New Forests (2026) 57:44
https://doi.org/10.1007/s11056-026-10191-4

Assessment of fertilization effects on 2.5-year growth dynamics of *Robinia pseudoacacia* L. and soil quality in the arid southern Nyírség region of Hungary

István Attila Kocsis[1,2,3] · Andrea Balla Kovács[1] · Rita Kremper[1] · Evelin Kármen Juhász[1] · Daniel A. Lowy[4] · Zsolt Sándor[1] · Ida Kincses[1]

Received: 5 August 2025 / Accepted: 12 May 2026
© The Author(s) 2026

Abstract
Recent climatic trends in the Southern microregion of Nyírség in Hungary indicate an increase in aridity, which threatens the persistence of native woody vegetation over the next 50–100 years. Black locust (*Robinia pseudoacacia* L.) is gaining ecological and silvicultural importance due to its rapid growth, drought tolerance, and ability to develop and survive in degraded sandy soils. This study evaluated the effects of various organic and inorganic fertilization treatments on the early growth of black locust seedlings and rhizosphere soil properties in a small-plot open-field experiment near Debrecen. Shoot height, basal stem diameter, soil organic carbon (SOC), pH and AL-extractable macro elements (K, P, Ca, and Mg) were monitored over 2.5 years. Low-dose mineral fertilizer, high-dose humic acids, sewage sludge in compost, and wool pellets significantly enhanced growth relative to the control. In contrast, bacterial inoculants showed moderate effects, consistent with slower microbial action. Strong correlations between soil pH, SOC, AL-extractable nutrients—especially Mg—and sapling growth parameters emerged from the second sampling onward. Notably, a positive correlation between soil pH and AL-extractable Ca strengthened over time (1st : $r=0.253$, $p=0.63$, 2nd : $r=0.311$*, $p=0.021$; 3rd : $r=0.789$**, $p<0.001$; 4th : $r=0.874$**, $p<0.001$). These results highlight the crucial role of soil nutrient availability in the early development of woody plants. Organic amendments, such as sewage sludge compost and wool pellets, offer viable alternatives or supplements to mineral fertilizers, supporting the preservation of soil quality and sustainable nutrient management in reforestation and land reclamation.

Keywords Soil fertility · Robinia pseudoacacia · Sewage sludge compost · Wool pellet · Seedling growth · Reforestation

Abbreviations

AL-Ca	Ammonium-lactate extractable calcium
AL-K_2O	Ammonium-lactate extractable potassium
AL-Mg	Ammonium-lactate extractable magnesium
AL-P_2O_5	Ammonium-lactate extractable phosphorus

Extended author information available on the last page of the article

Published online: 03 June 2026

AVG	Average
BL	Black locust (*Robinia pseudoacacia* L.)
Cont.	Control
Man.	Cattle manure
DB	Debrecen (Hungary)
H	High dosage
Hum.	Humic acid fertilizer
L	Low dosage
Min.	Mineral fertilizer
RCBD	Randomized complete block design
Bat.	Soil bacterial inoculant
SEM	Standard errors of the mean
Sludge	Sewage sludge compost
SOC	Soil organic carbon
SRS	Simple random sampling
Wool	Wool pellet

Introduction

Plants rely on soil-derived nutrients to maintain their metabolism, support growth, and produce biomass. These fundamental physiological processes are affected by both species-specific genetic traits and by environmental conditions, including climate, soil physical and chemical properties, and agricultural management practices (Németh 2002, 2004). In this respect, a balanced nutrient supply considering plant needs can enhance biomass production and improve water-use efficiency (Sándor et al. 2025). Various fertilization methods provide nutrient alternatives and a balanced nutrient supply aligned with plant demands. Therefore, in addition to conventional mineral fertilizers, increasing attention is paid to the environmental impact of replenishment. Sustainable nutrient management strategies aimed at preserving or enhancing long-term soil fertility (Gabriel et al. 2006). An effective approach is the application of microbial inoculants, which contain beneficial microorganisms that stimulate soil biological activity, increase microbial diversity, and improve nutrient availability (Wu et al. 2005; Makádi et al. 2007).

In turn, the stress tolerance of forest ecosystems is based on complex physiological and environmental interactions. Hirata and colleagues (Hirata et al. 2022) identified the key climate-related stressors responsible for the shift in forest boundaries as (i) high solar radiation at low temperatures and (ii) drought, being particularly relevant in temperate zones. Abiotic stressors, such as drought or heat, significantly affect ecosystem functioning and species distribution. Their impact on agricultural productivity is difficult to model because they often coincide with random disturbances that disrupt the dynamic equilibrium (Boisvenue and Running 2006; Cramer et al. 2011).

The organic matter content of the soil – particularly humus – is crucial for soil fertility, alongside nutrient accessibility (Németh 2004; Micskei et al. 2009). The use of organic fertilizers and humic substances significantly improves soil structure, enhances biological activity, and replenishes organic matter reserves (Loch and Nosticzius 2004; Kádár 2013). Humus, the main reservoir of organic matter in soil, plays a key role in determining biologi-

cal activity (Stefanovits et al. 1999). In soils with low humus content, seasonal fluctuations in microbial activity tend to be more pronounced (Csubák et al. 2007; Kotroczó and Fekete 2020).

These soils typically have reduced water- and nutrient-holding capacity, making appropriate soil preparation and improvement essential for successful afforestation. Many soils in the region are acidic, which reduces microbial activity and nutrient availability (Kátai 2008). These soils, particularly in arid and semi-arid regions, are nutrient-poor; their productivity can be maintained only with appropriate and sustainable management practices (Mayer et al. 2015). Land use contributes to greenhouse gas emissions, releasing N_2O and CO_2. Hence, emissions measured under horticultural crops are significantly higher than those originating from grasslands or forest soils (Kong et al. 2013), owing to woody plants, the primary structural elements of forest ecosystems, which can stabilize sandy surfaces and mitigate wind erosion (Kristó 2017).

Black locust (*Robinia pseudoacacia* L.) is a fast-growing, nitrogen-fixing species native to North America. Owing to its high adaptability, it has become widespread in temperate regions (Barrett et al. 1990; Vítková et al. 2017). In its early developmental stages (1–5 years), black locust exhibits rapid height growth and can form a closed canopy even under suboptimal conditions (Rédei 2006). In the sandy landscapes of Nyírség, black locust can develop tall, straight trunks with dominant tree heights of 25–30 m. Nonetheless, as an invasive species, black locust poses significant ecological risks by displacing native species and altering natural habitats (Rédei et al. 2008; Nascimbene et al. 2012; Lazzaro et al. 2018). Despite these concerns, black locust is widely used for land reclamation, particularly on degraded, nutrient-poor, or contaminated sites with shallow topsoil and low pH value (Böhm et al. 2011; Hu et al. 2017; Du et al. 2019; Liu et al. 2020; Manolopoulos et al. 2022). The neutralization of acidic soils, e.g., by calcium amendments, can enhance microbial activity, improve soil structure, and increase nutrient availability (Makádi et al. 2012). Such interventions are primarily justified following coniferous clear-cuts, as used in our study, which often cause severe acidification (Jereb and Kondor 1996; Kocsis et al. 2025a). In addition to its ecological role, the black locust is highly valued economically. Its durable, rot-resistant, and pest-resistant wood is ideal for outdoor applications (e.g., as fence material or vineyard posts) and for furniture manufacturing, being chosen for its strength and durability (Rédei et al. 2008; Brischke et al. 2024; Cassens 2025; Meier 2025).

The Nyírség region is Hungary's second-largest sandy region. It exhibits climatic and ecological features like those of the Danube–Tisza Interfluve, which are increasingly affected by warming and drying trends (Führer et al. 2017). Topographical differences between northern and southern Nyírség affect the extent of sandy surfaces. In areas with sparse vegetation cover, wind erosion causes the formation of shifting sands and humus-poor sandy soils (Kádár and Szemes 1994). In Hungary, black locust has been used to stabilize sand since the early 1800's, and its favorable properties have long been recognized (Keresztesi 1983). The nutrient-poor, acidic sandy soils of Nyírség are particularly vulnerable to climate change and improper land management. Due to adverse climatic changes, the decline of native tree species in the region is anticipated. Achieving afforestation and agricultural goals requires proper nutrient replenishment, strategic organic matter management, and precise soil amelioration. While black locust can play a key role in these efforts, its use must be approached with caution due to its invasive characteristics.

This paper examines the impact of various organic and inorganic fertilizers on the early growth of black locust seedlings and the associated changes in rhizosphere soil properties. Our primary aim was to assess both the physical and chemical properties of the soil and the growth parameters of the seedlings, and to investigate potential correlations between them. The experiment was conducted in a small, open-field plot near Debrecen. Over a period of 2.5 years, shoot height, basal stem diameter, soil pH, soil organic carbon (SOC), and AL-extractable macronutrients (potassium, phosphorus, calcium, and magnesium) were systematically monitored.

We highlight the crucial role of soil nutrient availability in the early development of woody plants. Organic amendments, such as sewage sludge compost and wool pellets, offer viable alternatives or supplements to mineral fertilizers, helping preserve soil quality and promoting sustainable nutrient management in afforestation and land reclamation efforts.

Materials and methods

Study area and climatic conditions

The study was conducted in a forest management area supervised by Nyírerdő Co. Ltd. in sub-district 369/A of the South-Nyírség microregion, near Debrecen (Fig. 1). The area is located 123–126 m above the Adriatic Sea level on an undulating sandy ridge that rises 3–6 m above the surrounding terrain. Its hydrological regime is entirely precipitation-dependent, with no significant impact from excess surface water. The mesoclimatic conditions are highly unfavorable to plant growth and development.

According to the HUNGAROMET database, weather conditions have shown significant interannual variability in recent years (Table 1).

