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Benefits and impacts of pig slurry application on agricultural production – evaluation by soil and remote sensing methods

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Original article

Abstract

This study examined the impact of organic pig slurry on soil properties over three years through regular sampling on calcareous chernozem soils near the city Orosháza, in the south-eastern part of the Great Hungarian Plain (Pannonian Basin). Field plots with varying slurry application histories were assessed using soil, groundwater and plant sampling, along with laboratory analysis of the physical and chemical parameters of the soil.

The results indicate that repeated slurry application markedly altered the microelement composition of the soil, in the newly established agricultural plot treated with pig slurry for the last three years zinc concentrations increased by approximately 60% and doubling sodium levels compared to control plots. The humus content steadily increased from 2.10% to 2.98%, reflecting improved soil structure and organic matter accumulation, particularly in the deeper layers. The control, untreated areas showed shallower humus layers and reduced nutrient levels. Notable changes in macronutrients emerged primarily in plots with multi-year slurry treatment, though some effects were already visible within the first year. Groundwater analyses did not reveal contamination; however, shifts in deeper soil strata underscore the need for careful timing and dosage of application.

In addition to soil analysis, plant data, meteorological records, and remote sensing were used. Spectral indices effectively detected vegetation differences, especially higher biomass peaks in treated areas. These findings indicate that repeated slurry application contributes to improved soil nutrient availability and organic matter content, which are associated with enhanced soil structural properties and water retention capacity The study supports a site-specific and environmentally

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responsible use of organic slurry, offering practical insights for improving soil health and productivity in similar agroecological zones.

Keywords: organic fertilizer, drought, Sentinel-2, nutrient supply

Introduction

Domestic nutrient supplementation emerged in Hungary in the late 19th century as an experimental practice inspired by international developments and gained prominence with the advent of intensive agriculture. The introduction of solid fertilizers and their widespread application during the early to mid 20th century led to significant increases in crop yields, with a sharp increase in use from the 1960s onward (BERTÁNÉ, 2016). Since then, fertilizer use has declined to approximately one-quarter of its 1990s level, while attention has shifted toward sustainable nutrient management strategies. Currently, the nitrogen balance of Hungarian soils is positive; however, the phosphorus and potassium balances remain negative (CSATHÓ & RADIMSZKY, 2005). In this context, green manures and organic fertilizers play an increasingly important role in sustaining crop productivity and improving soil health.

The results of small-plot field trials offer valuable insights into fertilization practices, plant nutrition, and the cultivation of arable crops. The calibration of fertilization regimes and soil testing methods is essential as it elucidates the relationship between soil nutrient levels and plant uptake, enabling the determination of optimal fertilizer doses (NÉMETH, 1996). Particular focus has been placed on the behaviour of nitrogen as a result of its high mobility. In a long-term rotary experiment using deep wells, HOLLÓ (1993) found that after 27 years, nitrate N from conventional fertilizers accumulated in deeper soil layers (150–200 cm), while nitrogen from serum water fertilizers remained within a depth of 0–50 cm. A positive nitrogen balance was achieved only with mineral fertilizers (NÉMETH, 1996). Trials carried out in Nyírlugos, Hungary, demonstrated yield increases of 50–80% from nitrogen fertilization, 20–40% from phosphorus and potassium, and 10–20% from liming. Prolonged fertilization and liming led to the accumulation of macroelements in the topsoil, while liming improved soil pH without significantly raising calcium or sodium levels. Similar findings were reported in Őrbottyán, Hungary, where the phosphorus balance turned positive under fertilization, but potassium equilibrium was achieved only with quadruple application rates (KÁDÁR, 1999).

Optimal nutrient supply is essential for maintaining crop performance, as overfertilization – particularly in cereals – can lead to lodging and consequent yield loss (KÁDÁR, 1996). Nutrient use is influenced by soil type and climatic conditions; excessive nitrogen application may promote weed proliferation, increase pest pressure, and result in yield decline (KÁDÁR, 1997). Although modern mineral fertilizers offer precise, easily manageable formulations with efficient application methods, their use contrasts with that of organic fertilizers, which remain underused despite the costs of mineral fertilizers (HORINKA, 2013). Although both organic and mineral sources supply essential plant nutrients, complex mineral fertilizers often provide a more balanced nutrient composition suited to crop requirements.

Unlike mineral fertilizers, organic manure has a positive effect on soil structure through the humus content of the constituent substances, and improves soil water and air management and heat balance in the long term (HORINKA, 2013). As they decompose, nutrients are released gradually, so their effect lasts 2–4 years. Manure increases the colloidal content of sandy soils, loosens bound soils, and has a positive effect on the cation exchange capacity and the biological activity of the soil. CO_2 released during decomposition helps solubilize nutrients and humus formation, maintaining soil fertility in the long term.

The use of animal slurry alongside mineral fertilizers has been practised in Switzerland and Austria since the 19th century, particularly in the context of litter-free livestock systems (LOCH & NOSTICZIUS, 2004). With the rise of industrialized animal husbandry, slurry production has increased substantially, making its effective management crucial for both nutrient cycling and environmental protection. Due to its high nitrogen, phosphorus, and potassium content, slurry is considered a valuable fertilizer (CSABA et al., 1978); however, its application in large quantities requires considerable storage capacity. From an environmental point of view, preventing soil water contamination and surface runoff is essential. Therefore, slurry application must be adapted to site-specific soil and weather conditions. Particular attention should be paid to the soil's water retention capacity and the risk of runoff on sloped terrain. The application on frozen ground is prohibited, as it increases the risk of leaching. Immediate incorporation into the soil is recommended to minimize nitrogen volatilization and air pollution (LOCH & NOSTICZIUS, 2004).

