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Water Balance of Irrigated and Rainfed Sweet Corn in Weighing Lysimeters

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ABSTRACT

Weighing lysimeters are suitable tools for complex studies of the soil–water–plant–environment system. The precise determination of crop water demand and water-use efficiency (WUE) is essential for irrigation planning. In 2025, two weighing lysimeters (Lx) were used at the University of Debrecen to investigate sweet corn (*Zea mays* convar. *saccharata* var. MS Erica) under irrigated (L1) and rain-fed (L2) conditions. Sensors mewasured soil water content and meteorological data. From May to August, precipitation totaled 177 mm, while irrigation amounted to 190 mm and 50 mm in the two treatments, respectively. Cumulative evapotranspiration reached 447.6 mm in L1 and 294.4 mm in L2, with both treatments showing a negative water balance. Dry biomass was 2418 g (L1) and 1588 g (L2), with WUE values of 6.6 and 7.0 g mm^{-1}. The results highlight the trade-off between yield increase and water-use efficiency. The research presented in the article was carried out within the framework of the Széchenyi Plan Plus program, with support from the RRF 2.3.1-21-2022-00008 project.
Keywords: weighing lysimeter, evapotranspiration, water use efficiency, irrigation management, sweet corn

1. LITERATURE REVIEW

Maize is one of the world's most extensively cultivated crops and serves as a major food and feed source (Nagy, 2010). Owing to its substantial water demand, it is particularly sensitive to variations in water supply, and weather conditions strongly influence its yield stability during the growing season. Among the different types, sweet maize generally exhibits a higher water requirement and greater sensitivity to water availability than grain maize. With the increasing frequency of heat and water-stress events and the decline in available freshwater resources due to climate change, efficient water use has become a key priority. Irrigation plays a crucial role in maintaining yield stability and crop quality; however, from a sustainability perspective, improving water-use efficiency has become ever more important (FAO, 2002; Fereres & Soriano, 2006; Pereira et al., 2012).

Maize water demand varies considerably across its phenological stages, with the tasseling–silking phase being the most critical for water supply, as water deficits during this period can drastically reduce yield. The total evapotranspiration requirement of the crop throughout the growing season typically ranges from 450 to 800 mm, depending on cultivar, soil characteristics, and climatic conditions (Allen et al., 1998; Carr, 2013). The dual crop coefficient approach described in the FAO-56 guidelines has become the most widely adopted method for irrigation scheduling and accurate assessment of crop water use, as it enables the separate quantification of soil evaporation and plant transpiration components (Allen et al., 1998; Allen et al., 2011).

Lysimeters are among the most precise field instruments for studying the soil–plant–water continuum (Zsembeli & Kovács, 2006). Weighing lysimeters allow direct measurement of all components of the water balance (precipitation, irrigation, percolation, and evapotranspiration), thus providing an excellent tool for quantifying crop water use and analysing hydrological processes. Lysimeter data provide a reliable basis for developing irrigation strategies and validating physically based hydrological models (Allen et al., 2011).

Modern weighing lysimeters use high-precision load cell systems capable of detecting mass changes as small as 0.01 mm of water loss, allowing accurate tracking of daily evapotranspiration (Evett et al., 2012; Howell, 2001). Despite this high accuracy, potential sources of error must be considered, such as those arising from rainfall collection, wind effects, and the temporal distribution of percolation. Recent European studies, including the Austrian and German TERENO and BOKU lysimeter networks, have further developed methodologies that enable the reproducible determination of seasonal and annual water balance components (Hannes et al., 2015).

In recent decades, global research efforts have increasingly focused on improving agricultural water-use efficiency, particularly in arid and semi-arid regions where water scarcity threatens the sustainability of agricultural production. With the expansion of precision agriculture, technologies that rely on real-time data for irrigation management have become widespread. The integration of sensor-based monitoring and modelling approaches enables detailed temporal and spatial characterisation of water fluxes, thereby supporting decision-support systems (Evans & Sadler, 2008; Jones, 2004). Lysimeter data serve as essential reference measurements in such systems, providing direct physical validation of modelled evapotranspiration values (Irmak et al., 2016).