The year 2022 was characterized by below-average precipitation, with rainfall approximately 22% below the long-term mean. This deficit adversely affected reforestation operations in the fall, as persistently dry soil conditions limited the establishment success and stand development. In contrast, the weather conditions in 2023 were more favorable for

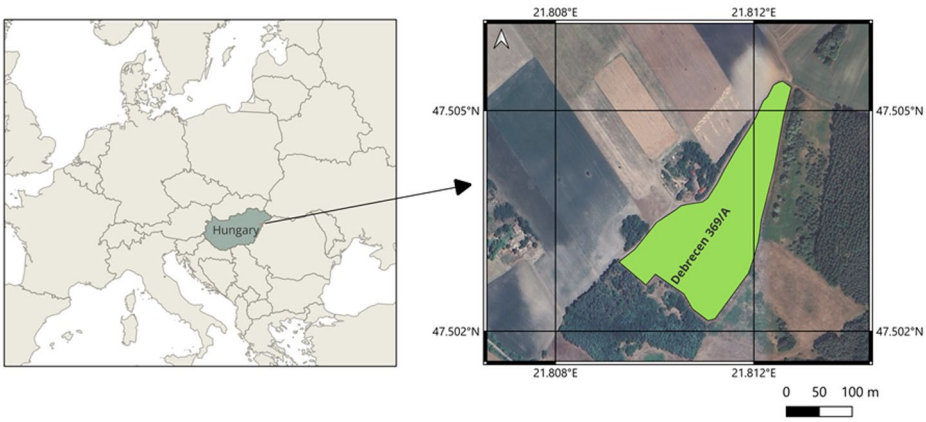

Fig. 1 The location of the examined forest area near Debrecen (Hungary) 369/A (GPSWGS84: 47.503, 21.811)

Table 1 Main meteorological characteristics of Debrecen over the years 2021–2025

Meteorological parameter	(1901–2020 AVG)	2021	2022	2023	2024	2025
Annual mean temperature [°C]	10.1	13.6	12.3	12.9	13.4	12.4
Annual precipitation [mm]	566.3	249.0	439.2	658.3	334.1	372.3

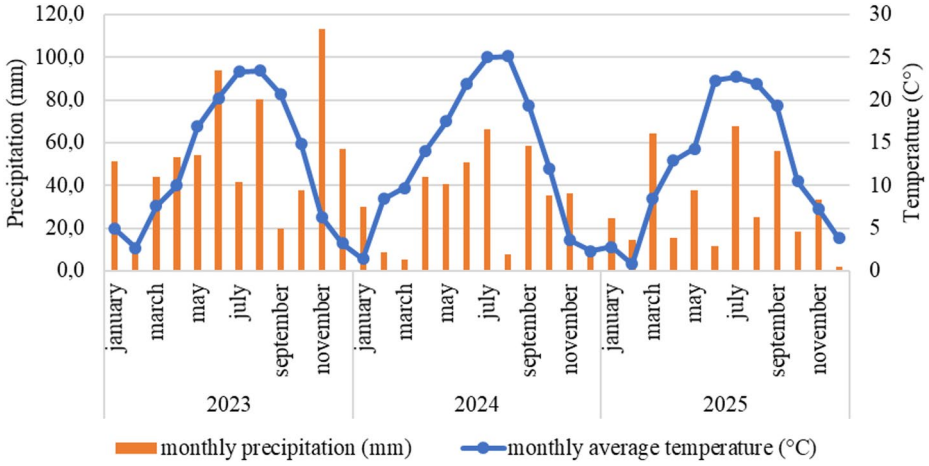

Fig. 2 Monthly precipitation (mm) and mean temperature (°C) during the experimental period (May 2023 – May 2025) in Debrecen, Hungary

plant growth and development. A second period of lower rainfall from late May to September 2024 (41% reduction relative to the long-term mean) caused high levels of defoliation of black locust seedlings over summer 2024. Moreover, a late frost in April 2025, with temperatures dropping to − 8 °C, affected the already leafed-out plants and caused further physiological damage. By the end of May, the total precipitation amounted to only 201.6 mm, increasing marginally to 213.2 mm by the end of June. Although occasional thunderstorms delivered 30–50 mm of rainfall within 24 h, accompanied by strong wind gusts, these events provided only a brief relief from drought stress and simultaneously caused considerable erosion and deflation of the loose sandy soils.

Monthly variations in precipitation and temperature (Fig. 2) showed pronounced differences in both parameters during the experimental period.

Soil characteristics

The forest stand described in the Study area section was an ex-58-year-old Scots pine (*Pinus sylvestris* L.) plantation, which caused significant soil acidification. Soil profiles excavated after the final harvest (2022) revealed an organic carbon content (SOC) of 4.33% in the 0–30 cm soil layer, while deeper than 30 cm, SOC values were below 0.10%. The topsoil contained undecomposed plant residues, which may have biased the measured SOC values. The soil was strongly acidic, with a pH (KCl) of 3.37 at 0–30 cm depth (Table 2).

Following deep ploughing (70 cm), the SOC content in the 0–30 cm soil layer decreased to 2.82%, while the pH (KCl) increased to pH 3.87, and the 30–70 cm layer contained

Table 2 The soil profile of the Debrecen 369/A forest section (Humus sand; WRB: Arenosols) (Kocsis et al. 2025b)

Horizon designation	Horizon depth (cm)	Description of the soil layer
Ah	0-3	Gray (7.5YR 5/1) color, single-grain sand, slightly humus-like level, rooted
E	3-20	Light Gray (7.5YR 7/1) color, single-grain sand, slightly humus-like level, rooted
Bw	20-55	Dark Brown (7.5YR 3/3) color, single-grain sand, heavily rooted
C	55-90	Reddish Yellow (7.5YR 6/6) color, single-grain sand, lightly rooted
Clr	90-160	Dark Gray (7.5YR 4/1) color, single-grain sand

Table 3 Elemental content (wt%) of fertilizers used at the Debrecen (DB) 369/A forest plot

Fertilizer wt%	Mineral fertilizer	Organic I. Humic acid	Organic II. Cattle manure	Organic III. Sewage sludge compost	Organic IV. Wool pellet
N	12.0	1.0	1.0	1.0	9.0
P	11.0	0.05	0.5	0.5	0.1
K	18.0	0.06	2.5	0.5	4.0
Ca	2.0	2.0	4.0	1.2	1.0
Mg	2.7	0.3	1.0	0.5	0.2

1.03% SOC. Prior to ploughing, SOC in this deeper layer was below 0.10%. These values indicate that deep ploughing redistributed organic matter within the soil profile, transferring part of the surface organic carbon into deeper layers. The soil at the site is classified as medium-deep humic sand with poor water-retention capacity and nutrient availability, being highly susceptible to wind erosion.

Forest restoration and soil treatments

Reforestation was conducted in December 2022 using black locust (*Robinia pseudoacacia* L.) seedlings sourced from the Nyírerdő Co. Ltd.'s Hajdúhadház Nursery (propagation material certificate No. HU/S-0000–151849; origin: Ramocsaháza 2 C; registration number: HU090125). Before mechanical planting, three central soil preparation interventions were performed: stump removal, land leveling, and deep ploughing. Stumps were removed using an excavator and subsequently piled into 100 m windrows using a tracked machine. After planting, various soil fertility treatments were applied in the strips (Table 3).

Bio stimulant Soil Bacterial Inoculant data are not available from the manufacturer.

Immediately after planting, the treatments were applied once by shallow incorporation (ca. 5–10 cm depth) into 50 cm wide planting strips using a hoe; no further treatments were applied during the study period. Black locust plants were cut at the base, just below the soil surface, to promote the development of new shoots. The incorporation was performed directly in the planting rows, ensuring localized placement of materials near the root zone.

Inter-row weed control was maintained by rotary cultivation. The dosage levels were determined based on nutrient content, local agronomic recommendations, and the characteristics of each material.

Layout of the experimental plots

Open-Field experiments were conducted to evaluate the effects of organic and inorganic soil amendments on early growth and soil responses in a black locust (*Robinia pseudoacacia* L.) plantation. A randomized complete block design (RCBD) with five replications was implemented, and stratified sampling ensured statistical validity and reproducibility. Sampling was restricted to the central 10 m of each 20 m treatment row to avoid edge effects. Rows were spaced 2.7 m apart, with 2.2 m buffer zones to account for field heterogeneity and prevent interactions between adjacent treatments. Within each replication, five trees were randomly selected, starting from a random point and then every second seedling, while five soil points were randomly designated. Leaf and soil samples were pooled into composite samples at four time points (May 2023, Oct 2023, Oct 2024, and May 2025) to provide representative, independent, and statistically robust data. Each treatment plot measured 10 m in length and 0.5 m in width, corresponding to the planting strips established by the machinery, and contained 20 evenly spaced seedlings. Seven treatments (T) were assessed, including a control (Cont.), and soil amendments were applied at one or two dosage levels. Specifically, mineral fertilizer (Min.), humic acid fertilizer (Hum.), cattle manure (Man.), and sewage sludge compost (Sludge) were utilized at two dosage levels: low (L) and high (H), whereas wool pellet (Wool) and soil bacteria inoculant (Bact.) were applied at a single dosage. Details of the treatments and their application rates are listed in Table 4.

The 11 treatment combinations (including the control) were replicated 5 times, resulting in 55 experimental plots.

