JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(1), 52–68
https://doi.org/10.12911/22998993/208846
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.07.24
Accepted: 2025.09.05
Published: 2025.11.25

Nitrogen and phosphorus cycling in long-term cropping systems: Environmental and agronomic insights

Arkadiusz Kuligowski[1], Tomasz Niedziński[2*]

[1] Faculty of Agriculture and Ecology, Warsaw University of Life Sciences-SGGW, Nowoursynowska 159, 02-776 Warsaw, Poland
[2] Division of Agricultural and Environmental Chemistry, Institute of Agriculture, Warsaw University of Life Sciences-SGGW, Nowoursynowska 159, 02-776 Warsaw, Poland
* Correspondence author's e-mail: tomasz_niedzinski@sggw.edu.pl

ABSTRACT

The choice of nutrient management strategy within cropping systems significantly influences the dynamics of mobile nutrient forms, thereby modulating their susceptibility to leaching via soil water movement. Intensive mineral fertilization A-NPK, resulted in the highest recorded nutrient losses during the growing season – 664.4 g N-NO_3·ha^{-1} and 23.9 g P-PO_4·ha^{-1} – accompanied by substantial water outflow (83 m^3·ha^{-1}). In contrast, systems integrating legumes, periodic liming, and farmyard manure (E-CaNPK, D-Ca+FYM) effectively reduced nutrient leaching - by up to 91% for nitrate - and significantly enhanced total nutrient uptake. The E-CaNPK system achieved the highest uptake values: 142.6 kg N·ha^{-1} and 24.1 kg P·ha^{-1}, highlighting the synergistic effects of diversified crop rotation and organic inputs. Seasonal variability strongly affected leaching intensity, with early spring conditions - characterized by low evapotranspiration and moderate precipitation – triggering peak nitrate losses. Improvements in soil chemical properties, particularly pH regulation via liming, were essential for nutrient retention. Statistical analyses identified subsoil ammonium concentrations and FYM application as significant negative predictors of nitrogen uptake, while elevated topsoil ammonium was associated with reduced phosphorus uptake. These findings underscore the critical role of integrated fertilization and diversified rotations in mitigating nutrient losses, enhancing soil functionality, and supporting sustainable nutrient management in temperate agroecosystems.

Keywords: nitrogen leaching, phosphorus leaching, soil water outflow, nutrients uptake, soil profile nutrients distribution, cropping system.

INTRODUCTION

Efficient and sustainable nutrient management in agricultural soils is essential for reducing environmental risks associated with nitrogen (N) and phosphorus (P) leaching. Monoculture systems, especially those reliant on unbalanced mineral fertilization, are particularly prone to nutrient losses due to poor synchrony between fertilizer supply and plant demand (Lehmann and Schroth, 2003; Yang et al., 2024). Leaching risk is governed by a combination of agronomic and environmental factors, including crop rotation, cultivar selection, pest and weed management, soil properties, hydrological conditions, and weather variability (Cameron et al., 2013; Macdonald and Gutteridge, 2012). Diversified crop rotations – particularly those involving legumes – provide both agronomic and ecological benefits (Beillouin et al., 2021). Legumes enhance soil quality through biological nitrogen fixation, increased organic matter input, and stimulation of microbial activity, thereby improving nutrient retention and reducing leaching potential (Jena et al., 2022; Jie et al., 2022; Kluger et al., 2025). Empirical evidence consistently shows that legume-based rotations outperform monocultures in nitrate recovery, biomass production, and nitrogen use efficiency (Van Groenigen et al., 2015; Zhang et al., 2019). Fertilizer form and timing are also critical. High rates of mineral NPK inputs, especially during early-season rainfall and low evapotranspiration, exacerbate leaching and soil acidification (Asadu et al., 2024; Beillouin et al., 2021; Tkaczyk et al., 2020) Even organic-intensive systems may contribute to nutrient losses if nutrient release is poorly synchronized with plant uptake (Dahan et al., 2013). In contrast, organic amendments such as manure and compost enhance soil structure and microbial biomass, buffer nutrient availability, and align nutrient release with crop demands (Brempong and Addo-Danso, 2022; Manna et al., 2023). The mobility of nutrients in the soil profile is strongly influenced by texture, pH, and baseline nutrient levels (Mühlbachová et al., 2024; Radulov and Berbecea, 2024). Sandy soils with low organic matter exhibit the highest vulnerability to N and P leaching (Peng et al., 2022)., while acidic conditions (pH < 5.5) reduce phosphorus retention due to impaired sorption capacity (Penn and Camberato, 2019). In contrast, high-clay and high-organic matter soils slow down nitrogen mineralization and lower leaching risk (Geisseler et al., 2024). Phosphorus loss is further intensified in coarse-textured soils with legacy P saturation and high concentrations of soluble P inputs (Djodjic et al., 2004; Suñer and Galantini, 2015). Climatic conditions further modulate nutrient transport. Early spring rainfall events, coupled with limited crop uptake, are often linked to high leaching rates (Teixeira et al., 2021). Sandy or acidic soils, especially those with low organic matter (Debicka et al., 2015), show heightened susceptibility to nitrate and phosphorus losses (Schroth et al., 2003). The phosphorus leaching risk increases with elevated P saturation and soluble P application (Summers and Weaver, 2022). Climatic conditions further modulate nutrient transport. Early spring rainfall events, coupled with limited crop uptake, are often linked to high leaching rates (Rupp et al., 2021; King et al., 2016). This study was conducted under the hypothesis that cropping systems incorporating legume-based rotations, in combination with organic amendments or lime-enriched fertilization regimes, would significantly reduce nitrogen (N) and phosphorus (P) leaching compared to conventional mineral-fertilized monocultures. It was expected that these integrated systems would improve soil chemical properties such as pH stabilization and nutrient retention capacity – and enhance water-holding potential, thereby increasing nutrient uptake efficiency by crops. The results confirm that diversified cropping, particularly when coupled with farmyard manure and liming, can mitigate nutrient losses to the environment by promoting tighter nutrient cycling and improving soil physical and biological functioning (Gleń-Karolczyk et al., 2018). These findings underscore the importance of integrated nutrient management as a tool not only for enhancing agronomic performance, but also for advancing the ecological sustainability and resilience of temperate agroecosystems.

MATERIALS AND METHODOLOGY

Wheather conditions, soil, water, plant analysis

The study on nitrogen and phosphorus uptake, as well as water and nutrient fluxes within the soil profile, was conducted during the 2024 growing season at the long-term Experimental Station of the Institute of Agriculture, Warsaw University of Life Sciences, located in Skierniewice, Poland (51.965071°N, 20.159540°E). Meteorological data, including daily air temperature and precipitation, were recorded throughout the vegetation period using an on-site automatic weather station. The experimental plots were established on Luvisol-type soil WRB (IUSS 2015), where various fertilization regimes have been continuously applied since 1923. The treatments included: Ca (liming only), Ca+FYM (liming with farmyard manure), NPK (mineral fertilization), and CaNPK (combined liming and mineral fertilization). Mineral fertilizers were applied at rates of 90 kg N·ha^{-1} (as ammonium nitrate), 26 kg P·ha^{-1} (as triple superphosphate), and 91 kg K·ha^{-1} (as potassium chloride). Liming was carried out every four years using calcium carbonate ($CaCO_3$) at a rate of 1.6 t CaO·ha^{-1} (average Ca dose: 285 kg·ha^{-1}). Farmyard manure (FYM) was applied only in the Ca+FYM treatment at a rate of 20 t·ha^{-1} annually.

- Fertilization regimes were evaluated across three cropping systems:
- A-system: arbitrary rotation without legumes and without FYM (A-NPK, A-CaNPK),
- D-system: continuous rye monoculture (D-Ca+FYM, D-CaNPK),
- E-system: five-field rotation including legumes, with FYM applied every five years (E-Ca, E-NPK, E-CaNPK).

Each treatment plot measured 36 m² and was replicated three times. Soil water was sampled during the growing season using a lysimetric drainage system, with PVC collection pipes installed at 120 cm depth to capture percolating water. The volume of drained water was recorded volumetrically at each sampling date. The soil texture consisted of 15–17% fine fractions in the arable layer (Ap, 0–25 cm), 10–12% in the Eet horizon (26–45 cm), and 25% in the Bt horizon (46–65 cm), as determined according to ISO 11277 (2009). Soil pH was measured potentiometrically in 1M KCl using an automatic pH meter (Schott, Mainz, Germany, type GC 842) (ISO 10390: 2005), and available nitrogen and phosphorus were determined using the Polish extraction method (PN-R-04020:1994) and Mehlich-3 method, respectively (Mehlich, 1984). Mineral nitrogen concentrations in soil and soil water were measured using a continuous flow analyser (CFA AA500 AutoAnalyser, SEAL Instruments, The Netherlands), with a cadmium reduction column for nitrate (NO_3^-) determination. Total nitrogen in grain and straw was determined by the Kjeldahl method (ISO11261: 1995), and total phosphorus was measured colorimetrically using the vanadomolybdate method and a UV-VIS spectrophotometer (Genesys 10S, Thermo Scientific, USA). Certified reference materials (CRM) were not used in the chemical analyses due to technical and logistical limitations. However, the accuracy and reliability of the analytical results were ensured through regular calibration of the instruments using laboratory-prepared standard solutions and routine analysis of control samples. Analytical precision was verified by performing duplicate measurements, and results were subject to internal quality control procedures.

Statystical analysis

Statistical analysis was performed using Statistica 13.3 software (StatSoft Inc., USA). A one-way analysis of variance (ANOVA) was conducted, followed by Tukey's post hoc test ($p < 0.05$), to assess differences between mineral and mineral-organic fertilization treatments, as well as across sampling time points. Statistically significant differences were indicated using letter notations. Additionally, Pearson correlation analysis was used to examine relationships between soil water outflow, nutrient concentrations in leachate ($N\text{-}NH_4^+$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$), and total nutrient efflux. Multivariate linear regression was applied to identify predictor variables influencing total nitrogen and phosphorus uptake, with statistical significance set at $p < 0.05$. The analysis included data from seven fertilization treatments, each replicated three times.