Previous international studies highlight the variability of slurry effects depending on soil type, climate, and management practices, underlining the importance of site-specific application strategies. In Canadian grasslands, slurry was shown to effectively substitute mineral nitrogen and phosphorus inputs (CAVANAGH et al., 2011), while pig slurry analyses in Spain reported a relatively consistent macroelement ratio of $N:P_2O_5:K_2O$ = 1:0.6:0.4 (SÁNCHEZ & GONZÁLEZ, 2004). In contrast, studies on sandy soils revealed increased leaching of nitrogen and potassium, whereas phosphorus tended to accumulate in the topsoil (LIU et al., 2012). Long-term experiments, such as a 65-year crop rotation trial in Prague-Ruzyně (Czechia), found no significant accumulation of trace metals (Cd, Cu, Pb, Zn) in soils treated with pig slurry or NPK fertilizers (BARŁÓG et al., 2024). Together, these findings demonstrate that both the agronomic benefits and environmental risks of slurry application are strongly site-dependent, supporting the need for integrated nutrient management strategies combining organic and mineral fertilizers.

This study aimed to evaluate the impacts of slurry application on soil over a three-year period, complemented by observations of plant development. The experimental site was divided into three sections: (I) a plot that had received regular slurry fertilization for more than 15 years, (II) a newly established plot, half of which was treated with slurry for three years from the beginning of the study, while the other half served as a control plot (III) without slurry application. Composite soil and soil water samples were collected annually, while plant samples were taken twice per growing season, and crop yield samples were collected at harvest. To support the interpretation of field measurements and to capture spatial and temporal variability in crop development, multispectral satellite-based remote sensing was applied during the vegetation period, complemented by data from local meteorological stations. The primary objective was to evaluate the soil-related effects of organic slurry application. Specifically, the study aimed to determine whether detectable changes could be observed within the first years of treatment and how these changes compared to those resulting from long-term application.

Materials and Methods

The Materials and Methods section describes the study site characteristics, experimental design, soil and plant sampling procedures, laboratory analyses, and remote sensing-based monitoring approach applied during the three-year investigation.

Study area

The study was carried out between September 2021 and August 2024 on an approximately 25.7 ha arable field, with 5 ha designated for detailed sampling, located on the Békési-hát small landscape located in the south-eastern part of Hungary near Orosháza (*Figure 1*). During the 3 years, the following crop rotation was implemented: winter wheat (*Triticum aestivum*) in 2022, maize (*Zea mays*) in 2023, and winter barley (*Hordeum vulgare*) in 2024. Organic pig slurry was applied annually to the treated plots at a rate of 25 m^3 ha^{-1}. To minimise nitrogen losses, the slurry was applied by injection.

The study sites cover approximately 20 ha and has an elongated field geometry, and is characterised by a flat to very gently sloping topography with no dominant aspect. The study area underlain by the typical alluvial conglomerate, situated approximately 85 m above sea level, is overlain by heterogeneous fluvial and aeolian sediments. The region features high-quality chernozem soils formed on a low-relief, nearly flat topography, where the original loess-steppe vegetation has been almost entirely removed – conditions that are highly favourable for arable crop production (DÖVÉNYI, 2010). The dominant soil type is calcareous loess chernozem, with a sandy loam-to-loam texture (URL1). The presence of floodplain plant species is minimal. However, the landscape exhibits low ecological resilience and the regeneration of natural resources is slow and limited. The region is poor in natural watercourses, with order III watercourses, and is characterised by poorly drained and water-scarce areas.

The study area is characterised by a warm and dry climate, with long-term mean annual temperature of 10.6 °C, annual sunshine duration of 2,000–2,200 hours, and mean annual precipitation of 520–540 mm, of which approximately 310 mm falls during the growing season (DÖVÉNYI, 2010). The last five years indicate a warming trend, with a mean annual temperature of 11.9 °C and a mean summer temperature of 18.4 °C and precipitation totals declining to about 460 mm since 2020 (URL2). According to the Hungarian Drought Index (HDI), the years 2021, 2022, and 2024 were classified as severe to extreme drought years.