Water-use efficiency (WUE) in crops depends not only on genetic traits but also on irrigation techniques and soil physical conditions. Experimental results indicate that micro-irrigation, strip or deficit irrigation, and soil moisture-based irrigation control can enhance WUE to varying degrees (Geerts & Raes, 2009; Zhang et al., 2017). Adaptive plant responses – such as increased rooting depth or stomatal regulation – may improve efficiency under moderate stress, whereas excessive water supply can paradoxically reduce WUE (Sinclair et al., 2010). Consequently, increasing water-use efficiency entails complex ecological and physiological trade-offs.

In Hungary's continental climate, summer precipitation deficits often lead to severe yield losses (Pálfai, 2004). Maize is particularly drought-sensitive in the Great Hungarian Plain, making irrigation

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a key element of yield security. Observations over recent decades show that the frequency and duration of dry periods have increased, accompanied by a 5-15 % rise in potential evapotranspiration (Bartholy & Pongrácz, 2010; Spinoni et al., 2015). Analyses of European and Hungarian drought indices (SPEI and SPI) revealed that the number of drought days and negative soil moisture anomalies are expected to increase further in the future, particularly across the Great Hungarian Plain (IPCC, 2021; Seneviratne et al., 2012; Vicente-Serrano et al., 2010).

The spatial and temporal redistribution of water resources is particularly pronounced in the Carpathian Basin due to its climatic characteristics. Regional hydrological modelling studies have demonstrated a close relationship between groundwater level variations, evaporation balance, and changes in land cover and irrigation extent (Fehér, 2019; Tamás et al., 2022). Research findings also emphasise that irrigation can induce local microclimatic effects, such as increased air humidity and mitigation of temperature extremes, which feed back into the regional water balance, meaning that agricultural water use can exert detectable climatic impacts, even at the modelling scale (Báder, 2023; Lobell et al., 2006).

As drought conditions intensify, the optimal maize-growing zones are projected to gradually shift northward, leading to a spatial redistribution of agricultural production. Such climate-induced regional shifts pose new challenges to the global maize trade and food security (Leng & Hall, 2019). According to Porfirio et al. (2018), the increasing frequency of drought years may shrink traditional maize-growing regions, whereas previously marginal areas could emerge as new potential production zones.

Integrating lysimeter data into hydrological and agrometeorological models is crucial for improving model calibration and the accuracy of mesoscale estimations. Physically based models, such as MIKE SHE or AquaCrop, can reproduce real water dynamics only when calibrated with field-measured evapotranspiration and soil moisture data (Groh et al., 2020; Steduto et al., 2009). The lysimeter research conducted at the University of Debrecen aligns with this international trend, providing experimental data that facilitate parameter refinement and enhance the reliability of spatial extrapolation.

In Hungary, maize cultivation under rainfed conditions remains particularly risky in areas classified as conditional irrigation zones (Magyar et al., 2023). Several studies have examined the relationship between water requirements and WUE (García y García et al., 2009; Szalókiné Zima, 2023). Therefore, it is essential to understand the differences in yield and water use between irrigated and non-irrigated conditions. Water-use efficiency, expressed as the ratio of biomass production to water consumed through evapotranspiration, is a key indicator for evaluating plant water management performance (Blum, 2009; Richards & Townley-Smith, 1987). Because lysimeter measurements capture total evapotranspiration, actual WUE values are typically lower than those estimated from transpiration alone. Advanced models such as AquaCrop provide a means to account for these differences and to optimise deficit-irrigation strategies (Hatfield & Dold, 2019; Steduto et al., 2009).