The plots designated as (Cont.) served as control treatments. A balanced, chloride-free compound mineral fertilizer (Min.-L), (Min.-H), was applied, containing nitrogen (12%), phosphorus (11%), and potassium (15–18%) in fully plant-available forms. Nitrogen was present as both nitrate (≈5%) and ammonium (≈7%), enabling immediate uptake and sustained release. The formulation also included secondary nutrients such as sulfur (8–20%), calcium (1.5–2.6%), and magnesium (1.6–2.7%), as well as trace elements like boron, zinc, iron, and manganese. This fertilizer was chosen for its broad spectrum of macro-, meso-, and micronutrients, which are expected to exert a more favorable effect on our nutrient-poor, low-organic, structureless sandy soil than a simple NPK fertilizer, which is typically suitable for nutrient-rich agricultural soils. In our experiment, it was applied according to the manufacturer's recommendations, with lower and higher rates selected to represent safe and favorable doses, enabling clear evaluation of the effects of mineral fertilization on growth parameters relative to other treatments. A humic acid–rich soil amendment containing zeolite (Hum.-L and Hum.-H) was produced from lignite (humic acid content: 50 wt%). The material was dark grey to black with the following chemical composition: Ca (2.0 wt%), S (2.5 wt%), Fe (0.6 wt%), K_2O (0.06 wt%), and P_2O_5 (0.05 wt%). The material was processed into cylindrical pellets with a diameter of 6–8 mm and a pH of 7.5 (H_2O). The cattle manure (Man.-L), (Man.-H) used in the experiment consisted of well-matured, three-year-old material. The sewage sludge compost (Sludge-L) and (Sludge-H) were commercially available products obtained by co-composting municipal green waste with sewage sludge under

Table 4 Fertilizer doses of the DB 369/A sample site

Treatment's doses (fertilizers)	Control	Mineral fertilizer [g/m^2]	Organic I. Humic acid [g/m^2]	Organic II. Cattle manure [g/m^2]	Organic III. Sewage sludge compost [g/m^2]	Organic IV. Wool pellet [g/m^2]	Biostimulant Soil bacterial inoculant [mL/m^2]
(Cont.)*	X						
(Min.-L)		20					
(Min.-H)		40					
(Hum.-L)			200				
(Hum.-H)			400				
(Man.-L)				2000			
(Man.-H)				4000			
(Sludge-L)					2000		
(Sludge-H)					4000		
(Wool)						2500	
(Bact.)							10

**Cont.* control, *Min.-L* mineral fertilizer low dose, *Min.-H* mineral fertilizer high dose, *Hum.-L* humic acid low dose, *Hum.-H* humic acid high dose, *Man.-L* cattle manure low dose, *Man.-H* cattle manure high dose, *Sludge-L* sludge compost low dose, *Sludge-H* sludge compost high dose, *Wool* wool pellet, *Bact.* soil bacterial inoculant

controlled conditions. The wool pellet (Wool) was applied as an entirely natural organic concentrate. The wool pellet amendment is a pelletized organic product produced from processed sheep wool fibers with minor mineral additives (e.g., zeolite or alginite) to improve pellet stability. Sheep wool is rich in keratin-bound nitrogen (9% wt% N in dry matter) and has a relatively high C ratio, resulting in gradual microbial decomposition and slow nutrient release. Owing to these characteristics, the pellets function as a slow-release organic fertilizer, while their high water-holding capacity may also improve moisture retention in sandy soils. The biostimulant soil bacterial inoculant (Bact.) contained microorganisms including *Azotobacter chroococcum*, *Bacillus megaterium*, *Azospirillum brasilense*, and selected *Rhizobium japonicum* strains, specifically adapted for symbiotic nitrogen fixation in leguminous species (e.g., Black locust). Suspended in a nutrient solution, it was used to improve nutrient availability and activate biological processes in the soil. All these fertilizers are suitable for use in arable, horticultural, viticultural, and forestry systems.

Laboratory procedures and analytical methods

The study was conducted during the 2023, 2024, and 2025 growing seasons, involving regular soil and plant sampling and continuous monitoring. Samples were collected using a simple random sampling (SRS) method (Boncz 2015). The primary objective of the investigations was to assess the soil's physical and chemical properties and the seedlings' growth characteristics, and to explore potential correlations between them. Seedling height was measured utilizing a measuring rod up to the highest shoot tip, while basal stem diameter was recorded at the soil surface with a digital caliper.

Soil analyses were performed in the Soil Chemistry and Soil Biology Laboratories of the Institute of Agricultural Chemistry and Soil Science, Faculty of Agriculture, Food Science and Environmental Management at the University of Debrecen.

The soil organic carbon (SOC) content was determined using the Székely colorimetric method, according to the Hungarian standard procedure (Bálint et al. 1988; MSZ-08–0210:1977). This procedure is based on the oxidation of soil organic matter by $K_2Cr_2O_7$, resulting in a color change from orange to green in the solution. Measurements were performed at 580 nm using a Philips Unicam PU 8600 UV spectrophotometer to determine the organic carbon content of the soil samples. Soil pH was determined by mixing 1.0 part soil with 2.5 parts of 1 mol L^{-1} potassium chloride solution, following the Hungarian standard procedure (MSZ-08–0206/2:1978). The pH was determined with a Jenway 570 digital pH meter (Takamoto et al. 2023). The amount of ammonium lactate (AL)-soluble K_2O, P_2O_5, Ca, and Mg represents the fraction of the nutrients that plants can absorb easily. The P2O5 content of the AL filtrates (Egner et al. 1960; Kristoffersen et al. 2020) was measured photometrically (Buzás 1988). The amounts of AL-K_2O, AL-Ca, and AL-Mg were measured with an AA spectrometer (Varian AA10 Plus).

Statistical analysis of the results of plant and soil parameters was performed using the one-way analysis of variance (ANOVA), applying Tukey's post hoc test for multiple comparison at a significance level of $p \leq 0.05$in IBM SPSS statistics (Version: 28.0.0.0.(190)). Different letter symbols on the figures indicate significant differences. Data visualization (tables and figures) was performed using Microsoft Excel 2016 and IBM SPSS Statistics. Results are presented as mean ± 2 standard errors of the mean (SEM). Pearson correlation analysis was also conducted to evaluate relationships among the examined parameters.

Results

Seedling survival

Seedling survival was systematically monitored throughout the experimental period, and was defined as the proportion of the initial 20 black locust seedlings planted per plot that remained viable until May 2025 (Fig. 3).

The average number of surviving seedlings per replicate ranged from 13 (Min.-H) to 19 (Man.-H, Sludge-H, and Wool), with survival ranging from 64% to 97% across treatments. These findings demonstrate significant treatment effects on seedling viability. High-dose sewage sludge compost (Sludge-H) and wool pellet (Wool) treatments achieved the highest survival rates, surpassing those observed under conventional chemical and mineral fertilization. This highlights their potential as effective and ecologically sustainable alternatives to traditional fertilizers, underscoring their relevance in environmentally conscious afforestation practices.

Plant height as a key indicator of woody seedling development

Plant height is an essential characteristic parameter for monitoring the development of woody species during afforestation in Hungary, with a target height of 1.5 m for black locust within five years, indicating afforestation success. Under the former Hungarian forestry regulation (Ministerial Decree No. 153/2009. (XI.13.) FVM) forest regeneration could

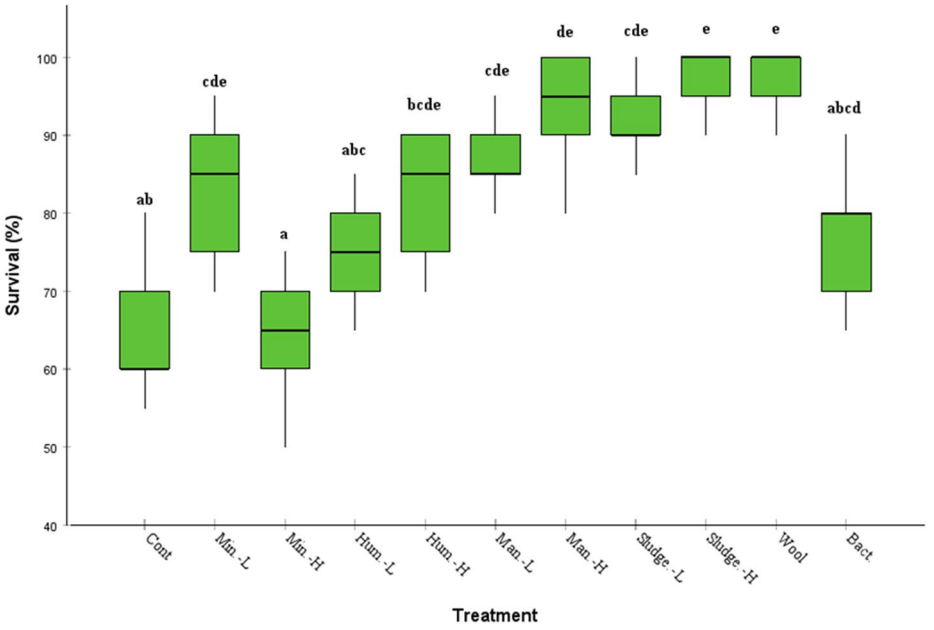

Fig. 3 Post treatment survival of black locust (*Robinia pseudoacacia* L.) seedlings after 2.5 years (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

be declared complete once the average height of the principal tree species exceeded 1.5 m. Although this requirement is no longer included in the current legal framework, it is still commonly applied by forestry authorities during field inspections.

Under the currently effective regulation (Ministerial Decree No. 61/2017. (XII.21.) FM) completion is primarily based on stocking density, species composition, and stand structure, rather than a fixed height threshold. Nevertheless, the height criterion remains relevant in specific cases: a mean height of 2.0 m remains a significant criterion for declaring completion when stocking density is insufficient, if crown closure exceeds 80% (Sect. 36(6)). Although the former Hungarian Ministerial Decree No. 153/2009 (XI. 13.) FVM, Sect. 30(1)(e) prescribed a general 1.5 m threshold, this requirement is no longer part of the present legal framework. Thus, while the former 1.5 m criterion persists in practice, current legislation applies height requirements mainly as an exceptional condition under reduced stocking scenarios.

Table S1 summarizes the effects of different fertilization treatments on plant height over two growing seasons. The listed data reveal that at the first measurement date, the applied fertilizers already exerted varying but overall positive effects on seedling growth. The smallest growth response occurred with high-dose mineral fertilizer (Min.-H), low-dose humic acid (Hum.-L), low-dose sewage sludge compost (Sludge-L), and bacterial inoculant (Bact.). By contrast, the greatest increase in height happened with the high-dose humic acid-based treatment (Hum.-H).

At the second measurement date, the beneficial effects of fertilization on plant height became more pronounced. The consistently favorable effects of low-dose mineral fertilizer (Min.-L) and high-dose sewage sludge compost (Sludge-H) on seedling height and development arose throughout the experimental period. By the end of the study (Fig. 4), seedlings treated with wool pellet fertilizer (Wool) reached the same height as the Min.-L and Sludge-H treatments. As expected, bacterial inoculants (Bact.) resulted in moderate but continuous growth. According to the experimental hypothesis, if the applied microorganisms can proliferate in the soil, their activity can be stimulated by increased litter input and decomposition, potentially triggering autocatalytic biological processes. Our results suggest that while the bacterial inoculant showed a height-enhancing effect compared to the control, it did not reach the effectiveness of the other fertilization treatments.