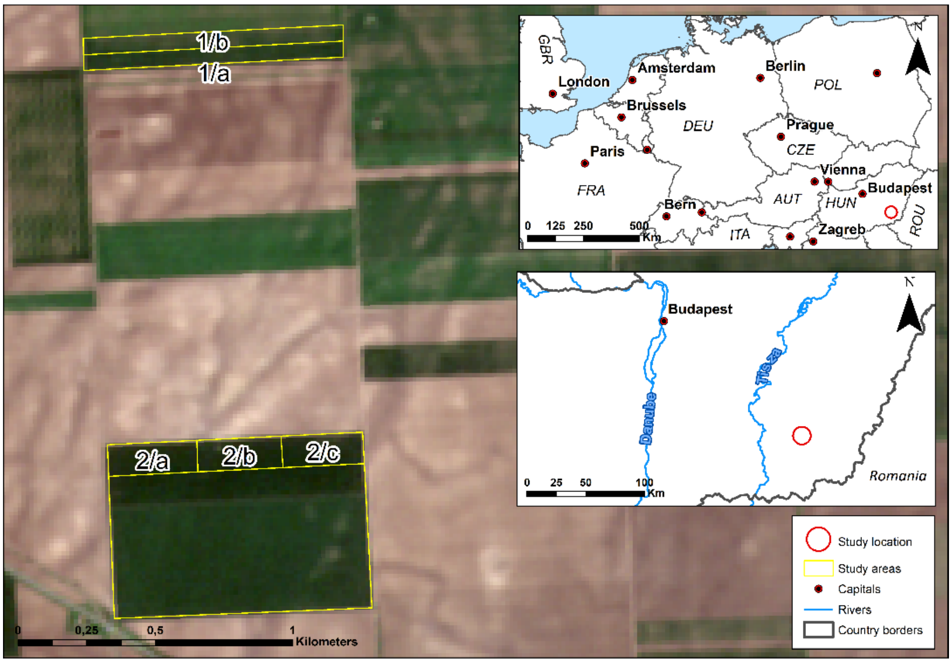

Figure 1
Description of the study area (background: Sentinel-2 image: 26.04.2022)

Selection of study areas and soil sampling

In our study, three distinct sample plots were established based on their history of slurry application (*Figure 1*). The first plot type (2/a–b–c) had received regular slurry treatments since 2011. The second plot type (1/a) was first treated with slurry in autumn 2021, while the third plot (1/b) served as the control and had not received slurry either during the study period or prior. Importantly, since 2020 all plots have been managed identically, with the same crop grown, and all agricultural operations (tillage, fertilization, sowing, and harvest) carried out in parallel or within a few days of each other. All plots were cultivated with winter rapeseed (*Brassica napus*) in 2020 and followed identical cultivation practices in subsequent years. Within the long-term treated area, a total of 5 ha was selected for sampling from a 20 ha field with a history of regular slurry application. The newly established treated plot (1/a) and the control plot (1/b) together covered a combined area of 5.7 ha.

The initial composite soil sampling was carried out in the autumn of 2021 and was repeated in the subsequent autumns of 2022 and 2023, specifically targeting the period between harvest and slurry application. As indicated in *Figure 1*, a 20-metre buffer zone was excluded along the plot boundaries to minimise edge effects from neighbouring fields. The remaining area was subdivided into approximately 1-hectare sampling units. Within each unit, 20 sampling points were selected using a diagonal transect method to enhance spatial representativeness. The GPS coordinates of each sampling point were manually tracked during fieldwork. Soil samples were collected from the upper 0–20 cm layer using a handheld auger, corresponding to the primary root zone and the depth typically homogenised by plowing. Point samples were thoroughly mixed in a bucket and approximately 1 kg of soil per unit was transferred to sampling bags for laboratory analysis. The following soil parameters were measured: Arany-type plasticity index, pH (H_2O), pH (KCl), Total salinity, Humus, $CaCO_3$, P_2O_5, K_2O, NO_3–N+NO_2–N, SO_4^{2}–S, Na, Mg, Cu, Zn, Mn. (MSZ 20135:1999; MSZ-08-0205:1978; MSZ-08-0206-2:1978)

Groundwater chemistry analysis provides information on soil water dynamics and nutrient movement, including the extent of nutrient leaching into deeper layers versus retention and uptake in the upper horizons. To complement the surface soil assessments, two borehole wells were established at opposite edges of the sample plots to capture spatial variability and gain a representative understanding of the subsurface profile. As with soil sampling, manual augering was used to drill several metre-deep wells each November, after the slurry application had been completed on all plots (*Figure 2*). These wells also provided valuable information on the stratification and chemical composition of the deeper soil horizons.

Figure 2
(A) Average soil sampling with a hand drill, (B) Homogenisation of the average soil sample, (C) Soil water sampling in plot 1 on 10.11.2022

A section description of the boreholes was made and after reaching the appropriate depth, groundwater sampling was carried out by pumping and cleaning. Groundwater was tested in the laboratory for the following parameters: pH, electrical conductivity, NO_2^-, NO_3^-, NH_4^+, PO_4^{3-}, SO_4^{2-}, Na, K, Ca, Mg, Cl^-, CO_3^{2-}, HCO_3^- suspended solid content, total dissolved solid content (MSZ 1484-22:2009; MSZ EN 27888:1998; MSZ EN ISO 13395:1999; MSZ EN ISO 10304-1:2009; MSZ EN ISO 11732:2005; MSZ 1484-3:2006; MSZ 1484-15:2009; MSZ 448-11:1986; MSZ 448-33:1985; MSZ 448-19:1986).

Plant and crop sampling

Crop development was monitored through two rounds of plant sampling, aimed at assessing how prior application of the slurry influenced nutrient uptake and internal plant composition, differences that may not be visible externally. The first sampling was carried out during the early vegetative stage: the tiller stage for winter cereals and the 6–8 leaf stage for maize. The second sampling occurred during the reproductive phase: the ear emergence stage for winter wheat and barley and the tasseling stage for maize. The sampling was aligned with the spatial framework of average soil sampling. From each of the five designated subplots, approximately 100 plant stem samples were collected for laboratory leaf analysis. The following parameters were measured: N, P, K, Ca, Mg, Cu, Zn, Mn, Fe, S, and B (MSZ-08-1783-6:1983; MSZ-08-1783-28:1985; MSZ-08-1783-26:1985; MSZ-08-1783-27:1985; MSZ-08-1783-34:1985; MSZ-08-1783-33:1985; MSZ-08-1783-32:1985; MSZ-08-1783-31:1985; MSZ-08-1783-38:1985; MSZ-08-1783-36:1985).