RESULTS

Wheather conditions in vegetation season

Air temperature and rainfall

The 2024 vegetation season was characterized by distinct meteorological gradients that substantially influenced hydrological conditions within the agroecosystem (Figure 1). In early spring (March), mean daily air temperatures remained low (5.9–6.5 °C), accompanied by moderate cumulative rainfall events of 21.2 mm and 14.0 mm on March 12 and 29, respectively. These precipitation inputs, coinciding with minimal evapotranspiration, created favorable conditions for deep water percolation.

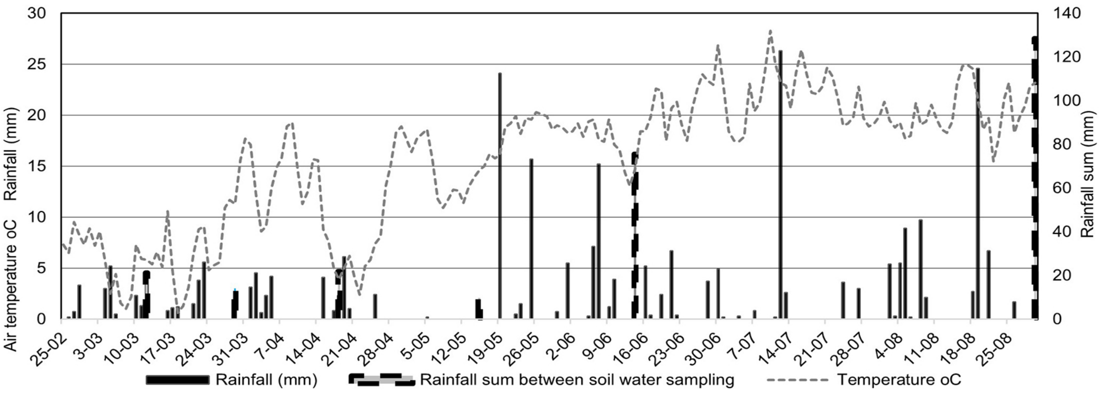

Figure 1. Wheater conditions throughout vegetation season, including daily air temperature, rainfalls, rainal sum in soil water sampling events

As the season progressed, temperatures increased steadily. During the period from April 3 to 18, daily maximum temperatures reached up to 18.9 °C, with a mean of 12.9 °C. Total rainfall in April amounted to 21.9 mm, mostly derived from isolated events (e.g., 6.1 mm on April 19 and 4.5 mm on April 2), indicating an overall dry pattern. By mid-May (May 15), the average temperature was 12.1 °C, while cumulative precipitation decreased to 9.7 mm, limiting soil moisture availability and percolation potential. In June, climatic conditions shifted, with a rise in mean temperature to 18.0 °C (June 14) and a substantial increase in precipitation (75.7 mm), including significant rainfall events of 15.2 mm (June 7) and 7.1 mm (June 6). This combination led to enhanced leaching potential due to saturated soil conditions and increased water fluxes. July, in contrast, was marked by persistently high temperatures, frequently exceeding 25 °C, and very low rainfall (< 5 mm), reflecting peak evaporative demand and limited leaching risk. By late August, total accumulated precipitation reached 128.5 mm (August 30), with major contributions from rainfall events on August 19 (24.6 mm) and August 8 (9.7 mm). Despite the relatively high rainfall, deep percolation remained limited during this period, likely due to dense crop canopies and high transpiration rates. Overall, the season exhibited a clear transition from early cool and moderately wet conditions—conducive to drainage and nutrient leaching—to later warmer, drier phases with increased evapotranspiration and improved water-use efficiency. These temporal climatic dynamics highlight the importance of integrating seasonal weather variability into agro-hydrological assessments and nutrient loss risk evaluations.

Soil water outflow dynamics in vegetation season

Soil water leaching throughout the growing season was predominantly influenced by fluctuations in air temperature, precipitation patterns, and fertilization regimes. During early spring (mean air temperatures of 5.9–6.5 °C; rainfall events totaling 21.2–14.0 mm), substantial leachate volumes were observed under mineral fertilization, particularly in the A-NPK treatment (up to 4.00 mm). This was attributed to low evapotranspiration rates and limited crop water and nutrient uptake at early phenological stages (Figure 2). As the season advanced into mid-spring (approximately 12 °C), with rainfall remaining moderate (21.9–9.7 mm), leaching rates declined considerably – especially in plots receiving calcium or organic amendments (e.g., D-CaNPK). This reduction likely resulted from improved soil structure and more effective root uptake associated with advanced vegetative growth and increased biological activity. Despite a pronounced increase in rainfall during early summer (75.7 mm, 18.0 °C), leachate volumes remained minimal (maximum 0.53 mm), indicating that higher evapotranspiration rates and deeper rooting systems effectively limited drainage losses. In late summer (mean temperature 21.1 °C; precipitation 128.5 mm), leaching remained very low (< 0.36 mm), likely due to peak crop water use and full canopy development, which maximized transpiration and minimized percolation. Importantly, the proportion of rainfall lost as leachate was highest in early spring (e.g., 29% under A-NPK) and decreased to negligible levels later in the season. This pattern underscores the dominant role of plant phenology and atmospheric demand over

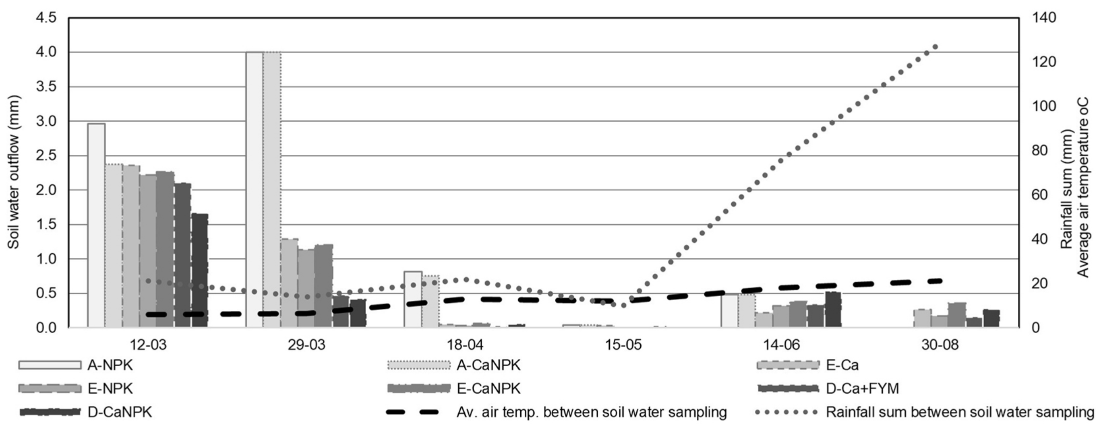

Figure 2. Soil water outflow during the vegetation season, average air temperature, and rainfall sum between soil water sampling events

rainfall volume in regulating water movement through the soil profile.

Overall, fertilization strategies that included calcium or organic matter consistently reduced leachate volumes, enhancing soil water retention and nutrient conservation. These findings highlight the necessity of adaptive, climate-responsive nutrient and water management strategies to mitigate nutrient losses and promote sustainable agricultural practices.

Soil water chemical composition and nutrients efflux

Ammonium nitrogen (N-NH$_4$)

Ammonium nitrogen (N-NH$_4^+$) concentrations and efflux exhibited substantial temporal variation and were strongly influenced by fertilization treatments. In March, initial concentrations were relatively low, averaging 0.26 mg N-NH$_4$·dm^{-3}, with a corresponding efflux of 2.67 g N-NH$_4$·ha^{-1} (Figure 3). By April 18, N-NH$_4^+$ concentrations increased markedly, reaching an average of 5.36 mg N-NH$_4$·dm^{-3}. The highest levels were observed in the A-CaNPK (10.71 mg N-NH$_4$·dm^{-3}) and E-CaNPK (15.95 mg N-NH$_4$·dm^{-3}) treatments, indicating significant ammonium mobilization following spring fertilization events.

Although elevated concentrations persisted into May, ammonium outflow was limited to 1.18 g N-NH$_4$·ha^{-1}, likely due to reduced drainage and higher plant uptake during this period. The maximum N-NH$_4^+$ efflux was recorded in late June (5.44 g N-NH$_4$·ha^{-1}), coinciding with heavy precipitation and increased percolation rates, particularly in treatments such as E-CaNPK and D-CaNPK.

These observations underscore the pronounced effect of mineral fertilization (NPK) and liming (Ca) on ammonium dynamics in the soil profile, especially under conditions of increased soil moisture. The interaction between fertilization type and hydrological flux plays a critical role in regulating the temporal patterns of ammonium leaching.

Nitrate nitrogen (N-NO$_3$)

Nitrate nitrogen (N-NO$_3^-$) exhibited the highest concentrations among all monitored nutrient forms. Peak concentrations were recorded in mid-May, averaging 22.21 mg N-NO$_3$·dm^{-3} across all treatments, with the maximum value observed in the A-NPK variant (38.83 mg N-NO$_3$·dm^{-3}) (Figure 4).