Basal stem diameter as an indicator of woody plant development

The development of woody plants is monitored effectively by tracking changes over time in their basal stem diameter. According to the data displayed in Table S2, variations in stem diameter were already evident at the first measurement, after applying different fertilization treatments.

Compared with the control, the most pronounced stem thickening occurred in seedlings treated with a low-dose mineral fertilizer (Min.-L) and a high-dose humic acid (Hum.-H). These findings align with the results obtained for plant height (Table S1). At this early stage, the bacterial fertilizer (Bact.) had no measurable effect on stem diameter. The remaining treatments produced varying degrees of positive responses.

At the second sampling, the enhancing effect on basal diameter of the low-dose mineral fertilizer (Min.-L) and the high-dose sewage sludge compost (Sludge-H) became even more

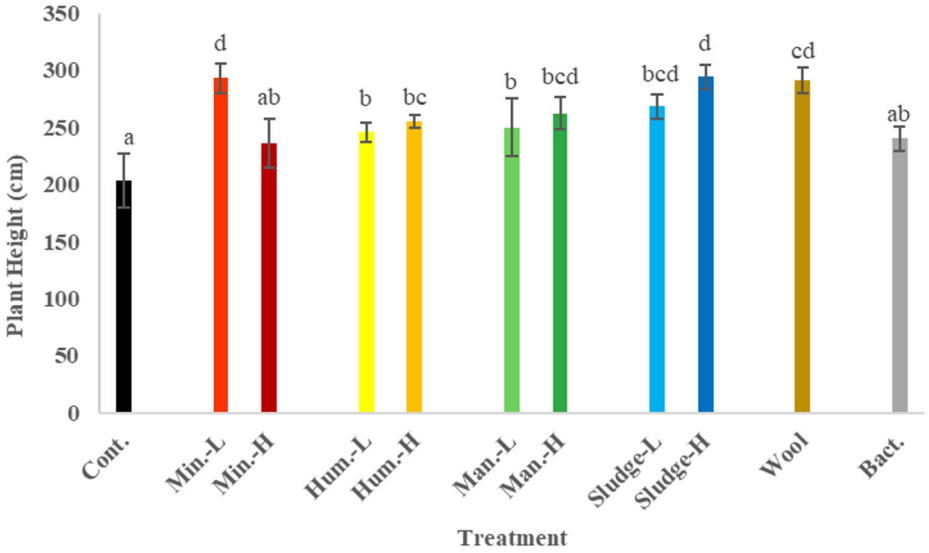

Fig. 4 Changes in plant height in response to different fertilization treatments by the end of the study (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

apparent. During this period, farmyard cattle manure, humic acid, and wool pellet treatments also significantly increased stem thickness.

By the fourth measurement date (Fig. 5), the low-dose mineral fertilizer (Min.-L) continued to produce the most significant increase in basal stem diameter. Nevertheless, the effects of organic treatments containing higher amounts of organic matter closely approached those of mineral fertilizer, indicating a similarly favorable effect on woody plant growth.

Humic acid treatments (HA-L and HA-H) produced the lowest sturdiness ratios (92.8; group a), indicating more compact growth and a more favorable height-to-diameter balance. In contrast, the wool pellet treatment resulted in the highest sturdiness ratio (105.7; group b). Other treatments, including mineral fertilizers, cattle manure, sludge compost, and soil bacterial amendments, showed intermediate values (93.6–102.8; group ab) and did not differ significantly from the control. These results indicate that certain organic amendments can impact the height-to-diameter balance, whereas most treatments have limited effects on tree morphology (Fig. 6). The RCBD design with 270 cm row spacing, 50 cm seedling spacing, and 220 cm treatment-free buffer zones ensured that the observed differences primarily reflected treatment effects while maintaining overall stand uniformity.

Soil test results

For the harmonious development of plants, they should absorb the necessary nutrients primarily from the soil. Several environmental factors affect the concentration of available nutrients, including soil pH, which modifies nutrient availability in the soil solution – and consequently plant uptake – both directly and indirectly. Its direct effect is related to nutrient solubility (Hartemink and Barrow 2023). Indirectly, soil pH changes the life of soil micro-

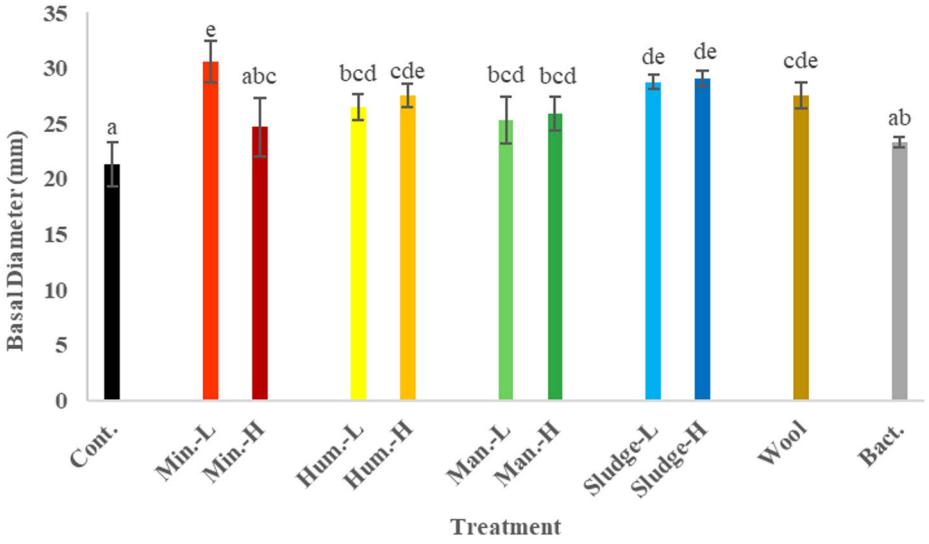

Fig. 5 Impact of fertilization on the basal diameter growth of black locust seedlings by the end of the study (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

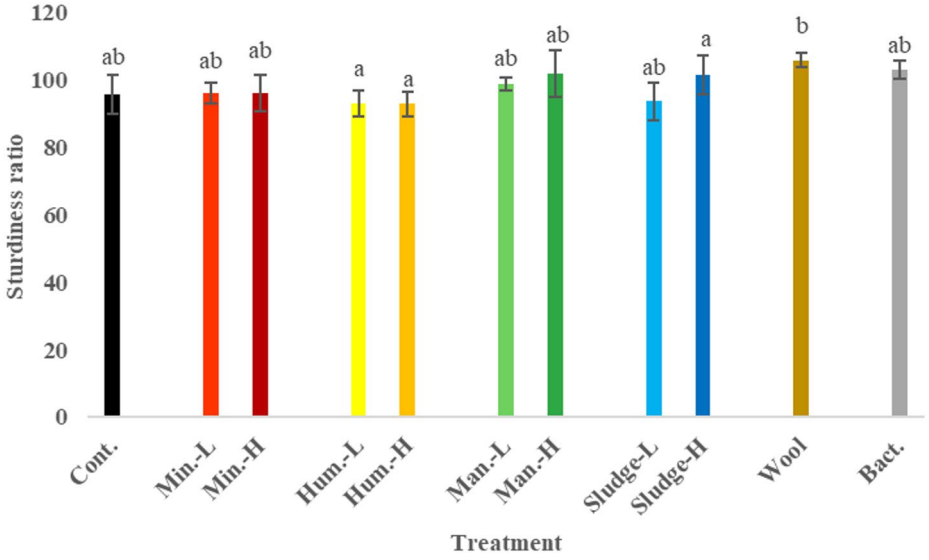

Fig. 6 Sturdiness ratio of black locust seedlings by the end of the study (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

organisms, thereby modifying the direction and outcome of decomposition and transformation processes. It also affects the physico-chemical properties of soils, including colloidal stability and cation exchange capacity (Neina 2019). Acidic conditions hinder the conversion of organic matter and the nitrification process (Cheng et al. 2013). Nutrient uptake by plants is most favorable under slightly acidic to neutral pH conditions (Loch and Nosticzius 2004). Therefore, soil treatments that increase the pH of the experimental soil from strongly acidic to less acidic values can benefit the growth of black locust seedlings.

Table S3 summarizes soil pH values; the listed data reveal that specific treatments have already increased soil pH in the year of application. Utilizing mature organic cattle manure (Man.-L and Man.-H) exerted a positive effect on this soil parameter, with higher doses resulting in a greater increase in pH. An even greater pH increase occurred following sewage sludge compost (Sludge-L and Sludge-H). The wool pellet (Wool), recently introduced for plant nutrition, modified the strongly acidic soil toward near-neutral pH within the studied soil layer. This change was statistically significant and sustained over the three-year-long experimental period.

By contrast, the bacterial inoculant (Bact.) did not alter soil pH. At the final sampling date (Fig. 7), the statistically significant pH-increasing effect, which is a consequence of the high-dose organic cattle manure (Man.-H), sewage sludge compost (Sludge-L and Sludge-H), and wool pellet (Wool) applications.