Meteorological dataset

Near the study area, meteorological monitoring was conducted by the Lower Tisza District Water Directorate as part of the Operational Drought and Water Scarcity Management System. A station in Székkutas and, from May 2022 onward, a closer station in Gádoros (4 km away) provided meteorological data relevant to drought monitoring and forecasting (URL2). The stations are equipped with OTT Pluvio 2 gravimetric precipitation gauges, which record precipitation with 0.1 mm accuracy regardless of form. They also measured air temperature, humidity, and soil moisture and calculated the Hungarian Drought Index (HDI) (FIALA et al., 2018), which was used to interpret plant development in the study.

Remote sensed data collection

Field measurements remain the most accurate method for assessing the effects of organic fertilizer application; however, they are costly and are typically limited to small-scale study areas. As a cost-effective alternative, remote sensing offers valuable potential, though its applicability depends on the characteristics of the sensor, specifically spatial, temporal, and spectral resolution. In particular, higher spatial resolution often comes at the expense of spectral detail. In monitoring studies, various spectral indices have proven useful for evaluating plant health, water content, phenological stages, and biomass production. Commonly used indices include the Normalized Difference Vegetation Index (NDVI) (ROUSE et al., 1974), the Normalized Difference Water Index (NDWI) (GAO, 1996), and the Enhanced Vegetation Index (EVI) (HUETE et al., 2002). Ground-based control measurements are essential for validating remote sensing data (GOZDOWSKI et al., 2020; MASHONGANYIKA et al., 2021). Satellite and drone imagery are often used in a complementary manner: drone-based data provide higher spatial resolution but cover smaller areas, while satellites enable large-scale monitoring. Both domestic studies (ERDŐDINÉ & KOVÁCS, 2021; KOVÁCS & LADÁNYI, 2021) and international studies (MASIALETI et al., 2010; SORIANO-GONZÁLEZ et al., 2022) confirm the effectiveness of spectral indices for plant health assessment and yield forecasting, particularly when contextualised by site-specific factors such as crop type, rainfall distribution, and irrigation practices. Sentinel-2 satellite imagery has also been successfully used to monitor agricultural diseases and detect soil salinization (SEGARRA et al., 2020).

For remote sensing data collection, we utilised pre-processed optical satellite imagery, prioritising datasets with high spatial, spectral, and temporal resolution. Sentinel-2A and -2B satellites provided the most suitable data, offering freely accessible imagery that dates back several years (URL3). Data were obtained at 10 m resolution in the red, green, blue and near-infrared bands, and at 20 m resolution in the shortwave infrared bands. Three spectral indices were selected for the monitoring study to assess vegetation status (*Table 1*).

Table 1
The spectral indices used in the study: Normalized Differential Vegetation Index, Enhanced Vegetation Index, Normalized Differential Water Index
(ρ_{NIR} = near-infrared wavelength range, ρ_{Red} = red wavelength range, ρ_{Blue} = blue wavelength range, ρ_{SWIR} = short-wave infrared wavelength range)

Index	Formula	Reference
NDVI	$NDVI = \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + \rho_{Red}}$	ROUSE et al., 1974.
EVI	$EVI = 2.5 * \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + 6 * \rho_{Red} - 7 * \rho_{Blue} + 1}$	HUETE et al., 2002.
NDWI	$NDWI = \frac{\rho_{NIR} - \rho_{SWIR}}{\rho_{NIR} + \rho_{SWIR}}$	GAO, 1996.

The NDVI and the EVI which we primarily use, are indicators of chlorophyll content, and therefore vegetation health and density at a resolution of 10 m. The NDWI shows vegetation water content at a resolution of 20 m. To facilitate time series analysis, a processing model was developed to automate the workflow that uses pre-processed Level-2 imagery and produces statistically evaluated index values for each sub-area and observation date.

Results

Results of soil and plant analysis

Laboratory analyses of soil samples collected over three consecutive years revealed remarkable spatial and temporal differences in soil chemistry, particularly among the various treated plots. Among macronutrients, phosphorus and potassium concentrations were markedly higher in plots that had received long-term pig slurry applications in the final year of the study compared to the control or newly treated areas. Phosphorus concentrations peaked at 3,746 mg kg^{-1} in long-term treated fields, while control plots recorded a maximum of only 219.5 mg kg^{-1}, representing a nearly 14-fold difference. Potassium concentrations followed a similar pattern, averaging 1,251 mg kg^{-1} in long-term treated plots, approximately four times the 330.7 mg kg^{-1} measured in the control area. Comparable trends were also observed for several meso- and micronutrients. Nitrogen, sulfur, sodium, and zinc concentrations were 1.5 to 2 times higher in long-term treated areas, suggesting a cumulative enrichment effect attributable to the continued application of the slurry. It is important to note that no baseline nutrient data are available for the plots treated since 2011; therefore, conclusions can only be drawn about changes that occurred during the three-year study period. Nevertheless, the findings clearly demonstrate that organic fertilization contributes not only to the enrichment of macronutrients but also to the sustained accumulation of micro- and meso-elements when applied consistently over multiple years.

