during cultivation were comparable among treatments. However, differences on percentage exploitation of the supplied nutrients within the three solutions differed to the expected nutrient levels (Figure 5; Table 6).

3.2 Biomass production

Under the benchmark conditions (Exp. 1), no significant differences in fresh or dry biomass were observed between DAPS and HP across all four cultivars (Figures 6a–d). In contrast, AP resulted in lower fresh weight in three of the four cultivars, with a similar trend observed for dry weight.

When K and P concentrations were reduced in DAPS ($DAPS_L$; Exp. 2), biomass production remained largely comparable to the regular DAPS treatment across all cultivars (Figures 6e–h). Although nutrient availability was reduced, no consistent decline in fresh weight relative to DAPS was observed. Minor cultivar-specific variation occurred, but these differences were not systematic, indicating that moderate macronutrient constraints in DAPS under fixed EC conditions did not necessarily translate into cultivar-specific impacts on biomass formation.

Under phosphorus-limited hydroponic conditions as investigated in Exp. 3 (HP_L), DAPS produced significantly higher biomass than HP across cultivars (Figures 7, 8). Fresh weight increased cultivar specific by 16–22% relative to HP (Table 3). It was evident that the growth difference between DAPS and HP_L accelerated with time of cultivation (Figure 8), while the four cultivars reacted similar with only minor differences in behavior. Measured weight was taken roughly every 4 days, and growth trajectories from

TABLE 4 Production systems and main variable consumables attributed to the crop-system per 1 kg lettuce as source-data within the consequential life cycle assessment at fully controlled indoor system (CEA; no heating, high electricity demand, lighting, climate control), Temperate climate zone greenhouse at 52°N (TCE; moderate heating demand, mixed energy inputs), and Mediterranean climate zone greenhouse at 38°N (MSE; low heating demand, higher irrigation requirement) with consumption of energy for heating (H), electrical energy power (P), and irrigation water (W).

	System	LAT	Direct Applied Consumables *Heating (H, MJ kg⁻¹)* *Electrical energy (P, MJ kg⁻¹)* *Water for irrigation (W, L kg⁻¹)*														
			HP			AP			DAPS			$DAPS_L$			HP_L		
			H	P	W	H	P	W	H	P	W	H	P	W	H	P	W
CEA	IF	–	0	29.0	9.6	0	49.2	0	0	29.0	0	0	29.0	0	0	36.9	9.6
TCE	GH	52°N	5.5	2.1	11.3	9.2	3.5	0	5.5	2.1	0	5.5	2.1	0	6.9	2.7	11.3
MSE	GH	38°N	1.1	0.2	29.6	1.8	0.3	0	1.1	0.2	0	1.1	0.2	0	1.4	0.2	29.6

TABLE 5 Nutrients (mg L^{-1}), pH and EC (mS cm^{-1}) at the four delivery dates indicated with date and day after transplanting (DaT) of the aquatic nutrient solutions for treatments in Exp. 3 with aquaponics solution (AP); and water samples of decoupled aquaponics solution (DAPS) and hydroponics after mixing on 23.01. in HP.

Date	AP				DAPS	HP_L
	09.01.	16.01.	23.01.	30.01.	23.01.	23.01.
DaT	0	7	14	21	14	14
Measurements						
EC (mS cm^{-1})	1.19	1.20	1.20	1.20	1.88	1.84
pH (−)	7.4	7.5	7.5	7.4	6.5	6.5
Nutrients (mg L^{-1})						
Al	0.01	0.01	0.01	0.01	0.01	0.01
B	–	–	–	–	0.08	0.06
Ca	124	139	123	138	162	195
Fe	0.01	0.02	0.02	0.01	1.79	0.61
K	22.3	22.7	16.3	27.0	168	147
Mg	17.8	17.6	15.8	20.0	19.8	16.2
Mn	0.08	0.01	0.00	0.08	0.03	0.01
Na	54	52	39	56	57	47
P	**6.0**	**4.2**	**3.1**	**4.7**	**18**	**4.2**
S	73	70	60	80	75	75
Si	7.4	7.4	7.0	7.9	8.6	7.3
Cu	–	–	–	–	0.016	0.013
Zn	–	–	–	–	0.03	0.03
NO_3-N	58	58	36	60	119	100
NO_2-N	0.01	0.01	0.05	0.02	0.007	0.005
NH_4-N	0.14	0.14	0.06	0.11	4.09	5.27
PO_4-P	5.8	5.8	5.8	4.8	19.5	11.4

Values written in bold indicate the active treatment.

transplanting to harvest followed a logistic pattern with distinct flattening after the 28-day cultivation period in HP_L and AP, while an ongoing growth could be observed in DAPS (cf. Supplementary Figure S1).

3.3 Nutrient uptake and tissue concentration

Plant nutrient composition was analysed for Experiments 2 and 3. For Exp. 1, only irrigation solution composition was determined. Nitrogen and carbon concentrations were only determined in Exp. 3 and are therefore not shown for Experiments 1 and 2.

Under benchmark conditions (Exp. 1), nutrient composition of irrigation solutions was comparable between DAPS and HP, while P and K was significant lower in $DAPS_L$ as tested in Exp. 2 (cf. Figures 3, 9). AP showed lower concentrations for selected macronutrients.

Under reduced macronutrient supply in DAPS ($DAPS_L$; Exp. 2), i.e., with reduced K and P supply in DAPS resulted in corresponding decreases in leaf tissue concentrations (Figure 9). The magnitude of reduction differed only little among cultivars.

Under phosphorus-limited hydroponic conditions (HP_L; Exp. 3), leaf P concentration in HP showed markedly lower levels than DAPS (Figure 10). As such, DAPS maintained higher P concentrations in leaf tissue, resulting in approximately 80% greater P accumulation

TABLE 6 Nutrient concentration in mg L⁻¹ after 7 days of recirculation of hydroponics (HP), aquaponics (AP), decoupled aquaponics (DAPS) at four time points indicated with date and day after transplanting (DaT) in controlled environment in HP_L (Exp. 3).

Date DaT	16.01. 7			23.01. 14			30.01. 21			06.02. 28		
	HP_L	AP	DAPS	HP_L	AP	DAPS	HP_L	AP	DAPS	HP_L	AP	DAPS
Nutrients (mg L⁻¹)												
Al	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01
B	0.08	0.11	0.10	0.06	0.08	0.09	0.05	0.07	0.07	0.04	0.06	0.07
Ca	221	137	116	200	139	185	228	135	196	242	152	240
Fe	0.50	0.01	2.39	0.62	0.02	0.70	0.76	0.02	2.12	0.78	0.02	2.03
K	135	18.1	213	141	4.29	156	84.3	0.17	94.3	93.8	0.11	30.3
Mg	17.3	17.8	14.4	18.0	18.5	21.5	19.6	18.2	23.6	20.7	19.8	33.7
Mn	0.03	0.10	0.12	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Na	43.6	67.7	38.6	56.4	63.8	65.8	63.6	60.0	77.6	65.1	52.9	83.5
P	**10.89**	**6.57**	**21.99**	**1.48**	**2.57**	**15.32**	**0.30**	**0.12**	**8.04**	**0.16**	**0.06**	**5.02**
S	75	66	42	87	77	83	99	91	99	109	106	128
Si	6.78	7.72	4.98	8.41	8.59	9.13	9.93	10.01	11.55	9.09	10.08	11.49
Cu	0.04	0.05	0.07	0.04	0.03	0.05	0.02	0.03	0.03	0.03	0.03	0.03
Zn	0.04	0.17	0.15	0.01	0.02	0.03	0.01	0.01	0.02	0.00	0.01	0.03
NO_3-N	176.0	60.4	164.0	100.0	42.6	129.6	70.3	18.7	89.7	74.3	13.0	79.7
NO_2-N	0.20	0.22	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.10	0.01	0.01
NH_4-N	3.18	0.14	7.38	0.09	0.08	0.15	0.07	0.07	0.19	0.07	0.07	0.14
PO_4-P	11.93	7.13	23.60	1.68	2.78	16.80	0.38	0.17	8.87	0.17	0.02	5.63

Values written in bold indicate the active treatment.