Maintaining and increasing soil organic matter content is a key objective for sustainable land management. Soil organic matter significantly affects soil water retention capacity (Rawls et al. 2003), redox conditions (Fiedler and Kalbitz 2003), microbial activity (Szoboszlay et al. 2017), and nutrient availability by reducing leaching losses (Bashir et al. 2021). Table S4 lists the soil organic carbon content and its changes over time under different treat-

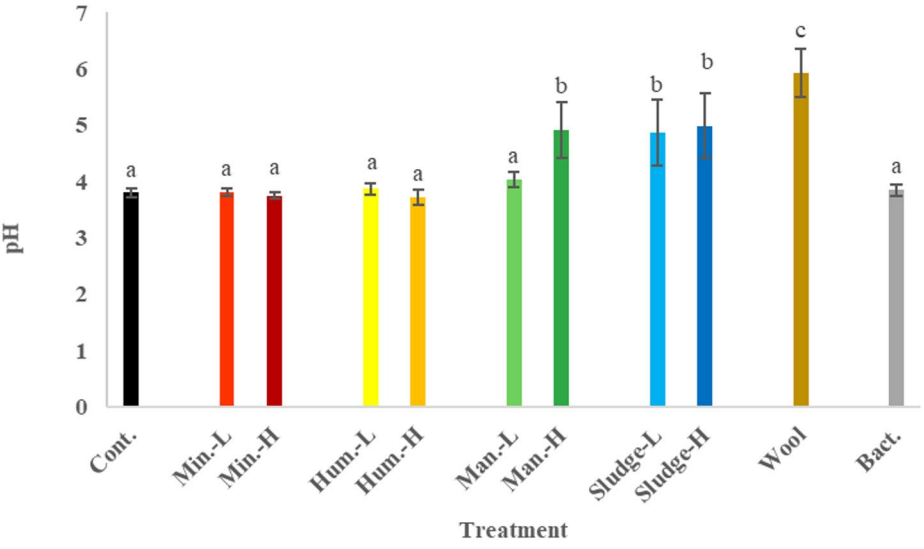

Fig. 7 Changes in soil pH as affected by different fertilization treatments by the end of the study (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

ments. The organic matter content increased significantly in all organic treatments during the studied period.

The amount of litter entering the soil depends on plant biomass, which is influenced by seedlings' nutrient status and physiological condition, as well as by environmental factors, such as wind and erosion. This may explain why, within a given treatment, the measured parameter did not always increase monotonically over time. The fertilizers impacted the soil organic carbon content as early as the first sampling after application. Compared with the control (Cont.) and mineral fertilizer treatments, Min.-L and Min.-H, the Hum.-H treatment, which contained a high dose of humic acids, showed a significant increase. In soils treated with cattle manure (Man.-L and Man.-H), the increase in organic carbon content was even greater, and this was also statistically relevant. The most pronounced statistically significant rise was observed with the application of the high-dose sewage sludge compost (Sludge-H). At this point, the positive effect of wool pellet treatment (Wool) was not yet evident, as its decomposition and conversion in the soil is time-consuming. Its beneficial effects, however, became increasingly apparent over time and were statistically verifiable. We established that two and a half years after the experiment (Fig. 8), soil treated with wool pellets had the highest organic carbon content.

Our experimental soil is classified as very poor in potassium supply (Buzás and Fekete 2004; Loch and Nosticzius 2004). Therefore, applying any fertilizer containing potassium can significantly increase the readily available potassium fraction in the soil, which is beneficial for plants. According to the data in Table S5, the readily available potassium content of the soils decreased over time, indicating that the rate of potassium uptake by the plants exceeded the rate at which potassium was converted into plant-available forms from soil reserves. The conversion of potassium occurred by physical, chemical, and biological processes.

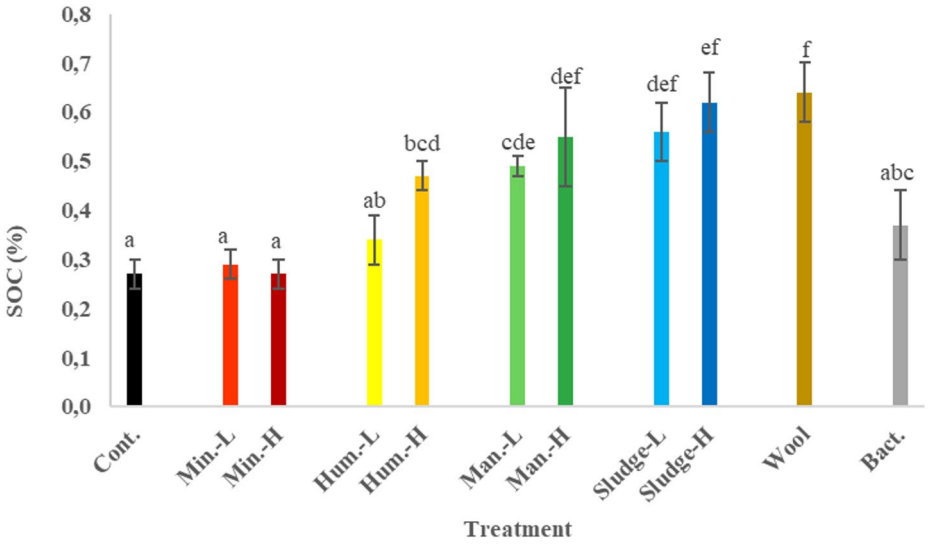

Fig. 8 Changes in soil organic carbon content in response to fertilizer treatments by the end of the study (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

At the first sampling date, a high dose of mineral fertilizer (Min.-H) was applied, resulting in a statistically significant increase in the soil's AL-extractable potassium (K_2O) content. Soils amended with organic cattle manure (Man.-L and Man.-H) and sewage sludge compost (Sludge-L and Sludge-H) exhibited higher K_2O concentrations than the control and other treatments, and the differences were statistically significant. This positive effect persisted throughout the experiment.

The beneficial impact of wool pellet treatments on soil potassium levels (Wool) became apparent by the second sampling date. This adjustment involved mixing zeolite powder with wool. The conversion of zeolite-bound potassium into AL-extractable forms required time for physical, chemical, and biological weathering processes to occur. The sustained positive effect of this treatment parallels that observed in cattle manure and sewage sludge compost (Fig. 9).

The phosphorus availability of our soil is very low (Buzás and Fekete 2004). Therefore, plants growing in it require supplemental phosphorus nutrition (Table S6). Following mineral fertilization (Min.-L and Min.-H), the soil phosphorus content increased by the first sampling date (Time Point 1), especially in the high-dose treatment (Min.-H). Nonetheless, this positive effect was not present in the later sampling periods.

The phosphorus in the mineral fertilizer was present in readily soluble forms, enabling efficient and rapid uptake by plants. However, these soluble P_2O_5 forms are also prone to loss through leaching or fixation, particularly in acidic soils, where aluminum and iron phosphates can readily form, thereby reducing phosphorus availability. Application of organic cattle manure (Man.-L and Man.-H) significantly increased the soil's AL-extractable phosphorus content during the initial phase of the experiment (first sampling), and this elevated level lasted over the subsequent years (Fig. 10). The highest phosphorus concentration was present in soils treated with sewage sludge compost (Sludge-L and Sludge-H) at the first

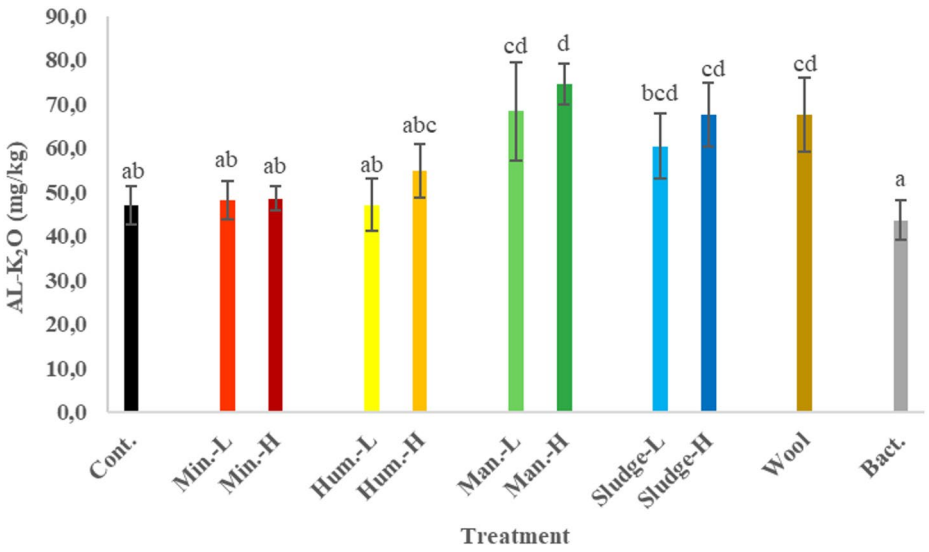

Fig. 9 Changes in soil AL-extractable potassium (K_2O) content in response to fertilizer treatments by the end of the study (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

sampling. Although values declined substantially in subsequent samplings relative to the initial measurement, the positive effect of sewage sludge compost on available phosphorus persisted throughout the study period. The decline over time may result from plant uptake, leaching, or conversion to less available forms.

Most applied fertilizers contain considerable amounts of calcium, resulting in a significant increase in AL-extractable calcium content of the soil by the first sampling—except for the bacterial inoculant (Bact.) and the wool pellet (Wool); see the data in Table S7.

The most significant increase in AL-extractable calcium content was in soil treated with high-dose mineral fertilizer (Min.-H), organic cattle manure (Man.-H), and sewage sludge compost (Sludge-H). The plant-available calcium fraction in the soil decreased over time across all treatments, although the rate and pattern of this decline varied. In treatments with fertilizers rich in organic matter, the decline in calcium content over time was slower than the faster decrease observed in mineral fertilizer treatments. This is likely due to a portion of organically bound calcium or Ca^{2+} in chelated complexes, offering a more stable calcium reservoir in the soil. Conversely, the opposite trend happened when using wool pellets (Wool). Due to the slow chemical and biological decomposition of wool pellets, the calcium they contain is released gradually. While plants absorbed part of the readily available calcium, a substantial amount remained protected from loss because of the high organic matter content of this fertilizer. (Fig. 11)

At the first sampling date, statistically significant increases in soil AL-extractable magnesium concentrations were present in soils treated with organic cattle manure, sewage sludge compost, and wool pellets, relative to the control (Cont.) (Table S8).