This peak likely reflects the combined effects of spring mineral fertilization and limited early crop uptake. A pronounced decline was observed in June, with average concentrations falling to 4.71 mg N-NO$_3$·dm^{-3}, followed by relatively stable levels throughout late summer. The highest recorded nitrate concentration (38.83 mg N-NO$_3$·dm^{-3}) corresponds to approximately 172 mg NO$_3^-$·L^{-1}, which substantially exceeds the World Health Organization (WHO) and European Union limit for nitrate in drinking water and groundwater (50 mg NO$_3^-$·L^{-1}; Directive 91/676/EEC). Although the measurements were conducted on soil water at 120 cm depth, this result indicates a significant potential for nitrate leaching into deeper soil layers and possibly groundwater, particularly under early spring conditions following fertilization. In contrast, seasonal averages (e.g., 22.21 mg N-NO$_3$·dm^{-3} ≈ 98.4 mg NO$_3^-$·L^{-1}) remained above but closer to regulatory thresholds.

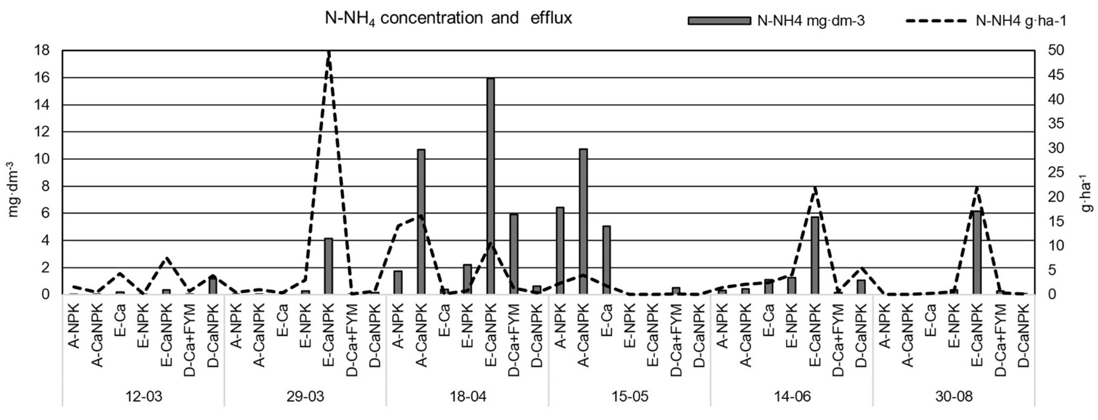

Figure 3. Effect of cropping and fertilization system on ammonium nitrogen (N-NH$_4$) concentration in soil water and ammonium nitrogen efflux from the soil profile through the growing season

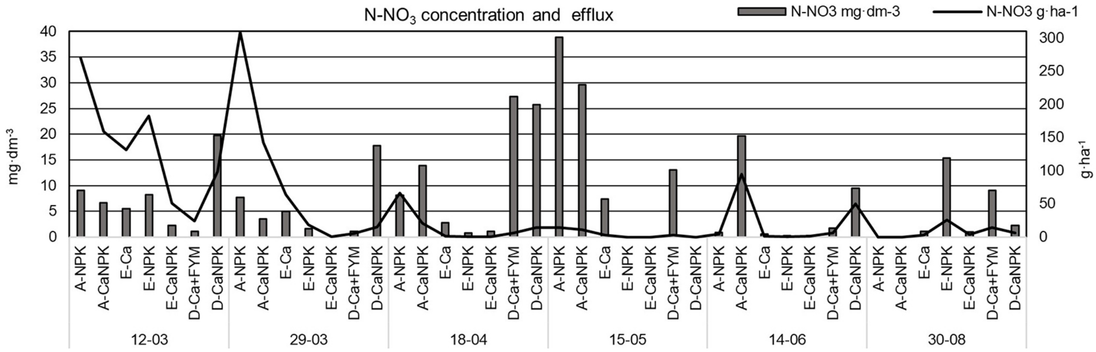

Figure 4. Effect of tillage and fertilization system on nitrate nitrogen ($N\text{-}NO_3$) concentration in soil water and nitrate nitrogen efflux from the soil profile through the growing season

In terms of nitrate outflow, the highest export occurred on March 12, reaching 131 g $N\text{-}NO_3 \cdot ha^{-1}$, particularly in treatments receiving intensive mineral fertilization such as A-NPK and D-CaNPK. This period coincided with low evapotranspiration and high percolation potential. Substantial reductions in nitrate leaching were observed in April and May, with outflow values decreasing to 15.67 and 4.46 g $N\text{-}NO_3 \cdot ha^{-1}$, respectively—likely due to improved plant uptake and reduced drainage. During July and August, nitrate concentrations and efflux remained relatively low, though moderate leaching was still recorded in selected treatments (e.g., E-NPK, D-CaNPK). These findings emphasize the critical importance of aligning nitrogen application timing with crop demand and suggest that integrating organic amendments, such as farmyard manure (FYM), may reduce nitrate mobility and mitigate leaching risk during vulnerable periods.

Phosphorus ($P\text{-}PO_4$)

Phosphate phosphorus ($P\text{-}PO_4^{3-}$) concentrations in soil water increased progressively over the course of the sampling period. The lowest average concentrations were recorded in March (0.51 $mg \cdot dm^{-3}$), with values ranging from 0.12 mg $P\text{-}PO_4 \cdot dm^{-3}$ in A-NPK to 1.37 mg $P\text{-}PO_4 \cdot dm^{-3}$ in E-CaNPK (Figure 5). A marked rise was observed by June, with mean concentrations reaching 2.59 $mg \cdot dm^{-3}$, ranging from 0.69 mg $P\text{-}PO_4 \cdot dm^{-3}$ in E-Ca to 7.13 mg $P\text{-}PO_4 \cdot dm^{-3}$ in E-CaNPK. This upward trend continued into August, with an average concentration of 3.34 mg $P\text{-}PO_4 \cdot dm^{-3}$ and a range from 1.65 mg $P\text{-}PO_4 \cdot dm^{-3}$ (D-CaNPK) to 7.03 mg $P\text{-}PO_4 \cdot dm^{-3}$ (E-CaNPK). The increase in phosphate levels was likely driven by the cumulative effects of phosphorus fertilization, soil saturation, and reduced plant uptake in the latter part of the season.

Phosphorus outflow exhibited a similar pattern. Although runoff volumes decreased over time, cumulative $P\text{-}PO_4^{3-}$ losses remained substantial: 10.77 g $P\text{-}PO_4 \cdot ha^{-1}$ in March, 10.60 g $P\text{-}PO_4 \cdot ha^{-1}$ in June, and 6.26 g $P\text{-}PO_4 \cdot ha^{-1}$ in August. Among the treatments, E-CaNPK consistently resulted in the highest phosphorus efflux, with cumulative losses frequently exceeding 25 g $P\text{-}PO_4 \cdot ha^{-1}$. In contrast, the organic-amended treatment (D-Ca+-FYM) and the unfertilized control plots maintained

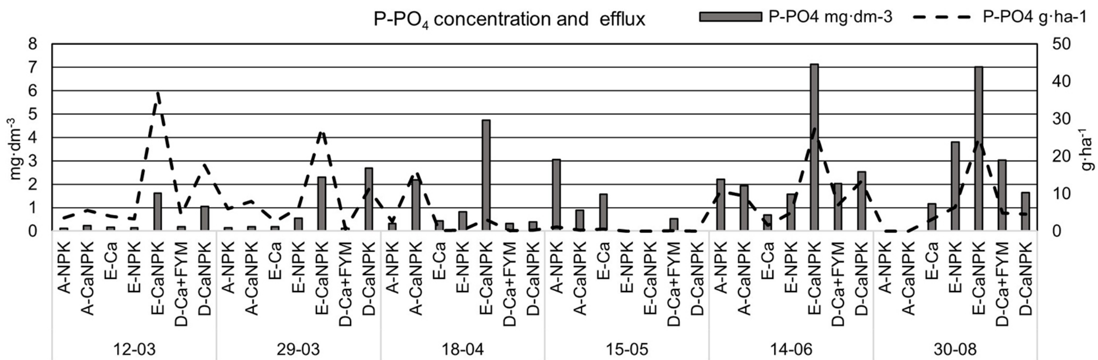

Figure 5. Effect of cropping and fertilization system on phosphorus ($P\text{-}PO_4$) concentration in soil water and phosphorus efflux from the soil profile through the growing season

considerably lower concentrations and outflows. These findings emphasize the strong influence of phosphorus input intensity and soil saturation status on phosphate leaching potential, particularly under combined liming and mineral fertilization regimes. The data underscore the need for carefully balanced P management strategies to mitigate environmental risks associated with phosphorus loss in agroecosystems.

Total soil water outflow and nutrients underground flux

The cumulative outflow of soil water and associated nutrient losses during the study period varied significantly depending on the fertilization treatments applied. The greatest total water outflow was recorded under the A-NPK treatment (82.96 $m^3 \cdot ha^{-1}$), followed by A-CaNPK (76.44 $m^3 \cdot ha^{-1}$), both of which received intensive mineral NPK fertilization (Table 1). In contrast, treatments incorporating organic amendments or integrated fertilization, such as D-CaNPK (29.39 $m^3 \cdot ha^{-1}$) and D-Ca+FYM (31.33 $m^3 \cdot ha^{-1}$), exhibited substantially lower water losses. These reductions likely reflect improved soil aggregation, increased water-holding capacity, and reduced nutrient solubility attributable to organic matter additions and long-term soil conditioning. In terms of nutrient efflux, the A-NPK treatment resulted in the highest cumulative nitrate ($N\text{-}NO_3^-$) losses (664.41 g $N\text{-}NO_3 \cdot ha^{-1}$), underscoring the leaching risk associated with high mineral nitrogen inputs.