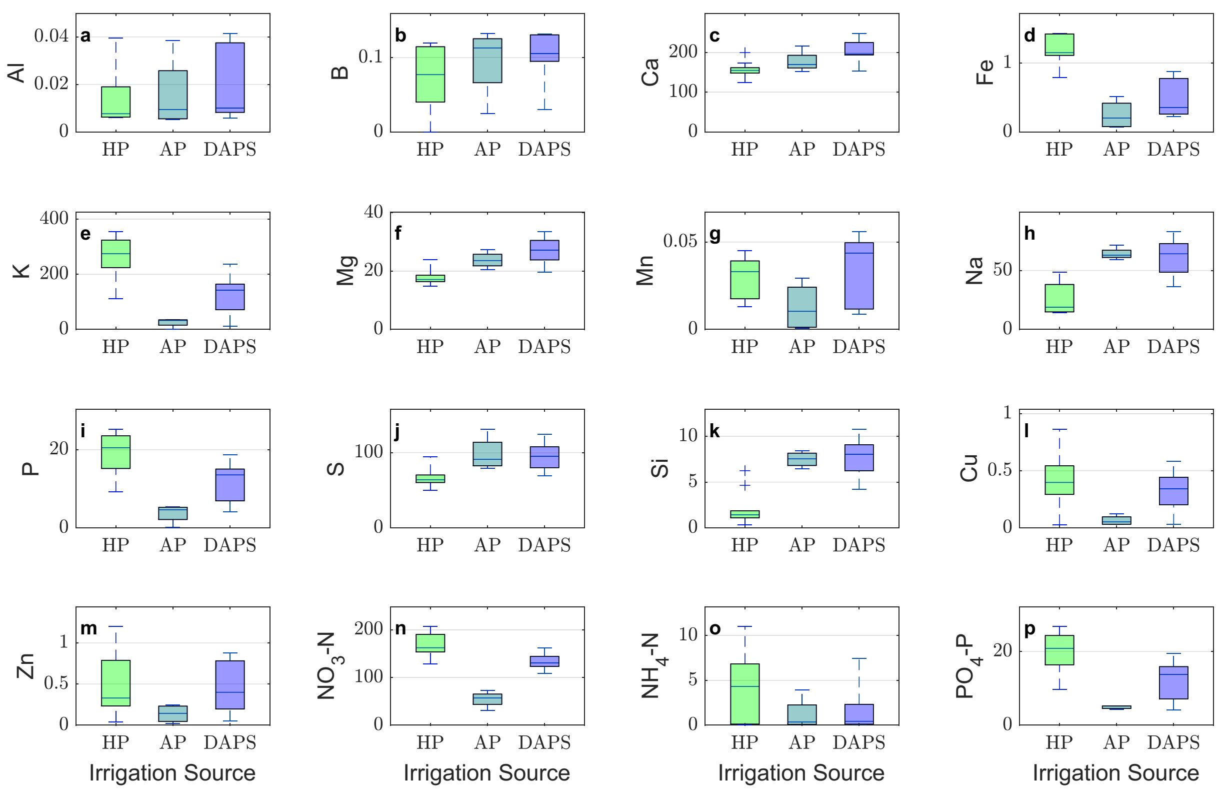

FIGURE 3
Average of nutrients in the weekly fresh-mixed irrigation water (mg L⁻¹) as supplement during the 21 days in hydroponics (HP), aquaponics (AP), and decoupled aquaponics (DAPS) in climate-controlled greenhouse in February (Exp. 1), for Al **(a)**, B **(b)**, Ca **(c)**, Fe **(d)**, K **(e)**, Mg **(f)**, Mn **(g)**, Na **(h)**, P **(i)**, S **(j)**, Si **(k)**, Cu **(l)**, Zn **(m)**, NO3-N **(n)**, NH4-N **(o)**, PO4-P **(p)**.

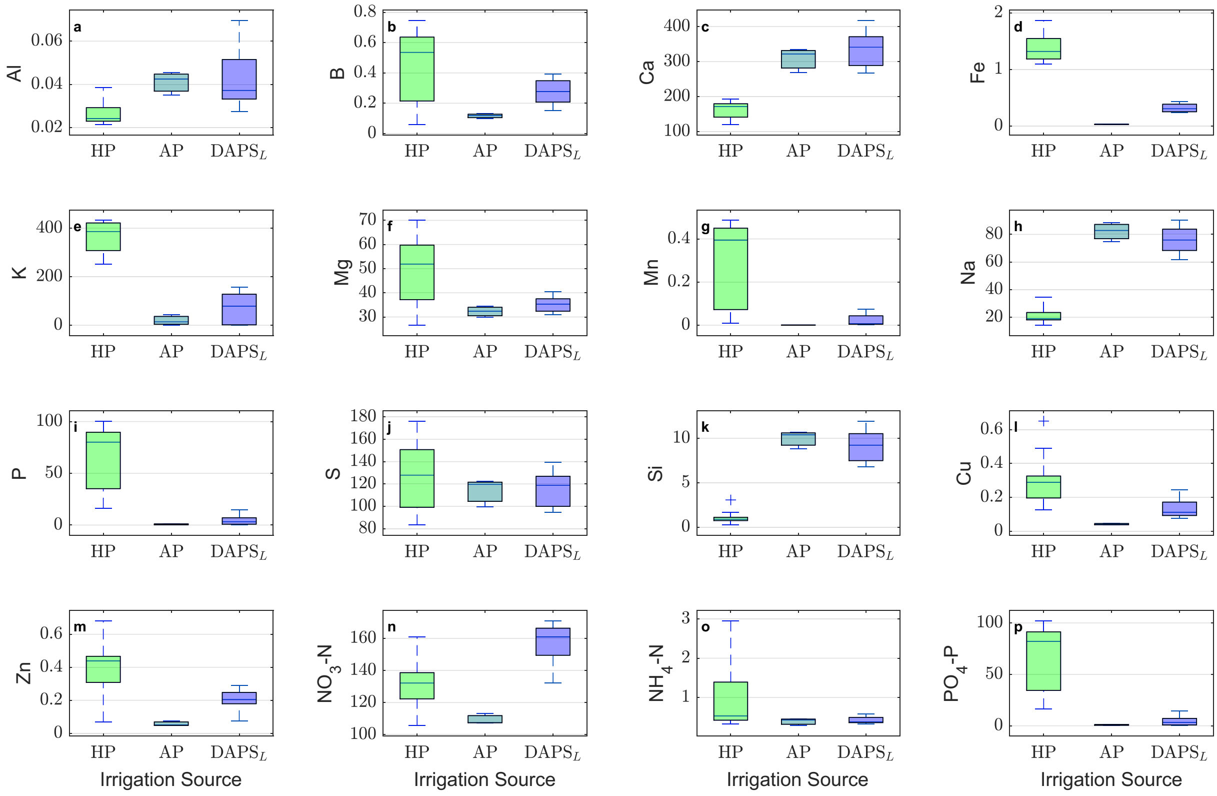

FIGURE 4
Average of nutrients in the weekly fresh-mixed irrigation water (mg L^{-1}) as supplement during 28 days in hydroponics (HP), aquaponics (AP), and decoupled aquaponics ($DAPS_L$) in climate-controlled greenhouse in August (Exp. 2), for Al **(a)**, B **(b)**, Ca **(c)**, Fe **(d)**, K **(e)**, Mg **(f)**, Mn **(g)**, Na **(h)**, P **(i)**, S **(j)**, Si **(k)**, Cu **(l)**, Zn **(m)**, NO3-N **(n)**, NH4-N **(o)**, PO4-P **(p)**.