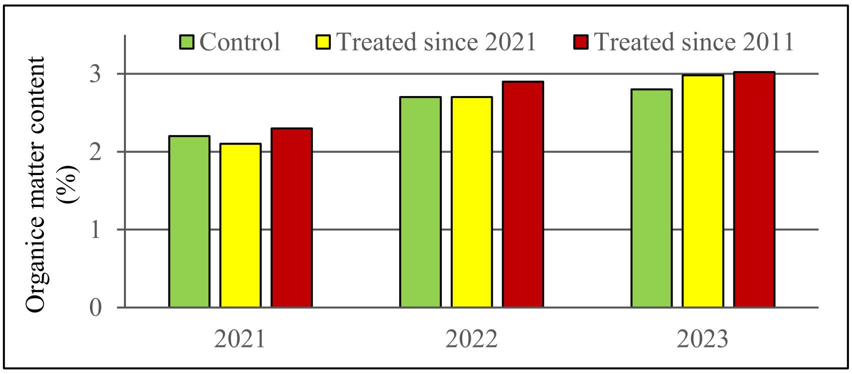

Figure 3
Changes in organic matter content in different sample areas between 2021 and 2023

The evaluation of soil chemistry changes during the three-year study period highlighted several considerable trends associated with the application of organic slurry. A notable finding was the organic matter content, which increased by 42% in the area that received slurry for the first time in 2021. This improvement in soil quality is further supported by the observation that the organic matter levels in the newly treated area were close to those measured in the plot that had been fertilized regularly for more than a decade (*Figure 3*), suggesting a rapid improvement in soil structure. Overall, long-term slurry application resulted in substantially higher macronutrient levels compared to the untreated control, confirming the cumulative enrichment effect observed in the concentration data. In contrast, trends in meso- and micronutrient concentrations were more variable. Sodium and zinc consistently showed higher concentrations in the long-term treated plots, whereas other elements exhibited weaker or inconsistent treatment-related responses. In particular, zinc concentrations in the untreated plot showed considerable variability, underscoring the stabilising effect of sustained fertilization (*Table 2*). For copper, remarkable treatment-related differences were only observed in 2023, suggesting a delayed or inconsistent response. In the case of manganese and magnesium, no consistent treatment-related differences were detected in the plots. The uncertainty in the conclusions may be due to the complexity of the processes involved, which means that only a longer time horizon will allow us to draw accurate conclusions.

Table 2
Soil nutrient concentrations (0–20 cm) in control, newly treated, and long-term slurry-treated plots at the end of the study period

Parameter	Control	Newly treated (3 years)	Long term treated
Organic matter (%)	2.8	3.0	3.1
N (mg kg^{-1})	6.4	10.6	37.5
P (mg kg^{-1})	193.4	201.2	316.6
K (mg kg^{-1})	259.6	293.7	730.3
Na (mg kg^{-1})	29.8	40.4	46.2
Zn (mg kg^{-1})	1.5	2.4	10.8

Soil profile analysis revealed clear differences between the treated and control plots in terms of humus depth and distribution. In the previously treated areas, a considerably deeper dark-coloured layer rich in humus was observed, directly improving soil fertility and plant development in the upper root zone (*Figure 4*). On the contrary, the control area exhibited a sharp decline in humus content beyond a depth of 60–70 cm, indicating a more limited accumulation of organic matter. In the long-term treated plots, the nutrient-rich soil layers extended beyond 1 m in depth. However, it is important to acknowledge that part of this deeper accumulation of humus may be due to inherent natural variability in soil formation and structure, regardless of the fertilization history, particularly in deeper horizons.

Figure 4
Soil section texture descriptions for treated (A) and control (B) areas since 2011

The quality of groundwater was assessed over 3 years as well. However, due to the fluctuation infiltration rates in the deeper soil layers combined with limited and irregular precipitation during the study period, no definitive conclusions could be drawn about the long-term impact of the application of slurry on the composition of groundwater. Considerable year-to-year variation was observed in several parameters. For example, sodium concentrations ranged from 379.91 mg l^{-1} to 597 mg l^{-1}, while potassium levels varied between 27.50 mg l^{-1} and 123 mg l^{-1} at the same sampling location over different years. These fluctuations are unlikely to be a direct consequence of the application of the slurry. First, all measured parameters remained within the allowed contamination thresholds, however observed temporal fluctuations likely reflect variations in hydrological conditions rather than systematic effects of slurry application. Second, the 4 to 5 m deep groundwater table provides a natural buffer that would reduce the likelihood of rapid leaching of nutrients from surface treatments. It is probable that other environmental or hydrological factors contributed to the observed variability.