Elevated nitrate losses were also observed in A-CaNPK (428.04 g $N\text{-}NO_3 \cdot ha^{-1}$) and E-NPK (228.26 g $N\text{-}NO_3 \cdot ha^{-1}$), highlighting the consistent influence of mineral fertilization intensity. Conversely, the lowest nitrate effluxes were recorded in D-Ca+FYM (59.09 g $N\text{-}NO_3 \cdot ha^{-1}$) and E-CaNPK (57.07 g $N\text{-}NO_3 \cdot ha^{-1}$). Interestingly, despite its low nitrate leaching, E-CaNPK exhibited the highest ammonium ($N\text{-}NH_4^+$) outflow (111.88 g $N\text{-}NH_4 \cdot ha^{-1}$), potentially due to the interaction between liming (Ca) and altered microbial nitrogen transformations in the soil profile. Phosphate ($P\text{-}PO_4^{3-}$) losses were most pronounced in the E-CaNPK treatment (120.17 g $P\text{-}PO_4 \cdot ha^{-1}$), suggesting enhanced phosphorus mobilization under combined liming and mineral fertilization. Substantial P outflows were also observed in D-CaNPK (46.98 g $P\text{-}PO_4 \cdot ha^{-1}$) and A-CaNPK (39.84 g $P\text{-}PO_4 \cdot ha^{-1}$), indicating a compounded effect of phosphorus inputs and elevated soil pH on phosphorus solubility and transport. Overall, fertilization regimes that included organic matter (FYM) and calcium amendments consistently resulted in reduced nutrient losses, highlighting their potential to enhance nutrient retention, mitigate environmental impacts, and support more sustainable nutrient management in agricultural systems.

The correlations between soil water amount outflow and chemical properties

The correlation matrix illustrates the relationships between soil water outflow and nutrient concentrations ($N\text{-}NH_4$, $N\text{-}NO_3$, $P\text{-}PO_4$) as well as total nutrient fluxes ($g \cdot ha^{-1}$) (Table 2). Strong positive correlations were observed between nutrient concentrations: $N\text{-}NH_4$ and $P\text{-}PO_4$ (r = 0.996), $N\text{-}NH_4$ and $N\text{-}NO_3$ (r = 0.960), and $N\text{-}NO_3$ and $P\text{-}PO_4$ (r = 0.956), indicating that increases in one nutrient are closely associated with increases in the others. In contrast, these concentrations negatively correlated with the corresponding nutrient fluxes, suggesting an inverse relationship between concentration and total nutrient loss.

Notably, soil water outflow exhibited a strong positive correlation with $N\text{-}NO_3$ flux (r = 0.857), implying that nitrate losses are particularly sensitive to water movement through the soil. These findings emphasize the interconnectedness of

Table 1. Effect of cropping system and fertilization on total soil water outflow and nutrients efflux

Treatments	Soil water outflow $m^3 \cdot ha^{-1}$	Nutrients efflux with soil water $g \cdot ha^{-1}$		
		$N\text{-}NH_4$	$N\text{-}NO_3$	$P\text{-}PO_4$
A-NPK	82.96	19.89	664.41	23.94
A-CaNPK	76.44	23.88	428.04	39.84
E-Ca	42.13	9.32	203.54	11.98
E-NPK	38.80	8.62	228.26	21.37
E-CaNPK	42.71	111.88	57.07	120.17
D-Ca+FYM	31.33	3.28	59.09	16.83
D-CaNPK	29.39	10.62	184.49	46.98

Table 2. Matrix of pearson correlations among soil water outflow, nutrient concentrations, and nutrient losses

Parameter	mg $N\text{-}NH_4 \cdot dm^{-3}$	mg $N\text{-}NO_3 \cdot dm^{-3}$	mg $P\text{-}PO_4 \cdot dm^{-3}$	g $N\text{-}NH_4 \cdot ha^{-1}$	g $N\text{-}NO_3 \cdot ha^{-1}$	g $P\text{-}PO_4 \cdot ha^{-1}$
Soil water outflow $m^3 \cdot ha^{-1}$	-0.313*	-0.323*	-0.298	0.015	0.857*	0.247
mg $N\text{-}NH_4 \cdot dm^{-3}$	-	0.960*	0.996*	-0.140	-0.251	-0.273
mg $N\text{-}NO_3 \cdot dm^{-3}$	0.960*	-	0.956*	-0.234	-0.202	-0.336*
mg $P\text{-}PO_4 \cdot dm^{-3}$	0.996*	0.956*	-	-0.159	-0.239	-0.258
g $N\text{-}NH_4 \cdot ha^{-1}$	-0.140	-0.234	-0.159	-	-0.141	0.668*
g $N\text{-}NO_3 \cdot ha^{-1}$	-0.251	-0.202	-0.239	-0.141	-	0.022
g $P\text{-}PO_4 \cdot ha^{-1}$	-0.273	-0.336*	-0.258	0.668*	0.022	-

Note: *- values are significantly correlated with each other at a significance level of $p < 0.05$.

nutrient forms and their transport dynamics under varying hydrological conditions.

Soil chemical properties

Soil pH

The effects of cropping systems and fertilization strategies on soil pH were assessed across three depth intervals, using the E-Ca treatment as a reference (100%) for relative comparisons. In the topsoil (0–25 cm), the highest pH values occurred under D-CaNPK (7.13), A-CaNPK (7.07), and D-Ca+FYM (7.03), highlighting the effectiveness of liming combined with mineral or organic fertilization in counteracting surface acidity (Table 3). In contrast, A-NPK recorded the lowest pH (5.92), illustrating the acidifying effect of mineral fertilization in monocultures. Similar trends were observed at 25–50 cm, with elevated pH under D-CaNPK (6.66) and A-CaNPK (6.60), and the highest pH in E-CaNPK (6.68), suggesting a buffering effect of legume rotations integrated with liming and mineral inputs. At 50–75 cm, the highest pH was found in D-Ca+FYM (6.82), reflecting the cumulative benefits of organic matter on subsoil chemistry. In contrast, the E-Ca treatment showed the lowest pH (4.64), indicating that liming alone, without nutrient supplementation, may be inadequate for sustaining subsoil pH over time.

Collectively, these findings highlight the importance of integrated fertilization strategies – particularly the combination of liming, organic inputs, and crop diversification – in maintaining optimal soil pH throughout the soil profile and mitigating acidification risks in intensive agricultural systems.

Available ammonium nitrogen ($N\text{-}NH_4$) in soil profile

The impact of cropping systems and fertilization strategies on the concentration of available ammonium nitrogen ($N\text{-}NH_4^+$) was evaluated across three soil depths. The E-Ca treatment was used as the reference baseline (100%) for relative comparison. In the surface layer (0–25 cm), the highest concentration of ammonium nitrogen was recorded under the A-CaNPK treatment (28.38 $mg \cdot kg^{-1}$; 217%), followed by A-NPK (23.66 mg $N\text{-}NH_4 \cdot kg^{-1}$; 181%) and D-Ca+FYM (22.76 mg $N\text{-}NH_4 \cdot kg^{-1}$; 174%) (Table 4). The E-Ca variant exhibited the lowest concentration (13.04 mg $N\text{-}NH_4 \cdot kg^{-1}$; 100%). At 25–50 cm depth, A-CaNPK again presented the highest ammonium N

Table 3. Effect of cropping and fertilization system on soil pH in three layers of soil profile

Treatment	0–25 cm	Relative value%	25–50 cm	Relative value%	50–75 cm	Relative value%
	Soil pH					
E-Ca	6.19	100	5.47	100	4.64	100
D-Ca+FYM	7.03	113	6.61	121	6.82	147
A-NPK	5.92	96	4.48	82	5.03	108
E-NPK	6.06	98	5.08	93	5.39	116
A-CaNPK	7.07	114	6.60	121	6.45	139
D-CaNPK	7.13	115	6.66	122	6.41	138
E-CaNPK	6.40	103	6.68	122	6.26	135

Table 4. Effect of cropping and fertilization system on available ammonium nitrogen status in soil profile

Treatment	0–25 cm	Relative value%	25–50 cm	Relative value%	50–75 cm	Relative value%
	Soil available $N\text{-}NH_4$ $mg\cdot kg^{-1}$					
E-Ca	13.04 a*	100	16.72 ab	100	13.60 a	100
D-Ca+FYM	22.76 b	174	16.12 a	96	12.60 a	93
A-NPK	23.66 bc	181	22.88 ab	137	47.07 c	345
E-NPK	15.48 a	118	15.88 a	95	12.97 a	95
A-CaNPK	28.38 c	217	25.50 b	152	29.23 b	214
D-CaNPK	16.77 a	128	17.21 ab	102	16.55 a	121
E-CaNPK	14.61 a	112	16.80 ab	100	11.61 a	85
Average	19.2 A**		18.7 A		20.5 A	

Note: * values marked with the same lowercase letter in the columns are not significantly different from each other at α=0.05; ** values marked with the same capital letter in the row do not differ significantly at α=0.05.

content (25.50 $mg\cdot kg^{-1}$; 152%), with A-NPK close behind (22.88 mg $N\text{-}NH_4\cdot kg^{-1}$; 137%). In contrast, the lowest concentrations were observed in E-NPK (15.88 mg $N\text{-}NH_4\cdot kg^{-1}$; 95%) and E-Ca (16.72 mg $N\text{-}NH_4\cdot kg^{-1}$; 100%). In the deepest layer (50–75 cm), the highest accumulation occurred under A-NPK (47.07 mg $N\text{-}NH_4\cdot kg^{-1}$; 345%), followed by A-CaNPK (29.23 mg $N\text{-}NH_4\cdot kg^{-1}$; 214%). The lowest values were recorded in E-Ca (13.60 mg $N\text{-}NH_4\cdot kg^{-1}$; 100%) and E-CaNPK (11.61 mg $N\text{-}NH_4\cdot kg^{-1}$; 85%).