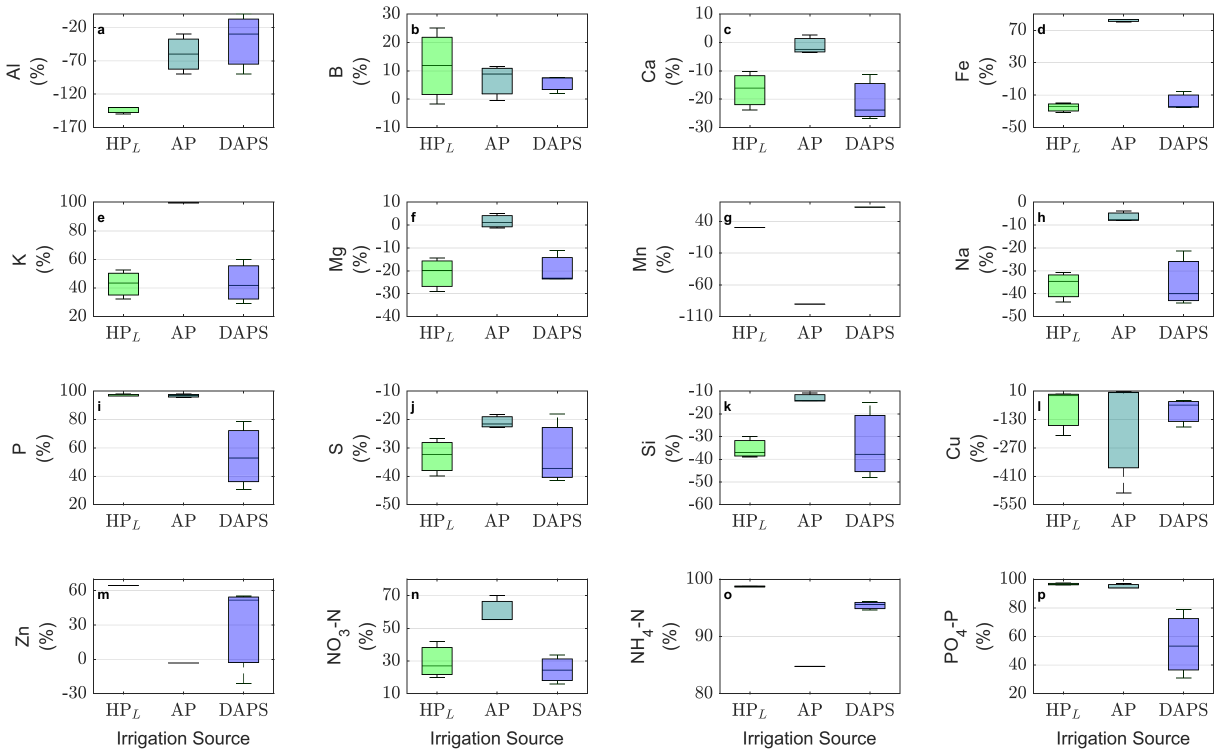

FIGURE 5
Percentage nutrient removal balance during week 3 in hydroponics (HP_L), aquaponics (AP), and decoupled aquaponics (DAPS) pooled over four lettuce cultivars in climate controlled systems (Exp. 3), for Al **(a)**, B **(b)**, Ca **(c)**, Fe **(d)**, K **(e)**, Mg **(f)**, Mn **(g)**, Na **(h)**, P **(i)**, S **(j)**, Si **(k)**, Cu **(l)**, Zn **(m)**, NO3-N **(n)**, NH4-N **(o)**, PO4-P **(p)**. Negative numbers indicate up-concentration due to selective nutrient uptake.

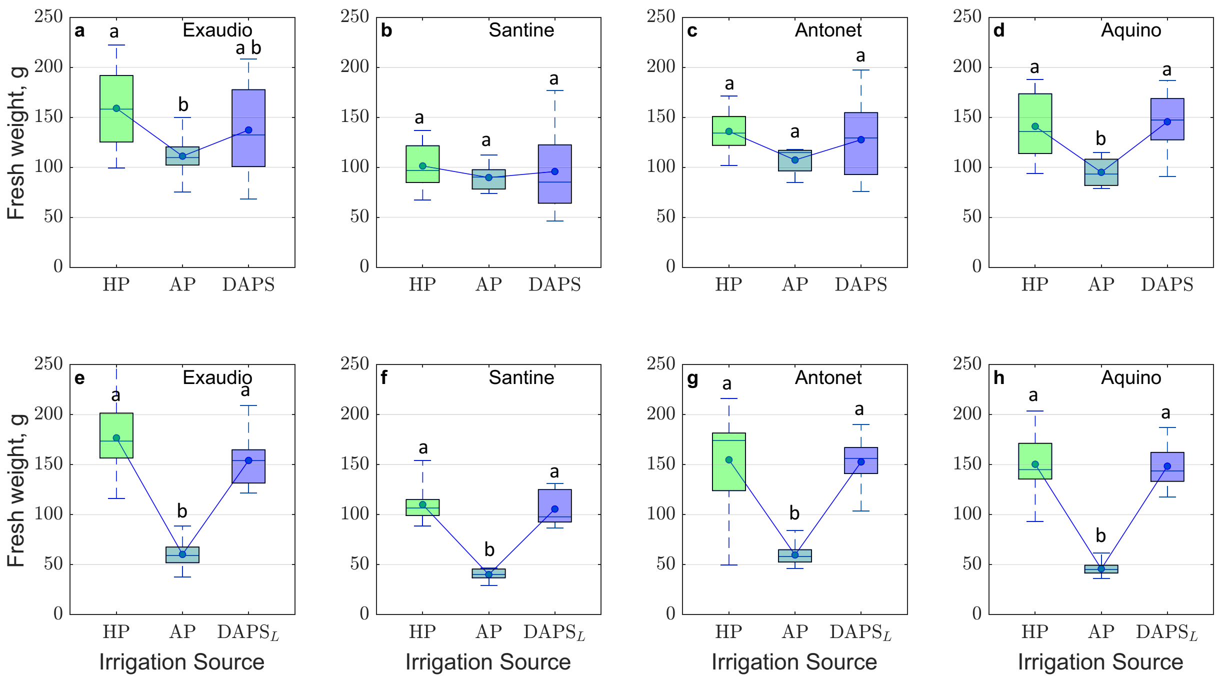

FIGURE 6
Final fresh weight of greenhouse produced lettuce in hydroponics (HP), aquaponics (AP), and decoupled aquaponics (DAPS) in the benchmark scenario [Exp. 1; **(a–d)**], and with DAPS$_L$ [Exp. 2; **(e–h)**]; for the four cultivars 'Exaudio' **(a, e)**, 'Santine' **(b, f)**, 'Anonet' **(c, g)**, and 'Aquino' **(d, h)**. Different letters indicate significant differences between treatments within each cultivar and experiment (ANOVA followed by post-hoc multiple comparison test, $p < 0.05$).

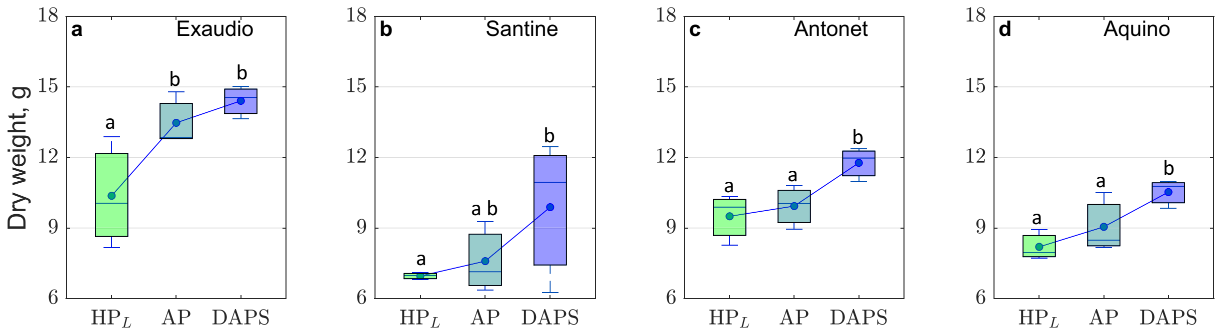

FIGURE 7
Final dry weight of climate controlled produced lettuce in hydroponics with low P (HP), aquaponics (AP), and decoupled aquaponics (DAPS); with mean value (point) and median in HP$_L$ (blue line) (Exp. 3); for the four cultivars 'Exaudio' **(a)**, 'Santine' **(b)**, 'Anonet' **(c)**, and 'Aquino' **(d)**. Different letters indicate significant differences between treatments within each cultivar (ANOVA followed by post-hoc multiple comparison test, $p < 0.05$).

compared to HP$_L$, with only minor differences between cultivars. As with macronutrients, consistent differences between treatments were observed in leaf C and N concentrations (Figure 11), resulting in potentially higher photosynthesis capacities in HP$_L$ and DAPS compared to AP. Only minor differences between cultivars could be observed. No significant differences in chlorophyll a, chlorophyll b, or total carotenoid concentrations were detected between treatments in any of the three experiments (data no shown).

3.4 Environmental foot-prints

The consequential life cycle assessment quantified environmental impacts per functional unit (1 kg fresh lettuce) using system expansion to account for nutrient reuse within the DAPS sub-systems. Under benchmark conditions (as experimentally investigated in Exp. 1), DAPS and hydroponics (HP) showed comparable biomass production (cf. Figure 6), and similar impact on the direct energy-use related impact category global warming potential (GWP_{100}). DAPS showed distinct lower impact on all other categories as fossil resource scarcity (FRS), mineral resource scarcity (MRS), freshwater eutrophication (FEP), water consumption (WCO) and land use (ALU) (Figure 12); e.g., FRS and MRS were reduced by around 50% due to reduced use of mineral fertilizer. This effect was even more pronounced in coupled aquaponics (AP) exhibited even lower impacts than DAPS across all categories but GWP_{100}. As such, despite no direct fertilizer input in AP, the reduced biomass production increased the relative contribution of energy demand per functional unit, particularly affecting GWP_{100}. As water for irrigation was allocated to the RAS-subsystem in both HP and DAPS, especially WCO showed a strong reduction compared to HP.