At later sampling dates, a gradual decline in soil AL-extractable magnesium concentration was observed across most treatments, with the wool pellets (Wool) showing a notably different pattern. By the fourth sampling (Fig. 12), the AL-extractable Mg content in soils

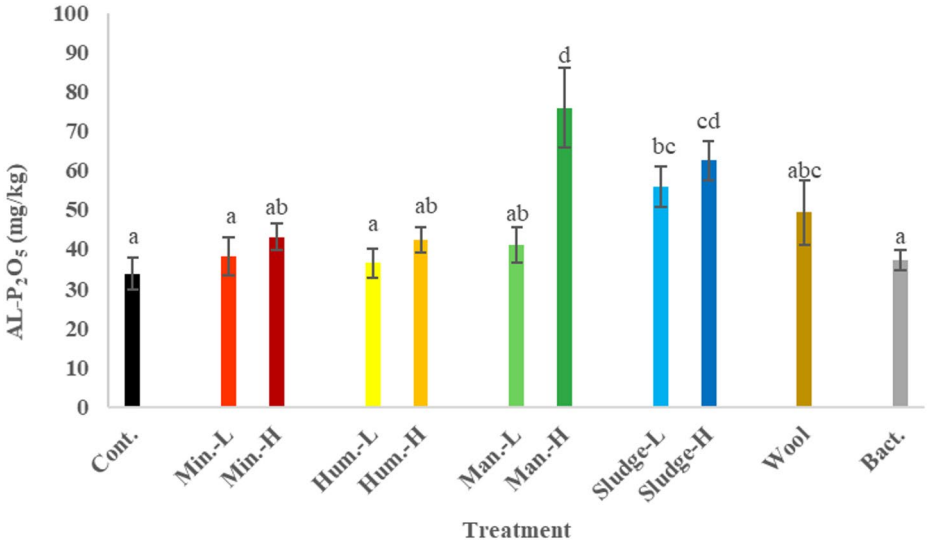

Fig. 10 Changes in soil AL-extractable phosphorus (P_2O_5) content in response to fertilizer treatments by the end of the study (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

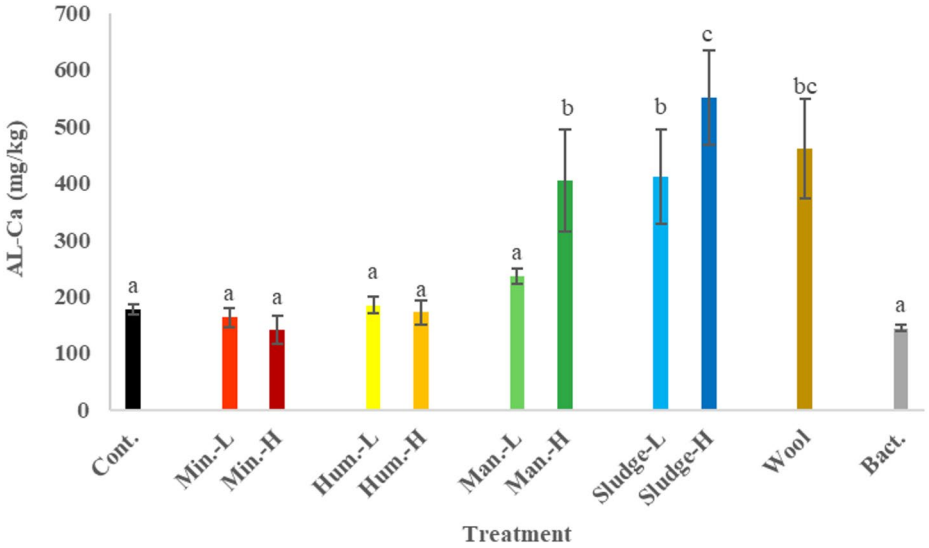

Fig. 11 Changes in soil AL-extractable calcium (Ca^{2+}) content in response to fertilizer treatments by the end of the study (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

treated with the wool pellet decreased only marginally, likely because of the sustained residual effects of the wool pellet compost.

Correlation analysis of soil parameters (Table S9) revealed strong positive relationships at the first sampling between soil pH, organic carbon content, and AL-extractable concentrations of potassium, phosphorus, and magnesium. Unexpectedly, there was no significant correlation between soil pH and AL-extractable calcium at this stage. Soil organic carbon content exhibited a consistent, strong positive correlation with all measured AL-extractable nutrients, and strong intercorrelations were also present among these nutrients themselves. At the second sampling, the strong relationships persisted, with the emergence of a statistically significant positive correlation between soil pH and AL-extractable calcium ($r=0.311^*$, $p=0.021$). This correlation was further strengthened in the third and fourth samplings (3rd: $r=0.789^{**}$, $p<0.001$; 4th: $r=0.874^{**}$, $p<0.001$), indicating an increasingly close relationship over time.

Correlation of results between plant and soil parameters

Initially, no significant correlation was found between soil pH and the measured plant parameters (Table S10). Over time, a robust correlation emerged with plant height and a strong correlation with stem diameter (Fig. 13). From the second sampling onward, we uncovered a powerful positive relationship between soil organic carbon content and plant parameters. Likewise, from the second sampling, strong to robust correlations were found between soil AL-extractable nutrient levels and both seedling height and stem diameter, and notably, at the first sampling, soil magnesium content already exhibited a strong correlation with seedling height.

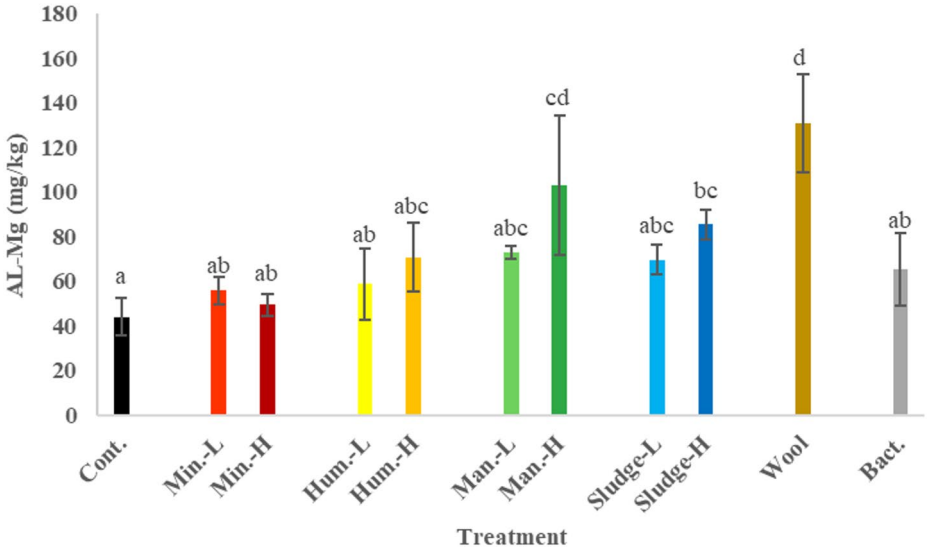

Fig. 12 Changes in soil AL-extractable magnesium (Mg^{2+}) content in response to fertilizer treatments by the end of the study (Control (Cont.), mineral fertilizer low and high dose (Min.-L, Min.-H), humic acid low and high dose (Hum.-L, Hum.-H), manure low and high dose (Man.-L, Man.-H), sludge low and high dose (Sludge-L, Sludge-H), wool amendment (Wool), and bacterial inoculum (Bact.))

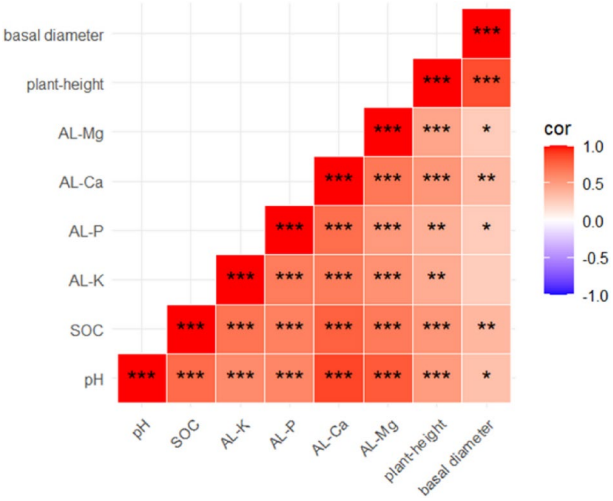

Fig. 13 Pearson correlation analysis results between seedling growth parameters and soil properties by the end of the study

Discussion

The early growth of woody plants is intricately linked to the physical and chemical characteristics of the soil and to nutrient availability. In experiments conducted on a strongly acidic, low in organic matter, and structurally poor soil, we investigated the effects of various organic and inorganic fertilizers on the growth dynamics of black locust (*Robinia pseudoacacia* L.) seedlings. Juvenile plant growth was monitored over 2.5 years by measurements

of shoot height and basal stem diameter. Among the treatments, low-dose chemical fertilizer and high-dose humic acid application have proven the most effective in stimulating initial vegetative growth. By the end of the second year, organic fertilizers—including cattle manure, sewage sludge-based compost, and wool pellets—also exhibited positive effects on biomass accumulation and morphological strengthening of the seedlings. The prolonged extreme drought event in 2024 significantly impacted the outcomes of the plant development assessments.

Over the 2.5-year evaluation period, black locust saplings treated with sewage sludge compost triggered the highest average height, reaching 294.4 cm, while those in the untreated control group had the lowest average height of 203.6 cm (Fig. 4). This represents a substantial height difference of 90.8 cm or 144.6% between the control and the compost-treated plants. Additionally, the low-dose mineral fertilizer (293.4 cm) and wool pellet treatments (291.4 cm) also resulted in notably high plant heights. Previously, wool pellets have been used primarily for vegetable cultivation (Bradshaw and Hagen 2022). The microbiologically based fertilizer (bacterial inoculant) demonstrated limited efficacy within the study period. Under the reported experimental conditions, we do not recommend short-term application of a bacterial inoculant and a high-dose, fast-acting mineral fertilizer, as these treatments do not provide significant improvements in growth parameters. Our results indicate that elevating soil pH—shifting from strongly acidic toward mildly acidic or slightly alkaline conditions—exerts both direct and indirect beneficial effects on nutrient uptake, notably by mobilizing cationic nutrients such as Ca^{2+}, Mg^{2+}, and K^{+}.