Overall, the A system – particularly under combined mineral fertilization and liming (A-CaNPK) or mineral fertilization alone (A-NPK) – was associated with the highest ammonium nitrogen accumulation throughout the soil profile. The monoculture system (D) showed moderate enhancement, while the rotation system including legumes (E) consistently demonstrated lower $N\text{-}NH_4^+$ concentrations, suggesting enhanced nitrogen turnover or increased plant uptake. These findings indicate that mineral fertilization, especially when coupled with liming, significantly elevates ammonium nitrogen availability, particularly in systems lacking biological nitrogen regulation through legumes or organic matter.

Available nitrate nitrogen ($N\text{-}NO_3$) in soil profile

The influence of cropping systems and fertilization strategies on the distribution of available nitrate nitrogen ($N\text{-}NO_3^-$) across three soil depths revealed significant differences among treatments (Table 5). In the surface layer (0–25 cm), the highest nitrate concentrations were observed in A-CaNPK (60.87 mg $N\text{-}NO_3\cdot kg^{-1}$; 214%) and E-NPK (44.04 mg $N\text{-}NO_3\cdot kg^{-1}$; 155%), reflecting the strong impact of intensive mineral fertilization. In contrast, the lowest concentrations were recorded in D-CaNPK (8.73 mg $N\text{-}NO_3\cdot kg^{-1}$; 31%) and E-CaNPK (9.10 mg $N\text{-}NO_3\cdot kg^{-1}$; 32%), suggesting enhanced nitrogen utilization or reduced mineralization in these systems.

Table 5. Effect of cropping and fertilization system on available nitrate nitrogen status in soil profile

Treatment	0–25 cm	Relative value%	25–50 cm	Relative value%	50–75 cm	Relative value%
	Soil available mg $N\text{-}NO_3\cdot kg^{-1}$					
E-Ca	28.42 ab	100	6.59 a	100	10.03 a	100
D-Ca+FYM	14.16 a	50	12.90 ab	196	6.51 a	65
A-NPK	26.11 a	91	21.18 b	322	45.55 c	454
E-NPK	44.04 bc	155	14.09 ab	214	12.17 a	121
A-CaNPK	60.87 c	214	46.55 b	706	25.78 b	257
D-CaNPK	8.73 a	31	16.94 ab	257	24.83 b	247
E-CaNPK	9.10 a	32	46.14 b	700	9.66 a	96
Average	27.3 B		23.5 AB		19.2 A	

Note: * values marked with the same lowercase letter in the columns are not significantly different from each other at α=0.05; ** values marked with the same capital letter in the row do not differ significantly at α=0.05.

At 25–50 cm depth, A-CaNPK and E-CaNPK again exhibited the highest nitrate levels (46.55 mg $N\text{-}NO_3 \cdot kg^{-1}$; 706% and 46.14 mg $N\text{-}NO_3 \cdot kg^{-1}$; 700%, respectively), whereas E-Ca (6.59 mg $N\text{-}NO_3 \cdot kg^{-1}$; 100%) and D-Ca+FYM (12.90 mg $N\text{-}NO_3 \cdot kg^{-1}$; 196%) recorded the lowest concentrations. The strikingly high values in A and E variants with mineral inputs reflect downward nitrate movement and limited plant uptake during the early growing period. In the subsoil layer (50–75 cm), nitrate accumulation was greatest in A-NPK (45.55 mg $N\text{-}NO_3 \cdot kg^{-1}$; 454%), followed by A-CaNPK (25.78 mg $N\text{-}NO_3 \cdot kg^{-1}$; 257%) and D-CaNPK (24.83 mg $N\text{-}NO_3 \cdot kg^{-1}$; 247%). The lowest values were measured in E-Ca (10.03 mg $N\text{-}NO_3 \cdot kg^{-1}$; 100%) and E-CaNPK (9.66 mg $N\text{-}NO_3 \cdot kg^{-1}$; 96%), indicating restricted nitrate leaching and greater stabilization in the diversified E system. Overall, the arbitrary cropping system (A), particularly under NPK and CaNPK regimes, was associated with substantial nitrate accumulation throughout the soil profile. In contrast, the legume-based rotation (E) consistently maintained lower nitrate concentrations, particularly under liming alone (E-Ca). These findings highlight the role of crop diversification and reduced mineral input intensity in minimizing nitrate accumulation and potential leaching, reinforcing the importance of integrative nutrient management for environmental protection and soil health.

Available phosphate ($P\text{-}PO_4$) in soil profile

The distribution of available phosphorus ($P\text{-}PO_4^{3-}$) across three soil depths (0–25, 25–50, and 50–75 cm) varied notably depending on the cropping system and fertilization regime (Table 6). In the surface layer (0–25 cm), the highest phosphorus concentrations were observed in A-CaNPK (115.25 mg $P\text{-}PO_4 \cdot kg^{-1}$; 125%) and E-NPK (108.75 mg $P\text{-}PO_4 \cdot kg^{-1}$; 118%), indicating strong phosphorus enrichment under intensive mineral fertilization. In contrast, the lowest value was recorded in D-CaNPK (63.50 mg $P\text{-}PO_4 \cdot kg^{-1}$; 69%), suggesting limited phosphorus mobility or availability under continuous monoculture with combined liming and mineral inputs. At 25–50 cm depth, phosphorus levels remained elevated in E-NPK (42.88 mg $P\text{-}PO_4 \cdot kg^{-1}$; 129%) and A-CaNPK (31.25 mg $P\text{-}PO_4 \cdot kg^{-1}$; 94%). Lower concentrations were found in E-CaNPK (18.50 mg $P\text{-}PO_4 \cdot kg^{-1}$; 56%) and A-NPK (20.40 mg $P\text{-}PO_4 \cdot kg^{-1}$; 61%), indicating greater vertical phosphorus retention in systems combining organic inputs or more diverse rotations.

In the deepest layer (50–75 cm), the highest values were again recorded under A-CaNPK (17.88 mg $P\text{-}PO_4 \cdot kg^{-1}$; 61%) and E-NPK (15.63 mg $P\text{-}PO_4 \cdot kg^{-1}$; 53%), while the lowest concentrations occurred in E-CaNPK (8.00 mg $P\text{-}PO_4 \cdot kg^{-1}$; 27%) and A-NPK (12.63 mg $P\text{-}PO_4 \cdot kg^{-1}$; 43%).

Phosphorus content in soil, determined using the Mehlich-3 method, was evaluated against agronomic classification thresholds used in Polish fertilizer advisory systems (Kęsik, 2016). The values in upper layer corresponded to the low (E-Ca) to very high class (A-CaNPK) for slightly acidic-neutral soils (pH 5.6–7.2). In a plot (notably A-CaNPK), values exceeded 115 mg $P \cdot kg^{-1}$, which is considered an environmental risk threshold. Overall, phosphorus availability was most enhanced in A and E systems subjected to intensive mineral fertilization, particularly A-CaNPK and E-NPK. Conversely, the D system—especially under Ca or CaNPK treatments—was

Table 6. Effect of cropping and fertilization system on available phosphorus (Mehlich 3) status in soil profile

Treatment	0–25 cm	Relative value%	25–50 cm	Relative value%	50–75 cm	Relative value%
	Soil available mg $P\text{-}PO_4 \cdot kg^{-1}$					
E-Ca	91.63 bcd	100	33.13 ab	100	29.13 b	100
D-Ca+FYM	74.00 ab	81	28.88 ab	87	15.38 a	53
A-NPK	78.00 abc	85	20.40 a	61	12.63 a	43
E-NPK	108.75 d	118	42.88 b	129	15.63 a	53
A-CaNPK	115.25 d	125	31.25 ab	94	17.88 a	61
D-CaNPK	63.50 a	69	27.50 ab	83	15.38 a	53
E-CaNPK	99.00 cd	108	18.50 a	56	8.00 a	27
Average	90.0 C		28.9 B		16.3 A	

Note: * values marked with the same lowercase letter in the columns are not significantly different from each other at α=0.05; ** values marked with the same capital letter in the row do not differ significantly at α=0.05.

associated with consistently lower phosphorus concentrations throughout the soil profile. These results suggest that diversified crop rotations and targeted nutrient management enhance phosphorus availability, while continuous monoculture without organic amendments restricts phosphorus mobility and limits long-term soil P enrichment.

Plant chemical composition and nutrients uptake

Content of N and P in grains and straw

The influence of cropping systems and fertilization strategies on nitrogen (N) and phosphorus (P) content in grain and straw revealed substantial treatment-dependent variation (Table 7).

Grain nitrogen content peaked in systems combining mineral fertilization with liming, particularly A-CaNPK (above 17 g N·kg^{-1}). Similar, though slightly lower, values were observed in A-NPK and E-NPK (around 15–16 g N·kg^{-1}). The lowest concentrations occurred in FYM-amended monocultures (D-Ca+FYM, D-CaNPK), with values near 12 g N·kg^{-1}, likely due to slower organic N release. Grain phosphorus content varied less across treatments, generally ranging from 2.5 to 3.3 g P·kg^{-1}, with A-CaNPK reaching the upper end. Liming combined with P fertilization likely enhanced P uptake under improved soil pH.

Straw nitrogen content followed a similar trend, but differences were more pronounced. High-input mineral systems (A-CaNPK, A-NPK) showed values above 4.5 g N·kg^{-1}, more than four times higher than in low-input systems like E-Ca. Straw in D-Ca+FYM also had elevated N levels (around 3.8 g N·kg^{-1}), indicating delayed nitrogen release from FYM favoring vegetative growth.

Straw phosphorus concentrations were highest in FYM and limed treatments, exceeding 1.0 g P·kg^{-1} in D-Ca+FYM and E-Ca, and lowest (below 0.4 g P·kg^{-1}) in mineral-only A-system plots. This suggests greater P allocation to structural tissues under organic management. This pattern suggests a delayed release and preferential allocation of nutrients to vegetative tissues under organic fertilization.