Under reduced macronutrient availability in DAPS (DAPS$_L$; as experimentally investigated in Exp. 2), mineral fertilizer inputs for K and P were lower than in the benchmark scenario, while biomass production remained comparable to DAPS (cf. Figure 6). Because area-based energy use, infrastructure and background processes

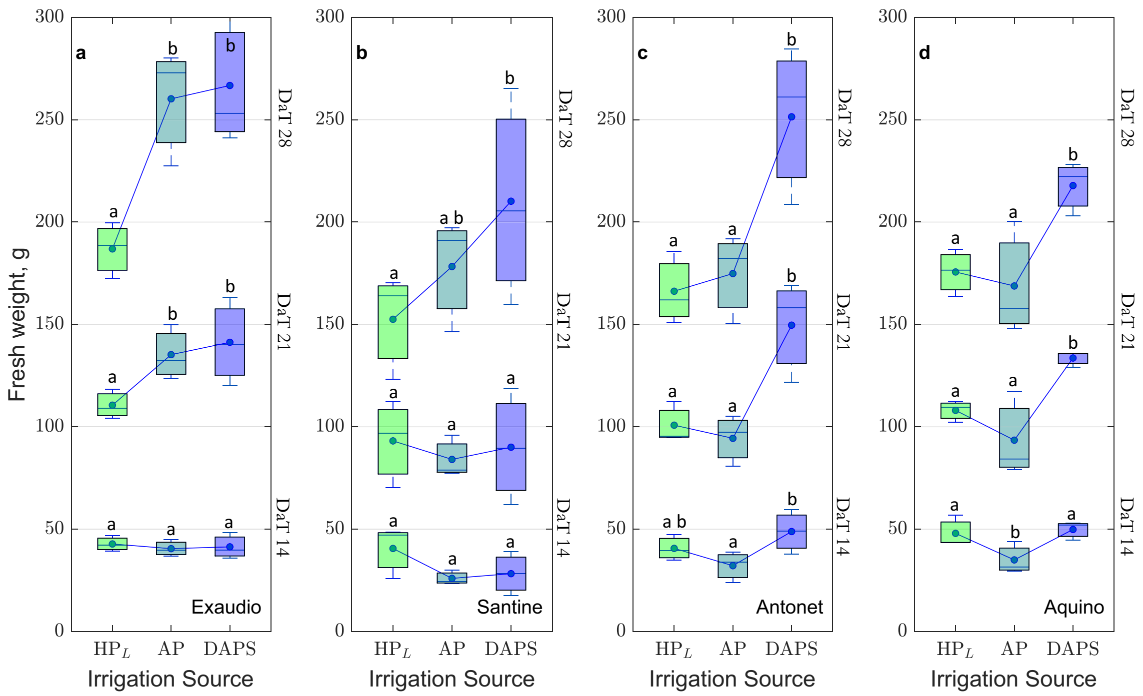

FIGURE 8
Fresh weight of four lettuce cultivars in P-deficient hydroponics (HP_L), aquaponics (AP), and decoupled aquaponics (DAPS) after 14, 21, and 28 days in HP_L (Exp. 3); for the four cultivars 'Exaudio' **(a)**, 'Santine' **(b)**, 'Anonet' **(c)**, and 'Aquino' **(d)**, Different letters indicate significant differences between treatments within each cultivar and day after transplanting (DaT) (ANOVA followed by post-hoc multiple comparison test, $p < 0.05$).

remained constant, reduced fertilizer input translated directly into lower impact intensities per kilogram of lettuce across most categories (Figure 12).

In the phosphorus-limited hydroponic scenario (HP_L; as experimentally investigated in Exp. 3), mineral P input in HP was reduced and biomass production declined (Figure 12). As shown above, DAPS formed higher yield under similar EC conditions than HP_L (cf. Figure 8), and accordingly, impact intensities per functional unit increased in HP_L relative to DAPS. Differences were most pronounced for GWP_{100}, FRS, WCO and ALU. In these four cases, the same effect yielded in higher impacts of HP_L compared to HP.

Across all scenarios, AP consistently combined lower fertilizer input with reduced biomass production. Impacts per functional unit of 1 kg lettuce in the AP scenario were higher than in HP and DAPS in selected impact categories, particularly for GWP_{100}, while AP had due to no added mineral fertilizer lower impacts than HP and DAPS in all other impact categories. $DAPS_L$ with on one hand reduced use of K and a similar growth than HP showed in all cases but GWP_{100} only small differences to AP (Figure 12).

3.5 Regional and site-specific environmental impacts

Across all climatic contexts as contextualized with the three scenarios controlled environment agriculture (CEA), temperate Central European greenhouse production (TCE), and Mediterranean Southern European conditions (MSE), environmental impacts per functional unit differed systematically. For AP, DAPS and $DAPS_L$, the Mediterranean scenario consistently exhibited the lowest impact ratios relative to hydroponics (HP = 100%), followed by TCE, whereas CEA showed the highest values. This regional ordering was consistent across impact categories and independent of axis scaling, as illustrated by both the normalized comparison (Figure 13) and the category-resolved representation (Supplementary Figure S2).

Under benchmark conditions, DAPS reduced GWP_{100} to approximately 85–95% of HP in CEA, 80–90% in TCE and to about 65–75% in MSE (Figure 13b). In contrast, moderate regional tendency was observed for fossil resource scarcity (FRS) and mineral resource scarcity (MRS), with impact ratios generally decreasing from CEA toward Mediterranean conditions with comparatively small regional variation, with DAPS values remaining around 45–50% of the HP reference across climatic contexts. Although, differences between TCE and MSE remained. These results indicate that the relative environmental advantage of DAPS over HP increased toward Mediterranean production conditions, primarily driven by reductions in energy- and resource-related impacts rather than mineral input differences alone.

Reducing macronutrient supplementation in $DAPS_L$ further decreased impact ratios compared to DAPS while biomass production remained largely unchanged. For GWP_{100}, $DAPS_L$ reduced impact ratios by approximately 2–5 percentage points relative to DAPS across climatic contexts (Figures 13b,c). Stronger differences were observed for the mineral-related impact categories: Mineral resource scarcity (MRS) decreased from approximately 50% of HP under DAPS to about 20% under $DAPS_L$, corresponding to an additional reduction of roughly 20–30 percentage points. Freshwater eutrophication potential (FEP) showed a comparable pattern, declining from approximately 50–60% of HP under DAPS to about 20% under $DAPS_L$. For water consumption (WCO), differences between DAPS and $DAPS_L$ remained small, typically within 1–4 percentage points, while maintaining the same regional ordering (CEA > TCE > MSE). Agricultural land use (ALU) also showed further reductions under $DAPS_L$, decreasing from approximately 25–30% of HP under DAPS to below 10–15% under $DAPS_L$ (Figures 13v,w).

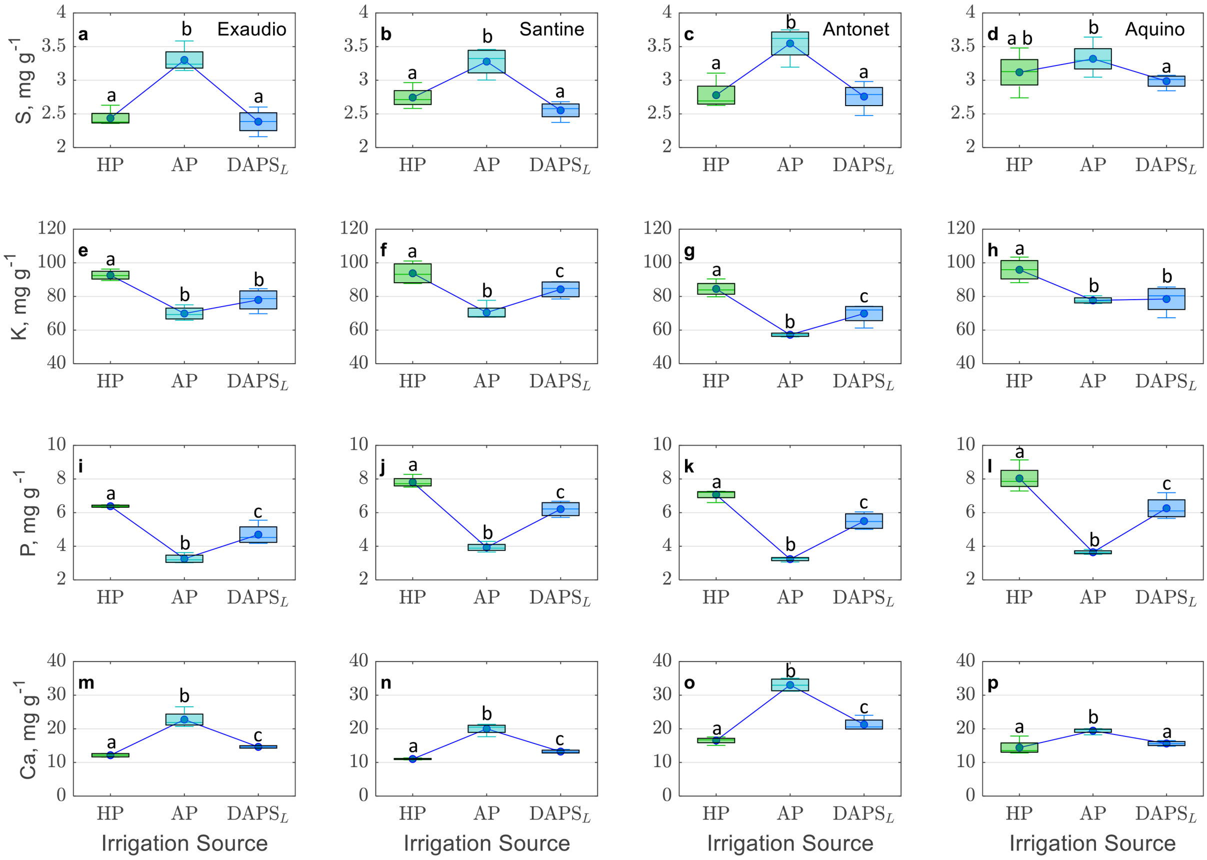

FIGURE 9
Nutrients in leaves of four lettuce cultivars [Exaudio, **(a,e,i,m)**; Santine, **(b,f,j,n)**; Antonet, **(c,g,k,o)**; Aquino, **(d,h,l,p)**] during 28 days in hydroponics (HP), aquaponics (AP), and decoupled aquaponics (DAPS) in $DAPS_L$ (Exp. 2). Different letters indicate significant differences between treatments (ANOVA followed by post-hoc multiple comparison test, $p < 0.05$).