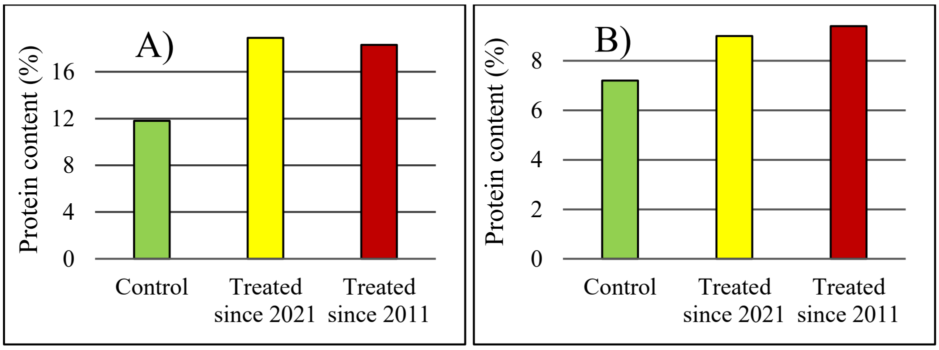

Figure 5
Protein content (N*6.25) (%) of winter wheat (A) and maize (B)

The micro- and macronutrient content of the plant was assessed in two phenological stages to evaluate how different crops developed over time in relation to the fertilization history. Differences in several nutrient concentrations were observed, particularly in plants from plots that had been regularly treated with slurry for more than a decade. In early-stage sampling, variations in nutrient content were already detectable between control plots and those that received slurry treatment for the first time. For example, on 1 April 2020, winter wheat across all fields exhibited a similar nitrogen concentration of approximately 4.2 m/m%. However, by mid-May, nitrogen levels had decreased to 2.74 m/m% in control plots, 3.38 m/m% in newly fertilized plots, and remained stable at 4.22 m/m% in long-term treated plots, reflecting differences in nutrient availability and uptake. These trends were also observable at the field level, where clear distinctions in plant size and health status emerged between treated and untreated plots, visually corroborated by remote sensing imagery (*Figure 5*). During the course of the three-year study, nutrients such as nitrogen and phosphorus showed noticeable increases in newly treated areas, suggesting a cumulative improvement in plant nutrition. Some nutrient concentrations remained below the levels recorded in long-term fertilized areas, indicating an adaptation of soil and plant systems to applied organic treatments.

Across the three types of crops, the quality parameters of the produce from the slurry-treated plots were consistently superior to those of the control plots. In particular, protein content (*Figure 5*) and macronutrient concentrations were consistenly higher in the treated areas, highlighting differences in crop quality. For example, in 2022, the phosphorus content in maize grains was measured at 0.25 mg kg^{-1} in the control plot, 0.27 mg kg^{-1} in the newly treated plot (since 2021), and 0.35 mg kg^{-1} in the long term slurry-treated plot (since 2011). The protein content in the treated fields was 60% higher than in the control areas. These improvements are relevant for crop quality classification and also crucial for end-use purposes, such as animal feed, where protein content is a key nutritional factor. However, no consistent differences in yield were recorded during the study period. Although the treated plots showed yield increases of several hundred kilograms per hectare each year, these gains remained below average expectations and were likely constrained by extreme weather events. All three growing seasons were affected by summer droughts of varying severity, which probably masked the full productive potential of fertilization treatments.

The analysis of the meteorological stations

Precipitation data were retrieved from the meteorological database on a weekly basis and hourly measurements were summarized. HDI values were obtained daily and used to explain the stages of plant development.

In none of the years examined did rainfall reach levels sufficient to meet the optimal water requirements of the cultivated crops (*Table 3*). The first year of the study, in particular, was marked by extreme drought, not only in terms of total precipitation but also in its temporal distribution. The irregular and infrequent rainfall events further exacerbated water stress for the crops (*Table 4–5*). Each year, the onset of severe drought conditions began in early summer and persisted until the harvest period, creating prolonged periods of water deficit that hindered plant development and yield potential (*Figure 6*).

Table 3
Annual precipitation amounts in the growing season

Growing season	**Crops**	**Rainfall during the growing season**	**Average, Optimal water demand**
2021. 09.–2022. 06.	Winter wheat	208 mm	350–500 mm
2023. 04.–2023. 09.	Maize	284 mm	450–700 mm
2023. 10.–2024. 06.	Winter barley	321 mm	300–450 mm

Table 4
Number of drought days during the growing season (2021–2024) at the Székkutas meteorological station, categorised by HDI values (ND Number of days in terms of drought)

Crops	**Drought-free**	**Mild**	**Medium**	**Strong**	**Extraordinary**	**ND**
Winter wheat	83	28	117	34	13	192
Maize	137	19	13	9	0	41
Winter barley	127	38	80	13	0	131

Table 5
Number of drought days during the growing season (2021–2024) at the Gádoros meteorological station, categorised by HDI values (ND Number of days in terms of drought)

Crops	**Drought-free**	**Mild**	**Medium**	**Strong**	**Extraordinary**	**ND**
Winter wheat	11	7	18	15	12	52
Maize	114	24	24	16	0	64
Winter barley	150	37	59	12	0	108

Results of the remote sensing data

In the first year of the study, the EVI was particularly effective in detecting vegetation stress in the winter wheat control areas. Before harvest, a drop in index values was observed by mid-summer, which was also confirmed by field observations and plant sampling (*Figure 6–7*). On the contrary, the areas treated since 2011 showed higher vegetation index values, peaking about a week earlier than in the control plots. The EVI value reached 0.90 and NDVI 0.65 in the treated plots, compared to 0.72 (EVI) and 0.60 (NDVI) in the control area, indicating more advanced and healthier crop development. A second key observation was the differential accumulation of biomass in early spring, as indicated by the vegetation indices. Between 15 March and 14 April 2022, biomass increased by 100% in the newly treated area, 133% in the long-term treated area, and only 92% in the control plots. These results highlight both the short- and long-term effects of organic fertilization on plant growth dynamics and early season development.