In summary, mineral fertilization increased grain nutrient content, while integrated systems, especially with FYM and legumes, promoted more balanced nutrient distribution. This balance may enhance nutrient recycling through straw and improve long-term soil fertility.

Uptake of N and P and distribution of both elements in grains and straw

The impact of cropping systems and fertilization regimes on nitrogen (N) and phosphorus (P) uptake by grain and straw (kg·ha^{-1}) revealed distinct patterns across treatments (Table 8). Grain nitrogen uptake reached maximum values in legume-based systems, particularly E-CaNPK and E-NPK, exceeding 115 kg N·ha^{-1}. These values were more than four times higher than those observed in A-NPK (approximately 27 kg N·ha^{-1}). A similar trend was evident for phosphorus: E-CaNPK reached over 20 kg P·ha^{-1} in grain, while A-NPK remained below 5 kg P·ha^{-1}. Straw nutrient uptake followed the same pattern. In E-CaNPK, straw N and P uptakes exceeded 25 kg N·ha^{-1} and 3.7 kg P·ha^{-1}, respectively—several times greater than in unfertilized or mineral-only systems. Notably, in D-Ca+FYM, FYM increased straw N accumulation, although grain uptake remained low, suggesting delayed nutrient

Table 7. Effect of cropping system and fertilization on nitrogen and phosphorus content in grain and straw (in dry mass)

Treatment	g N·kg^{-1}	Relative value%	g P·kg^{-1}	Relative value%	g N·kg^{-1}	Relative value%	g P·kg^{-1}	Relative value%
	Grain content				Straw content			
E-Ca	14.25 b	100	2.93 a	100	1.06 a	100	0.78 c	100
D-Ca+FYM	12.31 a	86	2.57 a	88	3.81 bcd	359	1.06 d	136
A-NPK	15.79 c	111	2.78 a	95	4.72 cd	443	0.38 a	49
E-NPK	15.37 c	108	2.53 a	87	2.91 b	274	0.53 ab	68
A-CaNPK	17.70 d	124	3.27 a	112	5.06 d	476	0.37 a	47
D-CaNPK	12.26 a	86	2.97 a	102	3.40 bc	320	0.68 bc	88
E-CaNPK	15.26 c	107	2.64 a	90	3.74 bcd	351	0.56 abc	72
Average	14.71		2.81		3.53		0.62	

Note: * values marked with the same letter in the columns are not significantly different from each other at α=0.05.

Table 8. Effect of system management and fertilization on nitrogen and phosphorus uptake

Treatment	kg N·ha^{-1}	Relative value%	kg P·ha^{-1}	Relative value%	kg N·ha^{-1}	Relative value%	kg P·ha^{-1}	Relative value%
	Grain uptake				Straw uptake			
E-Ca	64.08 c	100	13.16 b	100	4.31 a	100	3.16 b	100
D-Ca+FYM	29.51 a	46	6.17 a	47	10.97 b	255	3.05 b	96
A-NPK	26.63 a	42	4.68 a	36	6.36 a	148	0.52 a	16
E-NPK	119.63 d	187	19.71 d	150	19.95 c	463	3.64 b	115
A-CaNPK	57.25 b	89	10.56 b	80	13.09 b	304	0.95 a	30
D-CaNPK	54.07 b	84	13.10 b	100	18.13 c	421	3.65 b	115
E-CaNPK	117.58 d	183	20.34 d	155	25.05 d	582	3.75 b	119
Average	66.96		12.53		13.98		2.67	

Note: * values marked with the same letter in the columns are not significantly different from each other at α=0.05.

availability and preferential allocation to vegetative tissues.

Comparison between systems revealed that nutrient uptake efficiency was markedly enhanced by crop rotation and organic inputs. Under identical fertilization (e.g., CaNPK), grain N uptake was over twice as high in E-CaNPK as in A-CaNPK. Straw uptake also followed this order: E > D > A, highlighting the benefit of legumes and diversified rotations in nutrient recovery.

In summary, the integration of legumes, liming, and organic inputs significantly improved both the magnitude and efficiency of N and P uptake, reducing residual nutrients and enhancing long-term nutrient cycling.

Stepwise regression analysis was used to identify soil and management variables that significantly influenced total nitrogen uptake by crops (Table 9). Among all tested parameters, two variables emerged as statistically significant predictors: ammonium nitrogen concentration in the 50–75 cm soil layer and the application of farmyard manure (FYM). Both factors exhibited negative correlations with nitrogen uptake. Specifically, higher ammonium levels in the subsoil were associated with reduced N uptake by plants, likely reflecting leaching beyond the root zone or microbial immobilization. Similarly, FYM application—despite its long-term soil benefits—appeared to suppress nitrogen uptake within a single growing season, possibly due to slow mineralization and asynchrony between nutrient release and plant demand.

The model explained over 60% of the variance in nitrogen uptake, indicating a strong predictive relationship. These findings highlight the importance of managing nitrogen availability at depth and optimizing organic matter inputs to align with crop nutrient needs. Excess ammonium accumulation in deeper layers may signal inefficiencies in nitrogen use and potential environmental losses.

Multiple regression analysis was conducted to identify key factors influencing total phosphorus uptake. The model included variables related to soil chemistry (available N and P, soil pH at different depths), hydrology (water outflow), and fertilization practices.

Four predictors were statistically significant. Ammonium nitrogen in the topsoil (0–25 cm) showed the strongest negative effect, indicating that excessive NH_4^+ near the root zone may suppress phosphorus uptake, possibly due to rhizosphere acidification or nutrient imbalance. In contrast, nitrate nitrogen in the 25–50 cm layer had a positive impact, suggesting deeper root access to nutrients or synergy between N and P uptake. Soil water outflow negatively affected phosphorus uptake, highlighting the risk of P losses through leaching or dilution under high drainage

Table 9. Results of stepwise regression identifying predictors of total nitrogen uptake, including standardized and unstandardized coefficients (b, b) and significance levels (p)

Total N uptake R= 0.78764011 R^2= 0.62037695 Correct. R2= 0.57819661 p<.00016 Estimation std. error: 27.024			
N = 21	b*	b	p
50–75 cm mg N-NH_4·kg^{-1}	-0,698548	-2,2848	0,000202
FYM	-0,588695	-3,4157	0,001017

Note: *standardized regression coefficient; significance level p<0.05.

conditions. A moderate positive effect was also observed for surface nitrate, further supporting the role of nitrate-driven nutrient uptake efficiency.

Liming (Ca) had a slight but significant negative influence, potentially linked to phosphorus precipitation or reduced P solubility at higher pH. Overall, the model explained nearly 95% of the variation in phosphorus uptake, underlining the complex interplay between nutrient forms, water dynamics, and soil chemistry (Table 10).

These results underscore the complexity of nutrient dynamics in soil-plant systems and highlight the critical role of fertilization form, crop rotation, and subsoil nutrient distribution in optimizing nutrient uptake efficiency.

DISCUSSION

Cropping system design and fertilization strategy exert a significant influence on nitrogen (N) and phosphorus (P) availability, plant uptake, and leaching losses, with important implications for agroecosystem functioning. The A-NPK arbitrary cropping system exhibited the highest water percolation (82.96 $m^3 \cdot ha^{-1}$), whereas organic and limed treatments such as D-CaNPK and D-Ca+-FYM recorded considerably reduced outflows (29.39 and 31.33 $m^3 \cdot ha^{-1}$, respectively), representing a ~60% decrease. These findings align with previous reports (Wang et al., 2023), who reported improved water retention and reduced drainage when at least 75% of mineral nitrogen was replaced with organic manure.

The legume-inclusive rotation system (E) demonstrated superior nutrient uptake, with nitrogen uptake reaching 117.6 $kg \cdot ha^{-1}$ and phosphorus 20.34 $kg \cdot ha^{-1}$ in E-CaNPK, greatly surpassing uptake levels observed in monoculture (D) and non-legume systems (A), such as 26.6 $kg \cdot ha^{-1}$ N in A-NPK (Dinnes et al., 2002; Drinkwater et al., 1998). These results reinforce prior evidence that diverse rotations improve nutrient cycling through biological nitrogen fixation, increased root exudation, and enhanced microbial activity (Crews and Peoples, 2004; Ouverson et al., 2022). Climatic variables, particularly temperature and precipitation, also modulated nitrogen dynamics, with greater leaching under cool and wet conditions (Zhao et al., 2010). Climate change projections suggest more frequent extremes - longer droughts interrupted by intense rainfall (Easterling et al., 2000) - leading to increased soil moisture variability (Hlavinka et al., 2009). (Patil et al., 2010)) observed that rainfall quantity and frequency increased drainage by 46% and 10%, respectively, while soil warming raised evapotranspiration (18%) and reduced drainage (41%). Comparable dynamics were observed here: in early spring (5.9–6.5 °C), high leachate volumes occurred in A-NPK (up to 4.00 mm), attributed to low evapotranspiration and limited crop uptake. As temperatures rose (~12 °C in mid-spring and 18.0 °C in early summer), leaching sharply declined, with leachate volumes remaining below 0.53 mm. (Kreyling et al., 2015) reported that mean nitrogen leaching rates reached 3.4 ± 0.4 mg N $m^{-2} \cdot d^{-1}$ over 49 days, with an 82% increase following a winter warm spell (up to 18 mg $N \cdot dm^{-3}$). This trend was mirrored in our study, where mineral N concentrations rose from an average of 0.26 $mg \cdot dm^{-3}$ in March to peaks exceeding 20 $mg \cdot dm^{-3}$ (e.g., 38.83 mg $N\text{-}NO_3 \cdot dm^{-3}$ in A-NPK by mid-May). Notably, this value translates to approximately 172 mg $NO_3^- \cdot L^{-1}$, which is over three times higher than the WHO (Di Carlo, 2022)/EU (Council Directive 91/676/EEC) threshold (50 mg $NO_3^- \cdot L^{-1}$) for safe drinking water and groundwater protection. Although measured in water, such concentrations