The phosphorus-limited hydroponic scenario (HP_L) showed higher impact ratios relative to the other production systems and approached, even exceeding the HP reference (HP = 100%) in selected impact categories as GWP_{100}, FRS, WCO and ALU. This effect was most visible under controlled environment agriculture (CEA), while relative deviations decreased toward temperate (TCE) and Mediterranean conditions (MSE); in MSE impact ratios remained lowest overall (Figure 13; Supplementary Figure S2). These results indicate that phosphorus limitation in hydroponic production reduced environmental efficiency (i.e., high environmental impacts) in all regions with only small differences, while the Mediterranean region remains having the lowest relative environmental impacts compared to the HP benchmark. In general, differences between systems were primarily driven by nutrient inputs and substitution effects associated with nutrient reuse, whereas location-specific differences were mainly determined by energy and water demand.

4 Discussion

The present study aimed to disentangle the effects of macronutrient imbalances (P and K) from osmotic effects under constant EC conditions in order to better understand crop productivity and environmental performance in decoupled aquaponics (DAPS). By strategically modifying nutrient composition across three experimental scenarios and four lettuce cultivars, we were able to isolate structural ion constraints, system-specific resilience mechanisms and genotype-dependent responses under controlled environmental conditions. However, because $DAPS_L$ and HP_L were evaluated in separate experiments and environments, their comparison represents a scenario-based contrast derived from relative system responses rather than a direct factorial treatment comparison.

Beyond the experimental comparison of hydroponics (HP), coupled aquaponics (AP) and DAPS, this study further integrated a regionalised consequential life cycle assessment across three climatic contexts (CEA, TCE and MSE). This enabled linking nutrient composition, biomass formation and resource demand structures to environmental performance per functional unit of 1 kg fresh lettuce. Although absolute biomass differed between cultivars, the response patterns to the different nutrient regimes were consistent across cultivars. In particular, the relative effects of DAPS, AP and nutrient limitation (DAPSL and HPL) followed similar trends, indicating that the observed system-level responses were robust and not driven by cultivar-specific behavior.

Therefore, the interpretation of results focuses on treatment effects rather than genotype-specific responses. While cultivar-dependent differences in nutrient uptake and growth dynamics are well documented in controlled environment agriculture (Buzby and Lin, 2014; Xaxiri et al., 2023), such effects were not a primary driver of the patterns observed in this study. In the following, the findings are

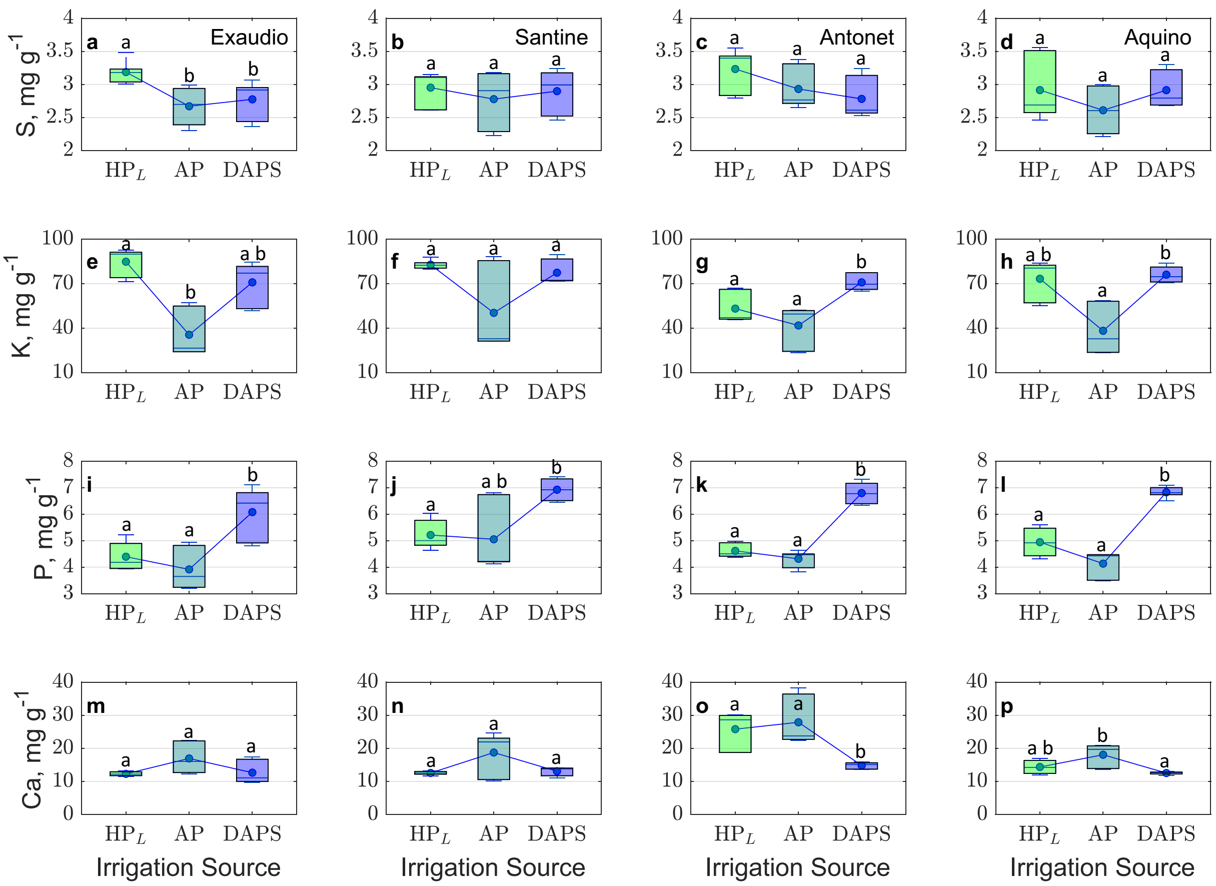

FIGURE 10
Nutrients in leaves of four lettuce cultivars [Exaudio **(a,e,i,m)**; Santine **(b,f,j,n)**; Antonet **(c,g,k,o)**; Aquino **(d,h,l,p)**] during 28 days in low-P hydroponics (HP_L), aquaponics (AP), and decoupled aquaponics (DAPS) (Exp. 3). Different letters indicate significant differences between treatments (ANOVA followed by post-hoc multiple comparison test, $p < 0.05$).

discussed in relation to (i) balanced versus constrained nutrient supply, (ii) system-level ion interactions and dynamic processes, (iii) implications for nutrient management, (iv) environmental performance, (v) regional and system-specific implications, and (vi) imitations and future perspectives.

4.1 Crop growth performance influenced by nutrient supply

The transition from traditional coupled aquaponic systems to decoupled multi-loop aquaponics (DAPS) represents a substantial step toward improved nutrient management and production stability (Delaide et al., 2016; Monsees et al., 2017a; Monsees et al., 2019). In the present study, biomass production under benchmark conditions was comparable between DAPS and conventional hydroponics (HP), confirming previous findings that properly adjusted DAPS can achieve yields similar to standard hydroponic systems (Suhl et al., 2016; Suhl et al., 2018; Monsees et al., 2019). In contrast, the coupled aquaponics treatment (AP) resulted in reduced biomass in all cultivars, consistent with reports describing nutrient limitations in single-loop systems (Monsees et al., 2017b; Chandrou et al., 2024). Lower nutrient concentrations in un-supplemented aquaponic solutions compared to hydroponic recipes are widely recognized as a major cause of reduced yield (Lunda et al., 2019; Monsees et al., 2019; Tellbüscher et al., 2025). These results demonstrate that RAS-derived water per se does not impair hydroponic-level productivity when nutrient composition is appropriately adjusted. Yield differences between systems therefore cannot be attributed solely to water origin, but rather to nutrient management strategy.