At the initial sampling date, when plant growth commenced, soil extractable magnesium content exhibited the strongest correlation ($r=0.358$**) with plant height, and this relationship persisted throughout the study period, with only a slight increase in correlation strength over time. A progressively stronger and statistically significant correlation was observed between AL-Ca (ammonium-lactate extractable calcium) concentrations and black locust plant height throughout the experimental period (Table S10). The correlation coefficients exhibited an increasing trend over time: in Year 1 (Date 1), $r=0.215$; in Year 1 (Date 2), $r=0.465$**, in Year 2, $r=0.486$**, and in Year 3, $r=0.537$**. Note: ** indicates statistical significance at $p<0.01$. A similar upward trend was observed for soil organic carbon content (SOC%) and soil pH. This pattern emphasizes the agronomic importance of magnesium and calcium availability in promoting biomass accumulation, particularly in the studied calcium-deficient soils. The results suggest that targeted nutrient supplementation can significantly boost plant growth on marginal soils by enhancing the availability of essential secondary macronutrients, such as calcium, which is critical for cell wall formation, root system development, and resilience to environmental stress (Németh 2004; Micskei et al. 2009; Makádi et al. 2012).

Achieving pH modification through the addition of organic matter is advantageous because it improves soil structure, water retention, and aeration. At the same time, it enhances the proportion of exchangeable and soluble nutrient forms. By the end of the experimental period, the strongest correlations with black locust plant height were observed with soil pH ($r=0.512$**) and soil organic matter content ($r=0.533$**). These results highlight the significant role of soil chemical properties—specifically pH and organic matter—in promoting tree growth, likely through their influence on nutrient availability, microbial activity, and overall soil fertility (Loch and Nosticzius 2004; Cheng et al. 2013).

Throughout the study, the most effective fertilizer treatments were cattle manure, sewage sludge compost, and wool pellets. For these organic amendments, application should precede seedling planting by at least 5–6 months to allow mineralization to release nutrients promptly for optimal plant uptake.

Humic acid-containing products showed pronounced effects primarily during the early growth stages but exhibited moderate long-term efficacy. Therefore, their use in combination with other organic fertilizers is advisable. Bacterial inoculants may have beneficial effects when applied in conjunction with organic amendments; however, further experiments are needed to confirm this under the given conditions. The average number of surviving seedlings per replicate varied from 64% to 97% across treatments. These findings demonstrate significant treatment effects on seedling viability, a key determinant of reforestation success. High-dose sewage sludge compost (Sludge-H) and wool pellet (Wool) resulted in the highest survival. In contrast, the low-dose mineral fertilizer treatment (Min.-L) yielded 83% survival, while the high-dose mineral fertilizer treatment (Min.-H) showed the lowest survival among all treatments, at only 64%.

These results highlight the potential of alternative fertilization strategies, demonstrating that both organic and low-input mineral amendments can produce similar growth outcomes. Notably, our study emphasizes that these fertilizers can be interchangeable, enabling the adoption of site-specific, environmentally sustainable nutrient management practices, especially in situations where conventional inputs are limited, expensive, or ecologically unsuitable.

We stress the need for extended-duration studies that incorporate detailed microbiological and nutrient-supply analyses to accurately assess the true efficacy of microbiological fertilizers.

Conclusions

Our study demonstrates that both organic and inorganic fertilizers significantly affect the growth and survival of woody plants, with plant height and survival emerging as particularly sensitive indicators. Positive effects were evident from the initial sampling, becoming more pronounced over time, with low-dose mineral fertilizer (Min.-L), high-dose sewage sludge compost (Sludge-H), and wool pellets consistently yielding the highest growth and survival outcomes. Humic acid (Hum.-H) enhanced early growth, whereas bacterial inoculants (Bact.) showed only moderate effects. Wool pellets matched the performance of the most effective mineral and compost treatments, highlighting their potential as a long-term, environmentally sustainable alternative, particularly for small-scale applications. These amendments were effective under challenging conditions—acidic, nutrient-depleted soils with limited plant-available water — in the Nyírség region of Hungary, offering the potential to enhance seedling establishment, growth, and resilience in areas exposed to climatic extremes. By promoting early development, high survival, and soil fertility, our results provide actionable guidance for afforestation, land reclamation, and soil restoration, supporting sustainable fertilization strategies that mitigate the negative impacts of climate change.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11056-026-10191-4.

Acknowledgements The authors express special thanks to the Institute of Agricultural Chemistry and Soil Science at the Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, for accommodating the authors in its laboratory, and to Nyírerdő Nyírségi Erdészeti, Ltd., (Nyíregyháza, Hungary), where the samples were collected for this investigation. This research was supported by the Ministry of Innovation and Technology of Hungary through the MEC_24 "Tudományos Mecenatúra Pályázat" program. This work was supported by the University of Debrecen Program for Scientific Publication.

Author contributions Conceptualization, I.A.K. and I.K.; methodology, I.A.K. and I.K.; software, I.A.K., R.K., K.E.J. and I.K.; formal analysis, investigation, I.A.K., I.K., and Z.S.; resources, A.K.B.; data curation, I.A.K. and I.K.; writing—original draft preparation, I.A.K. and I.K; writing—review, editing, proofreading, and style improvement, I.A.K. and D.A.L.; visualization, I.A.K.; supervision, Z.S.; project administration, Z.S. All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by University of Debrecen.

Data availability The data presented in this study are available on request from the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Bálint Sz Füleky, Gy, Győri D, Hargitai L, Kardos J, Lukács A, Molnár E (1988) Talaj- és agrokémiai vizsgálati módszerkönyv 2. (Soil and agrochemical test methods, Part 2). Mezőgazdasági Könyvkiadó Vállalat

Barrett RP, Mebrahtu T, Hanover JW (1990) Black locust: a multipurpose tree species for temperate climates. In: Janick J, Simon JE (eds) Advances in New Crops. Timber Press, pp 278–283

Bashir O, Ali T, Baba ZA, Rather GH, Bangroo SA, Mukhtar SD, Naik N, Mohiuddin R, Bharati V, Bhat RA (2021) Soil organic matter and its impact on soil properties and nutrient status. In: Microbiota and biofertilizers, Vol 2. Springer International Publishing, Cham, pp 129–159

Böhm C, Quinkenstein A, Freese D (2011) Yield prediction of young black locust (*Robinia pseudoacacia* L.) plantations for woody biomass production using allometric relations. Ann Res 54(2):215–227

Boisvenue C, Running SW (2006) Impacts of climate change on natural forest productivity-evidence since the middle of the 20th century. Glob Change Biol 12:862–882

Boncz I (2015) Kutatásmódszertani alapismeretek (Foundation of research methodology). University of Pécs, Pécs

Bradshaw T, Hagen K (2022) Wool pellets are a viable alternative to commercial fertilizer for organic vegetable production. Agronomy 12(5):1210. https://doi.org/10.3390/agronomy12051210

Brischke C, Stolze H, Koddenberg T, Vek V, Caesar CMC, Steffen B, Taylor AM, Humar M (2024) Origin-specific differences in the durability of black locust (*Robinia pseudoacacia*) wood against wood-destroying basidiomycetes. Wood Sci Technol 58(4):1427–1449. https://doi.org/10.1007/s00226-024-01571-0

Buzás I (1988) Physico-Chemical and Chemical Testing Methods of Soils. Mezőgazdasági Kiadó, Budapest

Buzás I, Fekete A (2004) Fertilization guidelines and farm calculation method. MÉM NAK, Budapest

Cassens DL (2025) Hardwood lumber and veener series – Black locust. Purdue University Extensions. https://www.extension.purdue.edu/extmedia/FNR/FNR-277-W.pdf. (Accessed 06 June 2025)

Cheng Y, Cai Z, Chang SX, Wang J, Zhang J (2013) Effects of soil pH and salt on N2O production in adjacent forest and grassland soils in central Alberta, Canada. J Soils Sediments 13(5):863–868. https://doi.org/10.1007/s11368-013-0663-9

Cramer GR, Urano K, Delrot S, Pezzotti M, Shinozaki K (2011) Effects of abiotic stress on plants: a systems biology perspective. BMC Plant Biol 11(1):163. https://doi.org/10.1186/1471-2229-11-163

Csubák M, Posta J, Zsuposné O (2007) Á Összefüggések a humuszsavak kémiai összetétele és a talaj biológiai aktivitása között (Relationships between the chemical composition of humic acids and the biological activity of soil). In: Food and Agriculture Organization of the United Nations. Rome, pp 1–10

Du B, Pang J, Hu B, Allen DE, Bell TL, Pfautsch S, Netzer F, Dannenmann M, Zhang S, Rennenberg H (2019) N2-fixing black locust intercropping improves ecosystem nutrition at the vulnerable semi-arid Loess Plateau region, China. Sci Total Environ 688:333–345. https://doi.org/10.1016/j.scitotenv.2019.06.245

Egner H, Riehm H, Domingo WR (1960) Untersuchungen über die chemische Bodeanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II Chem Extraktionsmethoden Zur Phosphor-Kaliumbestimmung. K Lantbrukshogskolans Ann 26:199–215

Fiedler S, Kalbitz K (2003) Concentrations and properties of dissolved organic matter in forest soils as affected by the redox regime. Soil Sci 168(11):793–801. https://doi.org/10.1097/01.ss.0000100471.96182.03

Führer E, Gálos B, Rasztovics E, Jagodics A, Mátyás C (2017) Erdészeti klímaosztályok területének változása (Change in the area of forest climate classes). Erd Lapok 152:174–177

Gabriel D, Roschewitz I, Tscharntke T, Thies C (2006) Beta diversity at different spatial scales: plant communities in organic and conventional agriculture. Ecol Appl 16(5):2011–2021

Hartemink AE, Barrow NJ (2023) Soil pH - nutrient relationships: the diagram. Plant Soil 486(1–2):209–215. https://doi.org/10.1007/s11104-022-05861-z

Hirata A, Kominami Y, Ohashi H, Tsuyama I, Tanaka N, Nakao K, Hijioka Y, Matsui T (2022) Global estimates of stress-reflecting indices reveal key climatic drivers of climate-induced forest range shifts. Sci Total Environ 824:153697. https://doi.org/10.1016/j.scitotenv.2022.153697

Hu B, Zhou M, Dannenmann M, Saiz G, Simon J, Bilela S, Liu X, Hou L, Chen H, Zhang S, Butterbach-Bahl K, Rennenberg H (2017) Comparison of nitrogen nutrition and soil carbon status of afforested stands established in degraded soil of the Loess Plateau, China. Ecol Manag Restor 389:46–58. https://doi.org/10.1016/j.foreco.2016.12.011