Table 10. Results of stepwise regression identifying predictors of total phosphorus uptake, including standardized and unstandardized coefficients (b*, b) and significance levels (p)

Total P uptake R= 0.97442658 R^2= 0.94950717 Correct. R2= 0.92786738 p<.00000 Estimation std. error: 1.8138			
N=21	b*	b	p
0-25 cm mg $N\text{-}NH_4 \cdot kg^{-1}$	-0.76638	-0.91584	0.00000
25-50 cm mg $N\text{-}NO_3 \cdot kg^{-1}$	0.69603	0.29585	0.00000
25-50 cm mg $P\text{-}PO_4 \cdot kg^{-1}$	0.09896	0.06815	0.32495
Soil water outflow $m^3 \cdot ha^{-1}$	-0.62347	-0.20568	0.00006
0-25 cm mg $N\text{-}NO_3 \cdot kg^{-1}$	0.37555	0.12969	0.00343
Ca ($kg \cdot ha^{-1}$)	-0.22396	-0.01146	0.01160

Note: *standardized regression coefficient; significance level p<0.05.

indicate a strong leaching risk, especially in the absence of organic inputs or crop coverage. These data align with previous research linking early spring fertilization, low evapotranspiration, and limited plant uptake with elevated nitrate transport to subsoil and potentially aquifers (Dinnes et al., 2002; Kreyling et al., 2015). Legume rotations and organic inputs (e.g., E-CaNPK, D-Ca+FYM) significantly reduced N and P losses. Nitrate losses were limited to 57.07 $g \cdot ha^{-1}$ and 59.09 $g \cdot ha^{-1}$ in E-CaNPK and D-Ca+FYM, respectively. (John et al., 2017) demonstrated a similar effect, where winter wheat after pea lost only 18 kg $N \cdot ha^{-1}$ compared to 54 kg $N \cdot ha^{-1}$ after fallow. These benefits stem from deeper root systems and better nutrient synchronization (Das et al., 2024; White, 2009). Nitrate leaching in E-CaNPK was nearly 12 times lower than in A-NPK (664.41 $g \cdot ha^{-1}$). Phosphorus leaching also depended strongly on fertilization strategy. Based on Mehlich-3 testing and interpretation thresholds for Polish soils (Kęsik et al., 2015), very high phosphorus availability at A-CaNPK treatment was recognized as posing a risk for environmental P losses, particularly through surface runoff or subsurface transport in light-textured soils. These findings support the need for site-specific P management and limitations on further P fertilization where P saturation is observed. Under our investigation the highest phosphate loss was recorded in E-CaNPK (120.17 g $P\text{-}PO_4 \cdot ha^{-1}$), where liming, manure, and legumes were combined. In contrast, D-Ca+FYM restricted P loss to 16.83 g $P\text{-}PO_4 \cdot ha^{-1}$. (Shen et al., 2025) similarly reported elevated P leaching under mineral fertilization (up to 3.87%) and lower losses with organic amendments (~3.0%). (Nyström et al., 2023) noted that long-term liming enhanced topsoil P solubility and desorption without necessarily increasing leaching risk. The acidic, sandy loam soil (pH < 6.0 in A-NPK) used in this study increased nutrient mobility. Comparisons between NPK and CaNPK treatments revealed that liming elevated P losses, especially on E-fields with legacy FYM and Ca inputs. However, these systems also demonstrated superior nutrient use: total nitrogen uptake in E-CaNPK reached 142.63 kg $N \cdot ha^{-1}$ and phosphorus 24.09 kg $P \cdot ha^{-1}$ - nearly threefold higher than in A-NPK (32.99 and 5.20 $kg \cdot ha^{-1}$, respectively). These trends echo observations by (Lynch, 2015; Lötjönen and Ollikainen, 2018), who linked high nutrient uptake efficiency to synchronized nutrient supply and plant demand.

In conclusion, although absolute nutrient losses in this experiment were relatively moderate by global standards, the relative performance of systems supports a growing body of evidence: diversified cropping systems that integrate legumes, liming, and organic inputs reduce nutrient leaching, improve nutrient recovery, and enhance soil chemical conditions. Such systems represent a sustainable path forward for temperate agroecosystem resilience and environmental protection.

CONCLUSIONS

Long-term fertilization and cropping strategies significantly influence nutrient dynamics and agroecosystem sustainability. Intensive mineral fertilization in monocultures led to substantial nitrogen and phosphorus leaching, soil acidification, and reduced nutrient use efficiency. Under A-NPK, nitrate losses reached 664 g $N\text{-}NO_3 \cdot ha^{-1}$, phosphate exceeded 24 g $P\text{-}PO_4 \cdot ha^{-1}$, and cumulative water outflow surpassed 83 $m^3 \cdot ha^{-1}$, accompanied by low soil pH (5.92). These losses were most severe in early spring, when nutrient uptake and evapotranspiration were limited. Conversely, diversified systems with legumes, organic inputs, and liming (E-CaNPK, D-Ca+FYM) markedly reduced nutrient losses. Nitrate leaching fell to 57 $g \cdot ha^{-1}$, phosphate to 17 $g \cdot ha^{-1}$, and water outflow dropped by over 50%. These treatments enhanced nutrient recovery, with nitrogen uptake exceeding 143 $kg \cdot ha^{-1}$ and phosphorus reaching 24 $kg \cdot ha^{-1}$ under E-CaNPK, supported by improved soil chemistry (pH > 7.0). Regression analysis showed that high ammonium levels in the 50–75 cm layer reduced nitrogen uptake, likely due to subsoil immobilization or leaching. Phosphorus uptake was also constrained by surface NH_4^+ accumulation, potentially acidifying the rhizosphere and impairing root function. These findings highlight the value of integrated nutrient management - combining balanced fertilization, organic matter, and crop diversification - to reduce leaching, preserve soil quality, and enhance agroecosystem resilience under increasing environmental pressures.

Acknowledgements

Special thanks to the Staff of Pro-Environment Polska – Joanna Kowalewska and Jacek Giersz for professional support for the conducted research.

REFERENCES

1. Asadu, C. O., Ezema, C. A., Ekwueme, B. N., Onu, C. E., Onoh, I. M., Adejoh, T.,…Emmanuel, U. O. (2024). Enhanced efficiency fertilizers: Overview of production methods, materials used, nutrients release mechanisms, benefits and considerations. *Environmental Pollution and Management*, *1*, 32–48. https://doi.org/10.1016/j.epm.2024.07.002
2. Beillouin, D., Jeuffroy, M.-H., Pelzer, E., Schneider, A., barranger, e., chezelles, E., Carroué, B. (2021). Diversifying cropping sequence reduces nitrogen leaching risks. *Field Crops Research*, *272*. https://doi.org/10.1016/j.fcr.2021.108268
3. Brempong, M., Addo-Danso, A. (2022). *Improving Soil Fertility with Organic Fertilizers*. In 1–11. https://doi.org/10.5772/intechopen.103944
4. Cameron, K. C., Di, H. J., Moir, J. L. (2013). Nitrogen losses from the soil/plant system: A review [Review]. *Annals of Applied Biology*, *162*(2), 145–173. https://doi.org/10.1111/aab.12014
5. Crews, T., Peoples, M. (2004). Legume versus fertilizer sources of nitrogen: Ecological tradeoffs and human needs. *Agriculture, Ecosystems & Environment*, *102*, 279–297. https://doi.org/10.1016/j.agee.2003.09.018
6. Dahan, O., Babad, A., Lazarovitch, N., Russak, E., Kurtzman, D. (2013). Nitrate leaching from intensive organic farms to groundwater. *Hydrology and Earth System Sciences Discussions*, *10*, 9915–9941. https://doi.org/10.5194/hessd-10-9915-2013
7. Das, S., Mohapatra, A., Sahu, K., Panday, D., Ghimire, D., Maharjan, B. (2024). Nitrogen dynamics as a function of soil types, compaction, and moisture. *PLOS ONE*, *19*. https://doi.org/10.1371/journal.pone.0301296
8. Debicka, M., Kocowicz, A., Weber, J., Jamroz, E. (2015). Organic matter effects on phosphorus sorption in sandy soils. *Archives of Agronomy and Soil Science*, *62*, 1–16. https://doi.org/10.1080/03650340.2015.1083981
9. Di Carlo, C. (2022). *Guidelines for drinking-water quality: Fourth edition incorporating the first and second addenda*.
10. Dinnes, D., Karlen, D., Jaynes, D. B., Kaspar, T., Hatfield, J., Colvin, T., Cambardella, C. (2002). Nitrogen management strategies to reduce nitrate leaching in tile-drained midwestern soils. *Agronomy Journal*, *94*. https://doi.org/10.2134/agronj2002.0153
11. Djodjic, F., Börling, K., Bergström, L. (2004). Phosphorus leaching in relation to soil type and soil phosphorus content. *Journal of environmental quality*, *33*, 678–684. https://doi.org/10.2134/jeq2004.0678
12. Drinkwater, L., Wagoner, P., Sarrantonio, M. (1998). Drinkwater LE, Wagoner P, Sarrantonio M.. Legume-based cropping systems have reduced carbon and nitrogen losses. *Nature 396*: 262–265. *Nature*, *396*. https://doi.org/10.1038/24376
13. Easterling, D., Meehl, G., Parmesan, C., Changnon, S., Karl, T. R., Mearns, L. (2000). Climate extremes: Observations, modeling, and impacts. *Science (New York, N.Y.)*, *289*, 2068–2074. https://doi.org/10.1126/science.289.5487.2068
14. Geisseler, D., Miller, K., Santiago, S., Abou Najm, M. (2024). The multi-faceted relationship between nitrogen mineralization and soil texture. *Soil Science Society of America Journal*, *88*, 1792–1807. https://doi.org/10.1002/saj2.20728
15. Gleń-Karolczyk, K., Boligłowa, E., Antonkiewicz, J. (2018). Organic fertilization shapes the biodiversity of fungal communities associated with potato dry rot. *Applied Soil Ecology*. https://doi.org/10.1016/j.apsoil.2018.04.012
16. Hlavinka, P., Trnka, M., Semeradova, D., Dubrovský, M., Žalud, Z., Mozny, M. (2009). Effect of drought on yield variability of key crops in Czech Republic. *Agricultural and Forest Meteorology*, *149*, 431–442. https://doi.org/10.1016/j.agrformet.2008.09.004
17. ISO 10390:2005. Soil Quality – Determination of pH. In.
18. ISO 11261:1995. Determination of Total Nitrogen – Modified Kjeldahl Method. In.
19. ISO 11277: 2009 Determination of Particle Size Distribution in Mineral Soil Material - Method by Sieving and Sedimentation. In.
20. IUSS Working Group WRB (2015) "World reference base for soil resources 2015, update 2015. International soil classification system for naming soils and creating legends for soil maps", World Soil Resources Reports, 106. Rome: FAO. In.
21. Jena, J., Maitra, S., Hossain, A., Pramanick, B., Gitari, H., Praharaj, S.,…Jatav, H. (2022). *Role of Legumes in Cropping System for Soil Ecosystem Improvement.* In 1–21.
22. Jie, Z., Chen, J., Beillouin, D., Lambers, H., Yang, Y., Smith, P.,…Zang, H. (2022). Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. *Nature Communications*, *13*. https://doi.org/10.1038/s41467-022-32464-0
23. John, A. A., Jones, C. A., Ewing, S., Sigler, W. A., Bekkerman, A., Miller, P. R. (2017). Fallow replacement and alternative nitrogen management for reducing nitrate leaching in a semiarid region. *Nutrient Cycling in Agroecosystems*, *108*, 1-18. https://doi.org/10.1007/s10705-017-9855-9
24. King, K., Williams, M., Fausey, N. R. (2016). Effect of crop type and season on nutrient leaching to tile