While DAPS and HP performed similarly under balanced nutrient supply, clear differences emerged under nutrient constraint. The imposed reductions in K and P ($DAPS_L$) as well as the induced phosphorus limitation in hydroponics (HP_L) exposed system-specific responses that were not visible under benchmark conditions. Under $DAPS_L$, reduced availability of K and P resulted from elevated Ca^{2+} and Na^+ concentrations originating from the RAS water, which constrained nutrient adjustment under a fixed EC. Such cation competition and EC-related restrictions are commonly encountered when RAS-derived water is used as the basis for plant nutrition. In these situations, achieving a hydroponic-equivalent nutrient profile becomes technically challenging, particularly for P and K, which are frequently reported as limiting elements in aquaponic systems (Goddek et al., 2019; Yep and Zheng, 2019). The present results confirm that these constraints can translate into measurable yield effects, although cultivar sensitivity differed. In contrast, under phosphorus-limited hydroponic conditions (HP_L), DAPS maintained higher biomass production and greater P accumulation. This indicates that system performance under nutrient stress cannot be explained solely by total nutrient concentration in solution. Rather, the dynamic characteristics of the recirculating system appear to influence nutrient availability and uptake.

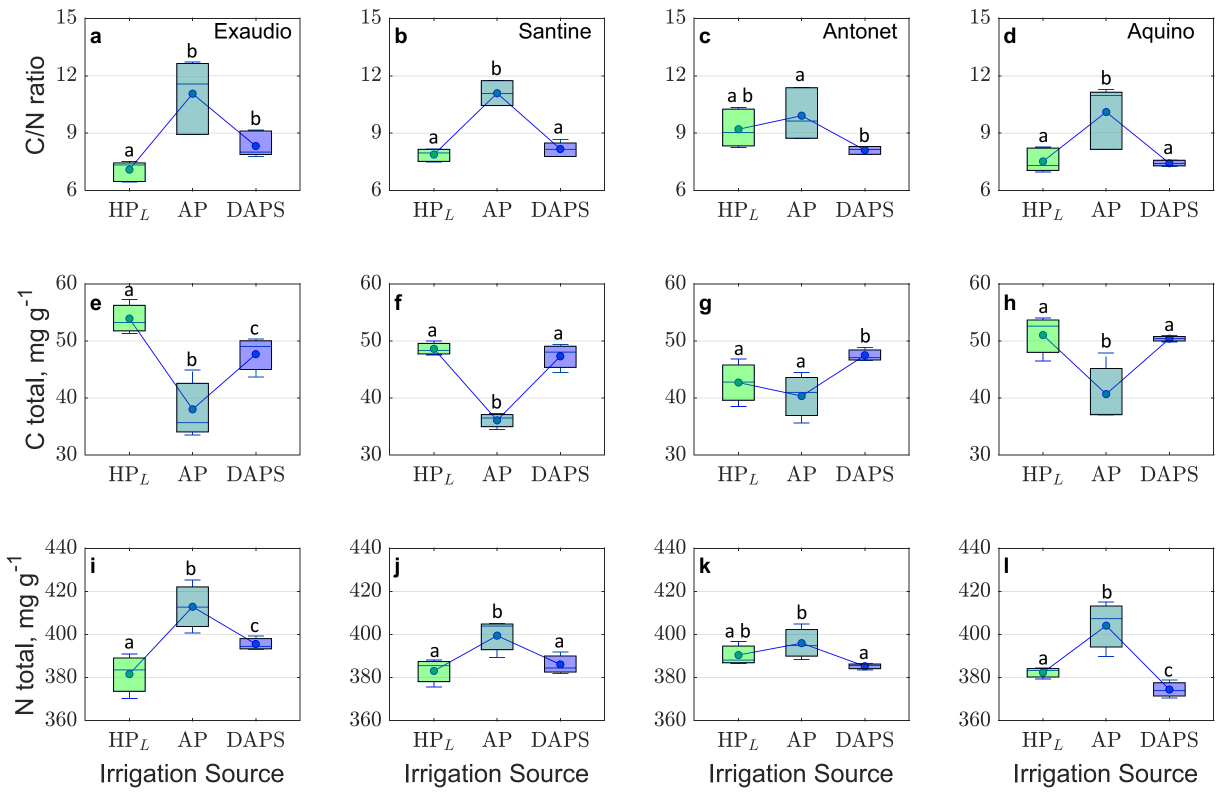

FIGURE 11
C, N, and C/N ratio for four lettuce cultivars [Exaudio **(a,e,i)**; Santine **(b,f,i)**; Antonet **(c,g,k)**; Aquino **(d,h,l)**] during 28 days of production in hydroponics (HP), aquaponics (AP), and decoupled aquaponics (DAPS) in HP_L (Exp. 3). Different letters indicate significant differences between treatments (ANOVA followed by post-hoc multiple comparison test, $p < 0.05$).

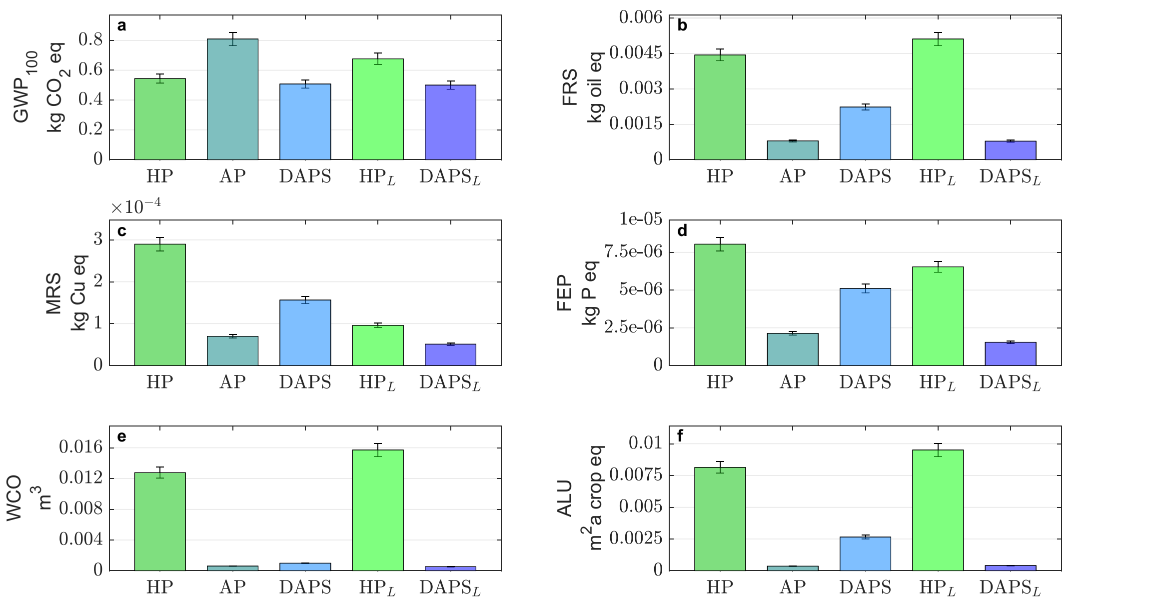

FIGURE 12
Comparing of life cycle impacts for 1 kg lettuce in a heated greenhouses in Germany (LAT 52° N) from hydroponics (HP), aquaponics (AP), decoupled aquaponics (DAPS), and hydroponics reduced P (HP_L) and decoupled aquaponics with reduced P, K, Mg ($DAPS_L$) for 6 LCA impact categories with global warming potential with 100 year horizon [GWP100, **(a)**], fossil resource scarcity [FRS, **(b)**], mineral resource scarcity [MRS, **(c)**], fresh-water eutrophication [FEP, **(d)**], water consumption [WCO, **(e)**], land use [ALU **(f)**].