Jereb O, Kondor A (1996) Erdőműveléstan III. (Silviculture III). Dinasztia Kiadó, Budapest

Kádár I (2013) Szennyvizek, iszapok, komposztok, szervestrágyák a talajtermékenység szolgálatában (Wastewater, sludge, composts, organic fertilizers in the service of soil fertility). Magyar Tudományos Akadémia ATK Talajtani és Agrokémiai Intézet, Budapest

Kádár I, Szemes I (1994) A nyírlugosi tartamkísérlet 30 éve (Thirty years of the Nyírlugos long-term experiment). MTA Talajtani és Agrárkémiai Kut. Int, Budapest

Kátai J (ed) (2008) Talajtan, Talajökológia (Soil science, Soil ecology). Észak-alföldi Régióért Kht, Debrecen

Keresztesi B (1983) Breeding and cultivation of black locust, *Robinia pseudoacacia*, in Hungary. For Ecol Manage 6(3):217–244. https://doi.org/10.1016/s0378-1127(83)80004-8

Kocsis I, Kincses I, László Z, Lowy D, Sándor Z (2025a) Effectiveness of soil nutrient supplements on Black locust reforestation in Eastern Hungary. In: Achieving forest establishment success at scale: IUFRO conference handbook. Rotorua, p 28

Kocsis IA, Tállai M, Zsuposné Oláh Á, László Z, Mokos B, Kincses I, Juhász EK, Lowy DA, Sándor Z (2025b) Unveiling the transformative effects of forest restoration on the soil chemistry and biology of sandy soils in Southern Nyírség, Hungary. Agriculture 15(10):1030. https://doi.org/10.3390/agriculture15101030

Kong Y, Nagano H, Kátai J, Vágó I, Zsuposné Oláh Á, Yashima M, Inubushi K (2013) CO_2, N_2O and CH_4 production/consumption potentials of soils under different land-use types in Central Japan and Eastern Hungary. Soil Sci Plant Nutr 59(3):455–462. https://doi.org/10.1080/00380768.2013.775005

Kotroczó Z, Fekete I (2020) Significance of soil respiration from biological activity in the degradation processes of different types of organic matter. DRC Sustain Future J Environ Agric Energy 1(2):171–179. https://doi.org/10.37281/DRCSF/1.2.10

Kristó L (2017) Erdészeti szaporítóanyag-termelés (Forestry reproductive material production). Hermann Ottó Intézet Nonprofit Kft., Budapest

Kristoffersen AØ, Krogstad T, Øgaard AF (2020) Prediction of available phosphorus in soil: combined use for crop production and water quality protection. J Environ Qual 49(6):1575–1584. https://doi.org/10.1002/jeq2.20165

Lazzaro L, Mazza G, d'Errico G, Fabiani A, Giuliani C, Inghilesi AF, Lagomarsino A, Landi S, Lastrucci L, Pastorelli R, Roversi PF, Torrini G, Tricarico E, Foggi B (2018) How ecosystems change following invasion by *Robinia pseudoacacia*: insights from soil chemical properties and soil microbial, nematode, microarthropod and plant communities. Sci Total Environ 622–623:1509–1518. https://doi.org/10.1016/j.scitotenv.2017.10.017

Liu Z, Hu B, Bell TL, Flemetakis E, Rennenberg H (2020) Significance of mycorrhizal associations for the performance of N2-fixing black locust (*Robinia pseudoacacia* L.). Soil Biol Biochem 145:107776. https://doi.org/10.1016/j.soilbio.2020.107776

Loch J, Nosticzius Á (2004) Agrochemistry and plant protection chemistry. Mezőgazda, Budapest

Makádi M, Tomócsik A, Orosz V, Lengyel J, Biró B, Márton Á (2007) Effect of digestate and Phylazonit MC on the yield of silage maize and the biological activity of the soil. Agrokém És Talajt 56(2):367–378. https://doi.org/10.1556/agrokem.56.2007.2.12

Makádi M, Kátai J, Zsuposné OÁ (2012) Nyírségi Homoktalajok termékenységének megőrzése és fenntartása (Preservation and maintenance of the fertility of sandy soils in Nyírség). University of Debreceni AGTC, Debrecen

Manolopoulos D, Vasileioris K, Milios E, Kitikidou K, Spyroglou G, Radoglou K (2022) Allometric models for estimating the height of *Robinia pseudoacacia* L. in restoration plantations. Land 11(4):471. https://doi.org/10.3390/land11040471

Mayer J, Gunst L, Mäder P, Samson M-F, Carcea M, Narducci V, Thomsen IK, Dubois D (2015) Productivity, quality and sustainability of winter wheat under long-term conventional and organic management in Switzerland. Eur J Agron 65:27–39. https://doi.org/10.1016/j.eja.2015.01.002

Meier E (2025) The wood database 2025. https://www.wood-database.com/black-locust/ (Accessed 06 June 2025)

Micskei G, Jócsák I, Berzsenyi Z (2009) Effect of farmyard manure and mineral fertiliser on the growth and the dynamics of the growth parameters of maize in different years. Novenytermeles 58:45–56

Ministerial Decree No. 153/2009. (XI.13.) FVM on the Implementation of Act XXXVII of 2009 on Forests, Forest Protection and Forest Management, § 30 (Hungary)

Ministerial Decree No. 61/2017. (XII.21.) FM on the Implementation of Act XXXVII of 2009 on Forests, Forest Protection and Forest Management, § 36 (Hungary)

MSZ-08- 0210:1977 Testing organic carbon content, Hungarian Standard (in Hungarian)

MSZ-08-0206/ 2:1978 Determination of the pH of soil, Hungarian Standard (in Hungarian)

Nascimbene J, Nimis PL, Benesperi R (2012) Mature non-native black-locust (*Robinia pseudoacacia* L.) forest does not regain the lichen diversity of the natural forest. Sci Total Environ 421–422:197–202. https://doi.org/10.1016/j.scitotenv.2012.01.051

Neina D (2019) The role of soil pH in plant nutrition and soil remediation. Appl Environ Soil Sci 2019:1–9. https://doi.org/10.1155/2019/5794869

Németh T (2002) A tápanyag-utánpótlás jelenlegi helyzete, időszerű kérdései (The current situation and current issues of nutrient supply). András Jávor, Editor: Current issues of agrochemistry: scientific meeting, Debrecen, November 6, 2002. [In honor of the 70th birthday of Professor Jakab Loch]. Debreceni Egyetem Agrártudományi Centrum

Németh T (2004) Organic matter cycles in agriculture. Pollution processes in agri-environment. A new approach. Akaprint Publishers, Budapest, Hungary, pp 123–146

Rawls WJ, Pachepsky YA, Ritchie JC, Sobecki TM, Bloodworth H (2003) Effect of soil organic carbon on soil water retention. Geoderma 116(1–2):61–76. https://doi.org/10.1016/s0016-7061(03)00094-6

Rédei K (2006) Az akác termesztés-fejlesztésének biológiai alapjai és gyakorlata (Biological foundations and practice of acacia cultivation and development). Erdészeti Tudományos Intézet, University of Sopron, Sárvár

Rédei K, Osváth-Bujtás Z, Veperdi I (2008) Black locust (*Robinia pseudoacacia* L.) improvement in Hungary: a review. Acta Silv Lignaria Hung 4(1):127–132. https://doi.org/10.37045/aslh-2008-0011

Sándor Z, Kocsis I, Kincses I, László Z, Lowy D (2025) Examination of the plant nutrient content of black locust (Robinia pseudoacacia L.) in reforestation with soil nutrient replacement in Hungary. In: Achieving forest establishment success at scale: IUFRO conference handbook. Rotorua, p 49

Stefanovits P, Filep Gy Füleky Gy (1999) Talajtan (Soil Science). Mezőgazda Kiadó, Budapest

Szoboszlay M, Dohrmann AB, Poeplau C, Don A, Tebbe CC (2017) Impact of land-use change and soil organic carbon quality on microbial diversity in soils across Europe. FEMS Microbiol Ecol. https://doi.org/10.1093/femsec/fix146

Takamoto A, Takahashi T, Togami K (2023) Estimation models from soil pH with a solid-to-liquid ratio of 1:2.5 to pH measured by other methods using soils in Japan. Soil Sci Plant Nutr 69(3):190–198. https://doi.org/10.1080/00380768.2023.2190749

Vítková M, Müllerová J, Sádlo J, Pergl J, Pyšek P (2017) Black locust (*Robinia pseudoacacia*) beloved and despised: a story of an invasive tree in Central Europe. Ecol Manag 384:287–302. https://doi.org/10.1016/j.foreco.2016.10.057

Wu SC, Cao ZH, Li ZG, Cheung KC, Wong MH (2005) Effects of biofertilizer containing N-fixer, P and K solubilizers and AM fungi on maize growth: a greenhouse trial. Geoderma 125(1–2):155–166. https://doi.org/10.1016/j.geoderma.2004.07.003

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

István Attila Kocsis[1,2,3] · Andrea Balla Kovács[1] · Rita Kremper[1] · Evelin Kármen Juhász[1] · Daniel A. Lowy[4] · Zsolt Sándor[1] · Ida Kincses[1]

✉ Zsolt Sándor
zsandor@agr.unideb.hu

István Attila Kocsis
kocsis.istvanattila@agr.unideb.hu; istvan.kocsis@nyirerdo.hu

Andrea Balla Kovács
kovacsa@agr.unideb.hu

Rita Kremper
kremper@agr.unideb.hu

Evelin Kármen Juhász
juhasz.evelin@agr.unideb.hu

Daniel A. Lowy
lowy.daniel@uni-obuda.hu

Ida Kincses
kincsesi@agr.unideb.hu

[1] Faculty of Agricultural and Food Sciences and Environmental Management, Institute of Agricultural Chemistry and Soil Science, University of Debrecen, Debrecen H-4032, Hungary

[2] Nyírerdő Nyírségi Erdészeti Zrt, Nyíregyháza H-4400, Hungary

[3] Kálmán Kerpely Doctoral School, University of Debrecen, Debrecen H-4032, Hungary

[4] Kálmán Kandó Faculty of Electrical Engineering, Óbuda University, Budapest H-1084, Hungary