drainage under a corn-soybean rotation. *Journal of Soil and Water Conservation*, *71*, 56–68. https://doi.org/10.2489/jswc.71.1.56

25. Kluger, D., Di Tommaso, S., Lobell, D. (2025). *Evaluating crop rotations around the world using satellite imagery and causal machine learning*. https://doi.org/10.48550/arXiv.2506.02384
26. Kreyling, J., Fuchs, J., Malyshev, A., Vogt, L., Werner, C., Jentsch, A. (2015). Nitrogen leaching is enhanced after a winter warm spell but mainly controlled by vegetation composition in temperate zone mesocosms. *Plant and Soil*, *396*, 1–12. https://doi.org/10.1007/s11104-015-2587-1
27. Kęsik, K., Jadczyszyn, T., Lipinski, W., Jurga, B. (2015). Adaptation of the Mehlich 3 procedure for routine determination of phosphorus, potassium and magnesium in soil. *Przemysl Chemiczny*, *94*, 973–976.
28. Lehmann, J., Schroth, G. (2003). Nutrient leaching. In 151–166. https://doi.org/10.1079/9780851995939.0151
29. Lynch, D. (2015). Nutrient cycling and soil health in organic cropping systems - importance of management strategies and soil resilience. *Sustainable Agriculture Research*, *4*, 80–80. https://doi.org/10.5539/sar.v4n3p80
30. Lötjönen, S., Ollikainen, M. (2018). Does crop rotation with legumes provide an efficient means to reduce nutrient loads and GHG emissions? *Review of Agricultural, Food and Environmental Studies*, *98*, 283-312. https://doi.org/10.1007/s41130-018-0063-z
31. Macdonald, A. J., Gutteridge, R. J. (2012). Effects of take-all (*Gaeumannomyces graminis* var. tritici) on crop N uptake and residual mineral N in soil at harvest of winter wheat [Article]. *Plant and Soil*, *350*(1–2), 253–260. https://doi.org/10.1007/s11104-011-0900-1
32. Manna, M., Ghosh, A., Subbarao, A. (2023). *Composting: A Green Technology for Soil Health Management.*
33. Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant [Article]. *Communications in Soil Science and Plant Analysis*, *15*(12), 1409–1416. https://doi.org/10.1080/00103628409367568
34. Mühlbachová, G., Růžek, P., Kusá, H., Vavera, R., Káš, M. (2024). Nutrient distribution in the soil profile under different tillage practices during a long-term field trial. *Agronomy*, *14*, 3017. https://doi.org/10.3390/agronomy14123017
35. Nyström, Å., Blomquist, J., Persson, L., Gunnarsson, A., Berglund, K. (2023). Long-term effects of liming on crop yield, plant diseases, soil structure and risk of phosphorus leaching. *Agricultural and Food Science*, *32*. https://doi.org/10.23986/afsci.130983
36. Ouverson, T., Boss, D., Eberly, J., Seipel, T., Menalled, F., Ishaq, S. (2022). Soil bacterial community response to cover crops, cover crop termination, and predicted climate conditions in a dryland cropping system. *Frontiers in Sustainable Food Systems*, *6*. https://doi.org/10.3389/fsufs.2022.911199
37. Patil, R., Lægdsmand, M., Olesen, J., Porter, J. (2010). Effect of soil-warming and rainfall patterns on soil N cycling in Northern Europe. Agriculture. *Agriculture, Ecosystems and Environment*, *139*, 195–205.
38. Peng, Y., Zhang, T., Tang, B., Li, X., Cui, S., Guan, C.-Y., Chen, Q. (2022). Interception of fertile soil phosphorus leaching with immobilization materials: Recent progresses, opportunities and challenges. *Chemosphere*, *308*, 136337. https://doi.org/https://doi.org/10.1016/j.chemosphere.2022.136337
39. Penn, C., Camberato, J. (2019). A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture*, *9*, 120. https://doi.org/10.3390/agriculture9060120
40. PN-R-04020:1994 - Chemical and agricultural soil tests - Determination of mineral nitrogen content. In.
41. Radulov, I., Berbecea, A. (2024). Nutrient Management for Sustainable Soil Fertility. In. https://doi.org/10.5772/intechopen.1006692
42. Rupp, H., Tauchnitz, N., Meissner, R. (2021). The effects of soil drying out and rewetting on nitrogen and carbon leaching—results of a long-term lysimeter experiment. *Water*, *13*, 2601. https://doi.org/10.3390/w13182601
43. Schroth, G., J, L., Barrios, E. (2003). Soil nutrient availability and acidity. In 93–130. https://doi.org/10.1079/9780851995939.0093
44. Shen, Y., Lin, H., Xue, R., Ma, Y., Song, Y. (2025). Impact of phosphorus fertilization on leaching, accumulation, and microbial cycling in new apple orchards. *Agronomy*, *15*, 952. https://doi.org/10.3390/agronomy15040952
45. Summers, R., Weaver, D. (2022). Lowering the water solubility of phosphorus fertilisers impacts leaching, plant growth and residual soil phosphorus. *Soil Research*, *61*, 20–36. https://doi.org/10.1071/SR22037
46. Suñer, L., Galantini, J. (2015). Texture influence on soil phosphorus content and distribution in semiarid pampean grasslands. *International Journal of Plant & Soil Science*, *7*, 109–120. https://doi.org/10.9734/IJPSS/2015/16939
47. Teixeira, E., Kersebaum, K. C., Ausseil, A.-G., Cichota, R., Guo, J., Johnstone, P., Ewert, F. (2021). Understanding spatial and temporal variability of N leaching reduction by winter cover crops under climate change. *Science of The Total Environment*, *771*, 144770. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.144770
48. Tkaczyk, P., Mocek-Płóciniak, A., Skowronska, M.,

Bednarek, W., Kuśmierz, S., Zawierucha, E. (2020). The mineral fertilizer-dependent chemical parameters of soil acidification under field conditions. *Sustainability*, *12*, 7165. https://doi.org/10.3390/su12177165

49. Van Groenigen, J. W., Huygens, D., Boeckx, P., Kuyper, T., Lubbers, I. M., Rütting, T., Groffman, P. (2015). The soil N cycle: new insights and key challenges. *SOIL*, *1*, 235–256. https://doi.org/10.5194/soil-1-235-2015
50. Wang, X., Wang, L., Wang, T. (2023). Effect of replacing mineral fertilizer with manure on soil water retention capacity in a Semi-Arid Region. *Agronomy*, *13*, 2272. https://doi.org/10.3390/agronomy13092272
51. White, P. (2009). Efficiency of Soil and Fertilizer Phosphorus Use: Reconciling Changing Concepts of Soil Phosphorus Behaviour with Agronomic Information. By J. K. Syers, A. E. Johnston and D. Curtin. Rome: Food and Agricultural Organization of the United Nations (2008), 108, US$49.00. *Experimental Agriculture - EXP AGR*, *45*. https://doi.org/10.1017/S0014479708007138
52. Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S.,… Butterbach-Bahl, K. (2024). Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health [Article]. *Nature Communications*, *15*(1), Article 198. https://doi.org/10.1038/s41467-023-44464-9
53. Zhang, W., Dulloo, M., Kennedy, G., Bailey, A., Sandhu, H., Nkonya, E. (2019). Biodiversity and Ecosystem Services. In 137–152. https://doi.org/10.1016/B978-0-12-812134-4.00008-X
54. Zhao, H., Zhang, X., Xu, S., Zhao, X., Xie, Z., Wang, Q. (2010). Effect of freezing on soil nitrogen mineralization under different plant communities in a semi-arid area during a non-growing season [Article]. *Applied Soil Ecology*, *45*(3), 187–192. https://