Previous studies have reported comparable or even increased yields in DAPS relative to hydroponics (Delaide et al., 2016; Goddek and Vermeulen, 2018; Monsees et al., 2019; Aslanidou et al., 2024). However, the underlying mechanisms remain debated, including the potential role of microbial processes and biologically active solution matrices (Schmautz et al., 2017). From a

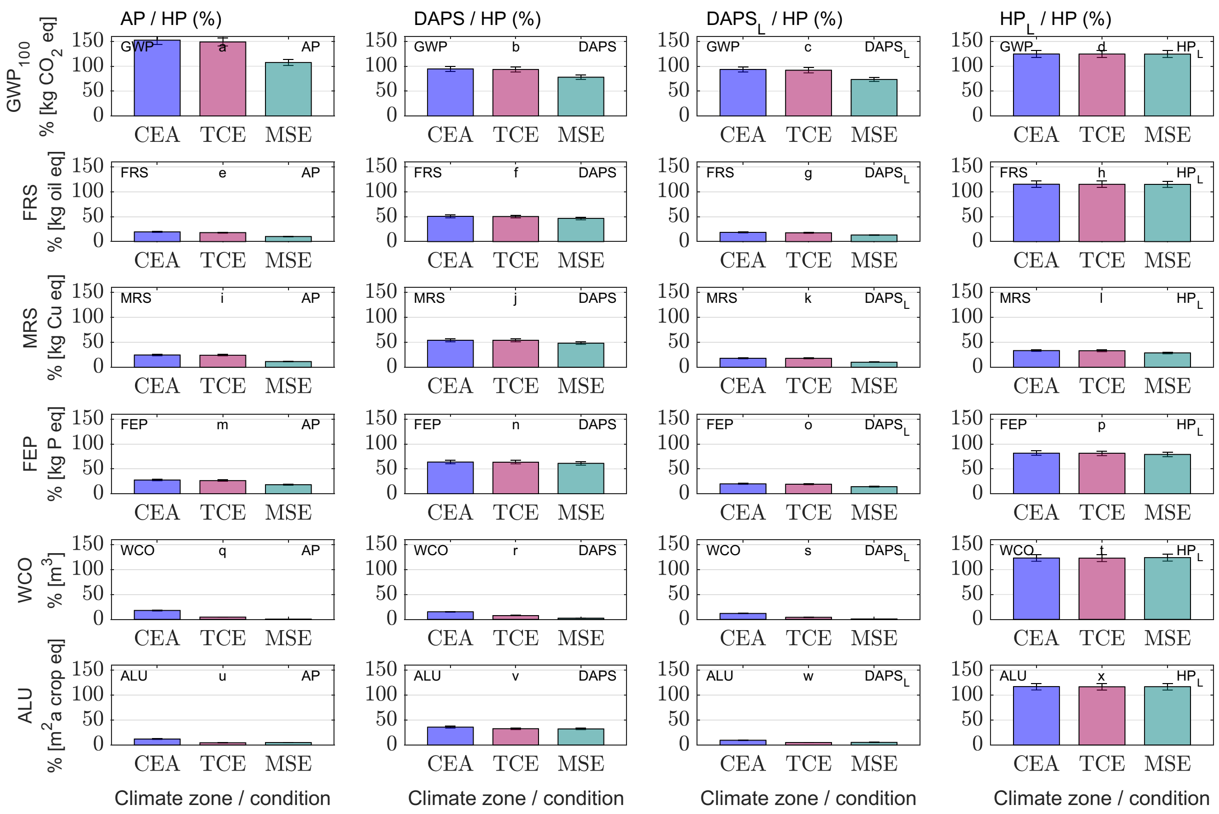

FIGURE 13
Percentage difference scaled to fixed 0–150% of aquaponics (AP), decoupled aquaponics (DAPS); decoupled aquaponics with reduced P, K, Mg ($DAPS_L$), and hydroponics reduced P (HP_L) to regular hydroponics (HP) for three different combinations of production systems and site-location with controlled environment indoor farm (CEA), passive climate controlled standard greenhouses (heating on demand) in temperate central European conditions (TCE), and Mediterranean southern European conditions (MSE); for LCA footprints on 6 LCA impact categories: global warming potential with 100 year horizon [GWP100, **(a–d)**], fossil resource scarcity [FRS, **(e–h)**], mineral resource scarcity [MRS, **(i–l)**], fresh-water eutrophication [FEP, **(m–p)**], water consumption [WCO, **(q–t)**], land use [ALU, **(u–x)**].

systems perspective, aquaponic solutions cannot be described as static nutrient reservoirs; instead, they represent biologically active media in which transformation processes, ion interactions and temporal dynamics shape nutrient accessibility (Körner et al., 2025).

The present findings suggest that under constrained nutrient supply, DAPS may provide greater functional resilience than hydroponics. This resilience does not necessarily result from higher nominal nutrient concentrations, but from the interaction between system configuration, ion composition and dynamic nutrient regulation within the recirculating environment (Zhu et al., 2026).

4.2 Beyond concentration matching: ion interactions and system dynamics

When nutrient constraints were introduced, system-specific differences became apparent, suggesting that nutrient concentration alone does not fully describe effective nutrient availability. A central mechanism revealed in the decoupled aquaponic treatments was the elevated presence of Ca^{2+} and Na^{+} originating from the RAS water. Under a fixed electrical conductivity (EC), increasing the fraction of one ion necessarily reduces the proportional availability of others. This structural constraint of EC-controlled fertigation systems has been described as a limiting factor in nutrient balancing of aquaponic solutions (Goddek et al., 2019; Yep and Zheng, 2019). In practical terms, elevated Ca and Na concentrations restrict the ability to adjust K and P to hydroponic target levels without exceeding EC thresholds. Consequently, nutrient imbalance in DAPS is not merely a formulation issue, but partly inherent to the ionic composition of the source water. Beyond ionic ratios, dynamic processes within recirculating systems may further influence nutrient accessibility. Aquaponic solutions are biologically active matrices, in which microbial transformation, mineralization and ion buffering processes occur continuously (Delaide et al., 2016; Goddek and Vermeulen, 2018). In contrast to conventional hydroponics, where nutrient composition is largely defined by deliberate dosing, DAPS solutions integrate both controlled supplementation and biologically derived nutrient fractions. Such interactions may alter the temporal availability of nutrients, particularly phosphorus, whose speciation and precipitation behavior are strongly influenced by Ca concentration and microbial activity.

The superior biomass production observed in DAPS compared to hydroponic P limitation (HP_L) together with the basically not-affected production of lettuce with P- and K-limitation ($DAPS_L$) showed that changes in productivity within HP_L cannot be attributed to nominal P concentration alone. Instead, it likely reflects system-specific differences in nutrient availability and utilization attributed to specific behavior within the biological active aquaponics. It suggests that effective P availability in DAPS may be influenced by dynamic transformation processes or by system-level buffering capacity. Similar discussions on the relative contributions of nutrient composition versus microbial effects in DAPS have been raised in earlier work (Delaide et al., 2016; Goddek and Vermeulen, 2018), yet the specific role of macronutrient imbalances has rarely been experimentally isolated.

In that context, evaluating system performance based solely on snapshot nutrient concentrations may underestimate the functional dynamics of recirculating systems. Ion competition, EC constraints and biological transformation processes interact to shape nutrient uptake conditions over time. Then, nutrient concentration dynamics in recirculating systems are influenced by multiple interacting processes, including plant uptake, evapotranspiration and replenishment strategies (Savvas et al., 2023). As a result, temporal trends are not necessarily linear. In particular, increases in concentration may occur when water loss through evapotranspiration exceeds replenishment, leading to temporary concentration effects despite ongoing nutrient uptake (Gang et al., 2025). Consequently, observed concentration patterns should be interpreted as system-level responses rather than direct indicators of nutrient supply alone (Zhu et al., 2026). However, the present study demonstrates that when nutrient stress is imposed, these interactions become visible as plant growth and yield.

Thus, DAPS cannot be interpreted simply as "hydroponics with fish water". Rather, it represents a hybrid nutrient regime in which ionic composition, biological background and recirculation dynamics collectively determine plant responses (Zhu et al., 2026). A mechanistic understanding of these interacting factors is essential for advancing decoupled aquaponic systems toward predictable and resilient production strategies (Keesman et al., 2019).

4.3 Implications for nutrient management and system engineering

The transition from traditional one-loop aquaponic systems to decoupled multi-loop systems represents a substantial step toward professional and controllable production systems (Delaide et al., 2016; Monsees et al., 2017a; Monsees et al., 2019). From a system engineering perspective, professional DAPS operation requires continuous monitoring of ion ratios in addition to total EC, as well as adaptive supplementation strategies that respond to dynamic changes in solution composition (Eck et al., 2019). Nutrient management must integrate cultivar-specific demand, since genotype-dependent uptake potential determine how ionic imbalances translate into growth responses (Wang et al., 2025). Where structural constraints arise from RAS water composition, dilution or targeted pre-treatment may be necessary to prevent persistent imbalances caused by elevated Ca^{2+} or Na^{+} levels. Such an approach distinguishes professional DAPS from small-scale hobby aquaponics, where nutrient balancing is often secondary to fish production and system control remains limited (Al Tawaha et al., 2025). Although decoupling technically enables precise nutrient control, this potential can only be realized when ion competition, EC boundary conditions and dynamic system behavior are explicitly incorporated into management decisions (Aslanidou et al., 2023; Al Tawaha et al., 2025).

Recent developments in ion-specific sensing and control systems enable more precise adjustment of individual nutrients in soilless systems, overcoming limitations associated with coupled fertilizer formulations (Neocleous and Savvas, 2022; Gang et al., 2025; Giannothanasis et al., 2025) as recently summarized in an extensive review (Ahamed et al., 2025). In this context, approaches such as model-based dosing and optimization frameworks (e.g., *NutriSense*, *OptiDose*) allow dynamic adjustment of nutrient supply and improved resource-use efficiency (Neocleous and Savvas, 2022; Savvas et al., 2023; Gang et al., 2025; Karimzadeh et al., 2026). These advances highlight the potential for integrating sensor-based control with system-level evaluation, as applied in the present study (Giannothanasis et al., 2025; Karimzadeh et al., 2026).