The NDVI values showed a change curve similar to that of the EVI but were less sensitive in detecting differences due to the saturation effect under dense vegetation cover. NDWI, which reflects the water content of the vegetation, was overall less representative; it showed a temporary increase after certain rainfall events, but no longer reliably reflected the condition of the plants as the phenological development progressed, particularly during the maturation phase, as the index was distorted by the drying of the natural vegetation. Among the spectral indices analysed, the EVI proved to be the most suitable for monitoring crop development throughout the three-year study period.

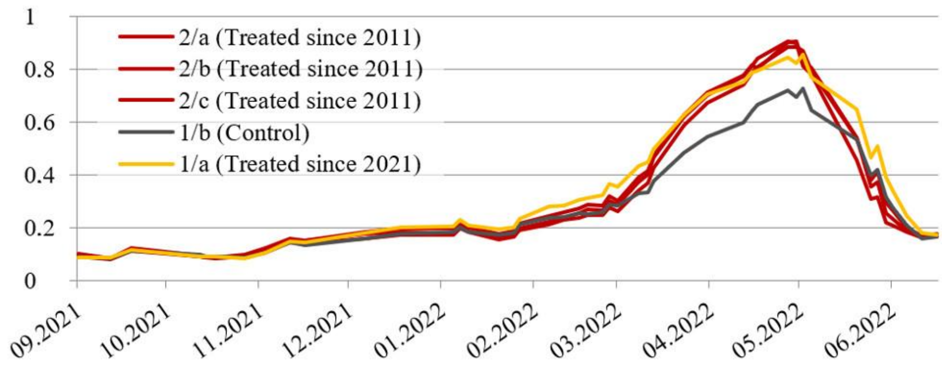

Figure 6
Changes in EVI values for winter wheat during the growing season

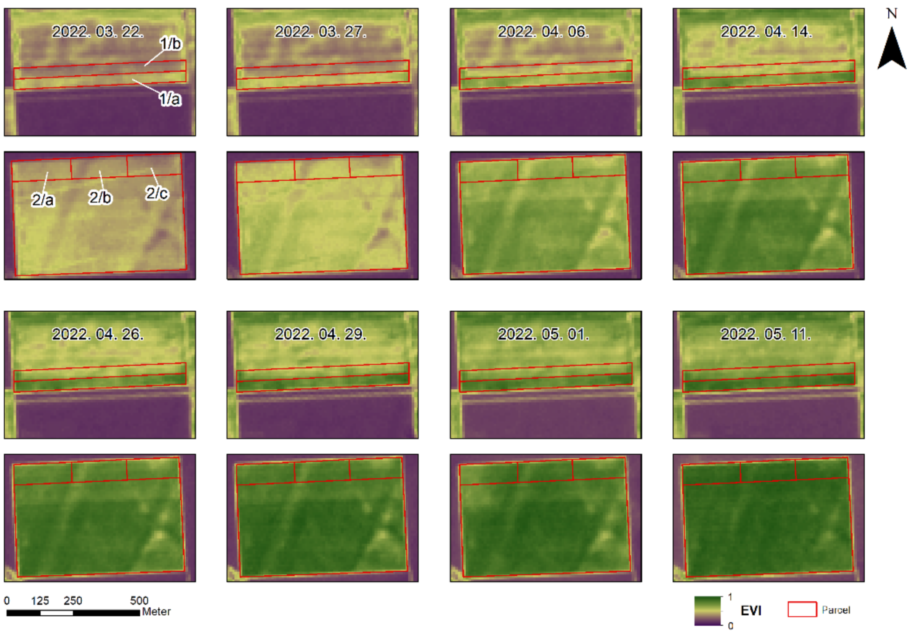

Figure 7
Spatial distribution of EVI values in winter wheat for freshly treated and control plots during the period from 22 March to 11 May 2022

In the second year, maize exhibited a different developmental trend due to the severe heat wave in June–July. During this period, the plants relied heavily on internal reserves. In plots with frequent and high levels of fertilization, maize tended to "burn out" earlier, as growth shifted rapidly toward ear development, a phase that requires high input of water and nutrients. This was reflected in the values of the vegetation index, which showed earlier peaks and subsequent declines in treated areas. In contrast, the plants in the untreated control plots continued vegetative growth longer, benefiting from delayed pollination and conserving energy until the next rainfall event. In general, prolonged heat and drought conditions in 2023 were unfavourable to maize, contributing to considerably reduced yields in all treatments.

In the third year of the study, due to differences in sowing dates, the plot that had received slurry treatment for several years could not be representatively compared with the other plots. As a result, only the development dynamics of the control plot and the plot treated for three years were considered relevant. Despite the minimal difference, the treated plot showed slightly higher biomass production than the control. According to vegetation indices, crop development reached its peak on 15 April, with the treated plot recording higher values (EVI = 0.82; NDVI = 0.63) compared to the control (EVI = 0.74; NDVI = 0.59) (*Figure 8*). These slight developmental differences were also reflected in both the quantity and the quality of the yield. The summer drought this year had a similar impact on the long-term treated plot as observed in maize the previous year. Although the crop initially appeared to be more vigorous and healthier, the final yields were considerably reduced.