4.4 Environmental implications

The performed consequential life cycle assessment indicates that environmental performance of decoupled aquaponic systems is not determined by fertilizer substitution alone, but by the interaction between nutrient balancing, biomass stability and region-specific resource demand structures. This observation is consistent with previous LCA studies in aquaponics showing that yield performance directly modulates impact intensities per functional unit (Jaeger et al., 2019; Körner et al., 2021; Ghamkhar et al., 2022). Within a consequential system-expansion framework, impacts are expressed per kilogram of product, while many foreground processes, including energy use, infrastructure and climate control, are primarily linked to cultivation area rather than yield (Ekvall and Weidema, 2004). When biomass production declines, these area-based inputs remain largely unchanged, resulting in higher impact intensities per functional unit (Antón et al., 2007). Environmental performance in the current assessment was therefore largely mechanistically coupled to yield stability rather than being solely governed by the degree of fertilizer substitution.

While DAPS partially substitutes mineral fertilizers through reuse of RAS-derived nutrients, this substitution represents only one component of the total environmental balance. The present results show that under reduced macronutrient supplementation in $DAPS_L$, biomass production remained largely comparable to DAPS and HP, while mineral fertilizer inputs were reduced. Consequently, impact intensities decreased particularly for mineral-related categories, demonstrating that improved environmental performance can be achieved when reduced supplementation is not accompanied by yield penalties.

Conversely, under phosphorus limitation in hydroponics (i.e., HP_L), regular full level DAPS maintained higher biomass formation. In this case, the reuse of RAS-derived nutrients combined with stable yield translated into lower mineral resource scarcity (MRS) and water consumption (WCO) per functional unit of 1 kg lettuce. Such behavior reflects the system-level coupling between nutrient composition, physiological performance and environmental indicators, previously highlighted in modeling studies on nutrient-demand-driven aquaponic optimization (Körner et al., 2025).

Overall, the environmental advantage of DAPS is conditional rather than intrinsic. It emerges when ion balancing maintains biomass stability under given climatic and infrastructural constraints. Yield stability thus constitutes the central control variable linking ionic composition, genotype-specific physiology and environmental footprint.

4.5 Regional and system-specific implications

Environmental performance was further modulated by regional boundary conditions. This site- and system specific assessment was based on previously reported ranges of yield and resource consumption in different production systems and climatic regions, including controlled environment agriculture (CEA), temperate Central Europe (TCE), and Mediterranean Southern Europe (Graamans et al., 2018; Körner et al., 2021; Pinho et al., 2024; Körner et al., 2025). While recent meta-analyses have highlighted substantial variability in reported yields and resource use across studies, reflecting differences in system configuration, climate, and management practices (Karpe, 2026), in the present study, constant yields derived from the experimental results were combined with literature-based resource consumption data to enable a consistent comparison across scenarios. This approach represents a simplified, scenario-based framework intended to illustrate relative system behavior and directional trends, rather than to provide a fully site-specific life cycle assessment.

The environmental impact of climate controlled systems as greenhouses is highly determined by heating demand, evaporative cooling and irrigation intensity (Körner et al., 2021; Danevad et al., 2023; Mousavi et al., 2023), and climate regions substantially redistribute environmental burdens between impact categories (Goddek et al., 2023). The present regional comparison confirms that under energy-dominated systems (i.e., CEA), fertilizer-related improvements remain proportionally small, whereas under Mediterranean greenhouse conditions nutrient and water management gains stronger leverage. These findings indicate that environmental evaluation of aquaponic systems requires integration of mechanistic nutrient management with regionalised LCA modeling (Keesman et al., 2019; Jansen and Keesman, 2022). Static comparisons between production systems are insufficient, and consequentially site-specific simulation models capable of incorporating climatic projections and resource-demand scenarios are required to anticipate future performance under climate change trajectories (Goddek and Körner, 2019; Goddek et al., 2023). Extending these tools with IPCC-based climate datasets and digital twin architectures represents a logical next step for predictive environmental assessment of aquaponic systems (Körner et al., 2026). Such scenario-based approaches are commonly used to explore system-level differences where fully harmonized site-specific datasets are not available (De Souza et al., 2023; Körner et al., 2025).

The climate-sensitive differentiation observed across CEA, TCE and MSE further aligns with previous work on latitude-dependent resource utilization in decoupled aquaponic systems, where physiological regulation and light-driven transpiration dynamics influence nutrient fluxes and overall system efficiency (Pinho et al., 2024). Regional differences in radiation regimes, evaporative demand and irrigation requirements therefore modify not only absolute resource consumption but also the relative contribution of nutrient recycling to environmental performance. The relative reductions observed in the Mediterranean context MSE across several impact categories indicate that the environmental advantage of decoupled aquaponics becomes more pronounced when baseline heating demand is lower, while nutrient- and water-related processes contribute proportionally more to total system burden. This pattern is consistent with previous regionalised LCA assessments of greenhouse systems (Antón et al., 2007; Torrellas et al., 2012; Körner et al., 2021), showing that climate-dependent energy demand largely determines impact intensity in temperate and northern production regions. In highly energy-intensive CEA, electricity consumption for lighting and climate control dominates impact categories such as global warming potential or fossil resource scarcity (Muñoz-Liesa et al., 2021). Under such conditions, fertilizer substitution and nutrient recycling contribute comparatively less to overall environmental performance, which explains the smaller relative differentiation between DAPS and HP in CEA scenarios. Similar conclusions were drawn in earlier simulation-based assessments of greenhouse production, where energy structure and regional electricity mix were identified as primary determinants of impact intensity (Körner et al., 2021).

Thus, decoupled aquaponics should not only be regarded as inherently superior to conventional hydroponics, but its environmental advantage emerges under specific regional configurations in which fertilizer- and water-related burdens represent a substantial share of total impacts and where biomass stability can be maintained. The interaction between climatic boundary conditions, nutrient management and yield performance thus becomes decisive for evaluating aquaponic systems within a broader sustainability context.

4.6 Limitations and future perspectives

The present study is based on a scenario-driven LCA approach combined with experimental data from controlled experiments (cf. Figure 1). While this allows consistent comparison across systems, it does not capture the full variability of site-specific production conditions. In addition, nutrient manipulation was constrained by the use of standard fertilizer salts, limiting fully independent control of individual ions.

At the same time, the study provides a structured framework that links experimental observations with system-level environmental assessment. By integrating relative productivity responses into a consistent functional-unit-based LCA, the approach enables comparison of production systems under varying nutrient regimes and environmental contexts. This represents an important step toward bridging experimental plant science and system-level evaluation in controlled environment agriculture.

Future work should integrate sensor-based nutrient monitoring and model-based optimization approaches to enable dynamic and site-specific nutrient management. Coupling such approaches with system-level evaluation frameworks may further improve resource-use efficiency and environmental performance in controlled environment agriculture.

5 Conclusion

This study demonstrates and confirms that decoupled aquaponics (DAPS) can achieve biomass production comparable to conventional hydroponics (HP) under balanced nutrient conditions, whereas coupled aquaponics (AP) generally resulted in reduced growth. RAS-derived water therefore does not inherently compromise hydroponic-level productivity when nutrient composition is appropriately adjusted.

However, under macronutrient imbalance, system-specific differences became evident. Ion interactions and EC constraints associated with RAS-derived water limited nutrient adjustment flexibility in DAPS, while under phosphorus limitation in hydroponics, DAPS maintained superior biomass production. These findings indicate that crop performance in decoupled systems is governed not merely by nominal nutrient concentrations, but by the interaction between ionic composition, dynamic system behavior and genotype-specific nutrient responses.

Environmental assessment further revealed that impact intensity per functional unit is directly linked to yield stability. The environmental advantage of DAPS is therefore conditional rather than inherent and depends on maintaining biomass performance under site-specific ionic constraints. Regional scenario analysis confirmed that environmental performance is both site- and location-specific, as variations in absolute energy and water demand substantially altered impact magnitudes despite constant crop productivity.

In conclusion, the results demonstrate that decoupled aquaponic systems can maintain hydroponic-level productivity under reduced mineral fertilization, thereby enabling simultaneous improvements in resource efficiency and environmental performance. However, nutrient recycling alone does not guarantee improved sustainability outcomes: Instead, the environmental and productivity performance of DAPS depends on mechanistically informed nutrient balancing, ion-ratio management and adaptive control strategies that account for cultivar-specific responses and regional production conditions. Given that climatic boundary conditions and energy systems are expected to evolve under IPCC climate projections, sustainability assessments of aquaponic systems must be regarded as dynamic rather than static. Future optimization requires integration of site-specific climate scenarios within model-based digital twin frameworks to enable adaptive, climate-resilient production planning.

Data availability statement

The data are available from the corresponding author upon reasonable request.

Author contributions

OK: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. SP: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Methodology. LC: Data curation, Methodology, Writing – original draft, Writing – review & editing. JO: Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. HM: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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