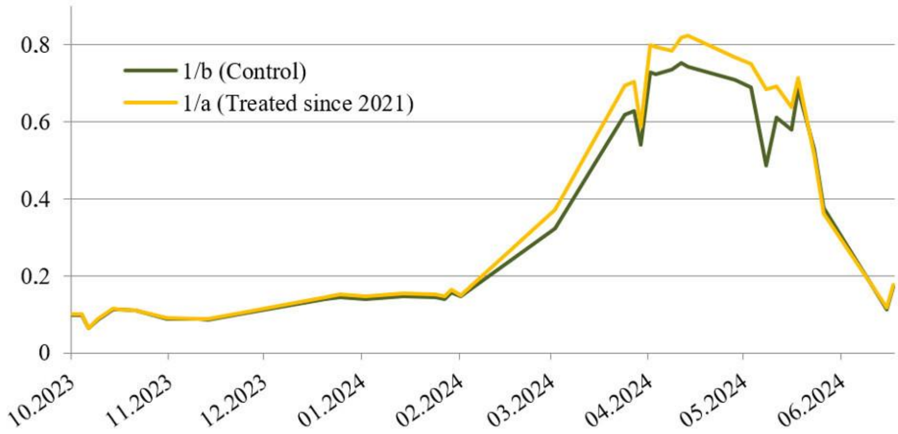

Figure 8
Changes in EVI values for winter barley during the growing season

Discussion

The results of the three-year study demonstrate that the application of pig slurry has a clearly beneficial effect on plant development, and crop quality, soil nutrient levels and leads to an increase in soil organic matter content, which is commonly associated with improved soil structure. These findings are consistent with those of KÁDÁR (1999), who observed that long-term nutrient supplementation, particularly from organic sources, enhances both the macro- and micronutrient composition of soils, as well as humus content. Our data confirm that regular organic fertilization not only improves nutrient supply but also contributes to favourable structural development in the soil. Consistent differences were observed between the treated and control areas, especially in terms of microelement concentrations. For example, zinc levels in treated plots increased from 1.5 mg kg^{-1} to 2.4 mg kg^{-1}, while remained unchanged in the control. This agrees with the findings of BARŁÓG et al. (2024), who also observed significant enrichment of Zn in long-term pig slurry trials. Sodium levels rose from 17.6 mg kg^{-1} to 40.4 mg kg^{-1} in the newly treated area, compared to 29.8 mg kg^{-1} in the control. These effects were already noticeable after the first year of application but became more pronounced with time, indicating a cumulative benefit of repeated use of slurry. The observed increase in humus depth and improvements in soil structure support earlier findings by HOLLÓ (1993) and NÉMETH (1996), who emphasized that organic fertilizers primarily enhance the upper soil layers, but can also induce beneficial changes at greater depths over time. However, contrasting results were reported by LIU et al. (2012) in Sweden, where the application of slurry in sandy soils led to the leaching of nitrogen and potassium, posing potential environmental risks. In our study, groundwater analyses did not indicate similar nutrient leaching, likely due to the lower permeability of calcareous chernozem soils and the controlled timing and method of slurry application.

Analysis of plant samples and yields revealed clear differences in phenological stages, both in plant morphology and in yield quality. Crops from slurry-treated areas exhibited higher protein content and elevated nutrient concentrations, which is particularly advantageous for feed production. However, no clear yield differnces were observed. This limited response in yield quantity can be attributed to the persistent drought and extreme weather conditions experienced during the three study years. These findings support the conclusion of KÁDÁR (1996), who emphasized that nutrient supply has a strong influence on yield quality, although in this case no substantial increase in yield quantity could be demonstrated.

Our remote sensing results align with the findings of ERDŐDINÉ & KOVÁCS (2021) and KOVÁCS & LADÁNYI (2021), confirming that the EVI is more effective than the NDVI in distinguishing the stages of crop development, particularly under environmental stress conditions such as drought. On the contrary, the NDWI showed short-term increases after rainfall events, but its reliability decreased during the ripening phase due to natural water loss. This observation supports the conclusion of MASHONGANYIKA et al. (2021), who found that the accuracy of the vegetation water indices declines as crops mature.

Several limiting factors affected the accuracy and generalisability of our short-duration study, and these constraints must be taken into account when interpreting the results. These included adverse weather conditions, inconsistencies in the timing of agricultural operations across plots, the absence of baseline data for the long-term managed area, and challenges related to the spatial representativeness of small-plot sampling. Despite these limitations, the application of multiple measurement approaches and the use of large multiyear datasets improved the reliability and robustness of the findings.

Conclusion

The three-year study demonstrated that the application of organic slurry had a beneficial impact on soil nutrient levels and the nutritional parameters of plants and crops. Increased soil organic matter content suggests a potential indirect improvement in soil structure, although physical soil structure parameters were not directly measured. Positive changes were evident even in the short term, particularly increases in the zinc and sodium content, while long-term treated plots showed considerably higher accumulation of macroelements. Importantly, no leaching of harmful nutrients was observed into groundwater. Among the vegetation monitoring tools, the EVI was most effective, showing high sensitivity to both plant stress and nutrient availability. Although differences in yield averages remained small, this was probably due to persistent drought conditions that characterised the three study years.

In general, slurry represents a long-term and sustainable alternative to synthetic fertilizers, particularly in intensively cultivated agricultural areas with low organic matter content. Continued monitoring under varying climatic conditions will be essential to further refine the findings presented in this study and to evaluate the applicability of slurry-based fertilization in different types of soil. Moreover, the integration of the application of slurry with precision remote sensing technologies presents a promising direction to improve the efficiency and sustainability of nutrient management in future agricultural practices.

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