The objective of this study was to compare the water balance and water-use efficiency of irrigated and rainfed sweet maize using two precision weighing lysimeters. Continuous monitoring of precipitation, irrigation, soil moisture, and evapotranspiration (ET) was performed in parallel with biomass measurements to quantify crop water productivity. These findings contribute to the development of irrigation strategies for sweet maize and offer new insights into the complex interactions within the soil-plant-water system.

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2. MATERIALS AND METHODS

Our research was conducted in Debrecen, Hungary, at the courtyard research facility of the Institute of Water and Environmental Management, University of Debrecen, Faculty of Agricultural and Food Sciences and Environmental Management. The site is located in a lowland environment typical of the Great Hungarian Plain (*Figure 1*), characterized by a continental climate with frequent summer drought. The soil placed in the lysimeters was collected from Látókép, approximately 15 km from Debrecen, and was classified as meadow chernozem. This soil type represents the regional pedological conditions well, with medium water-holding capacity, making it suitable for investigating soil–water balance processes.

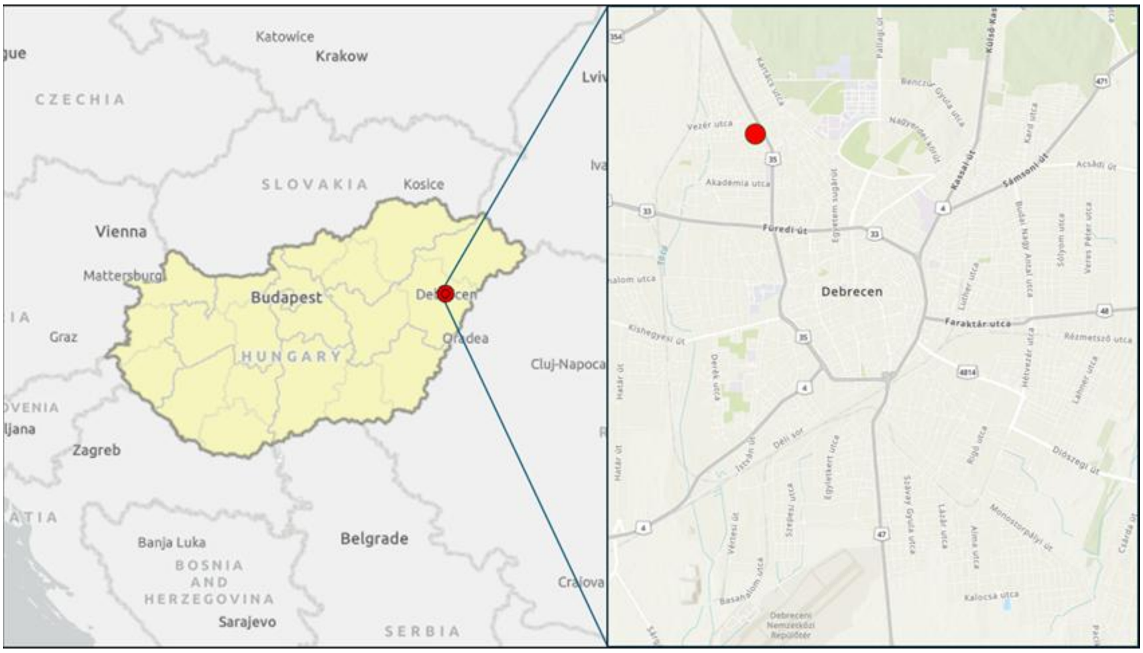

Figure 1: Location of the experimental site in Hungary and the Debrecen region

Source: Authors' data

The mean annual precipitation in the area is approximately 560 mm, although the seasonal distribution is highly variable. *Figure 2* presents the total annual precipitation for the period 2015-2024, compared with the 30-year climatological average (1991-2020). More than half of the examined years fell below the long-term mean; thus, six out of ten years were classified as dry and only two as wetter-than-average. Meteorological data were obtained from the Debrecen (Kismacs) station of the Hungaromet Automatic Station Network, which records precipitation, air temperature, relative humidity, and potential evapotranspiration (PET) calculated using the Antal method (Antal, 1968).

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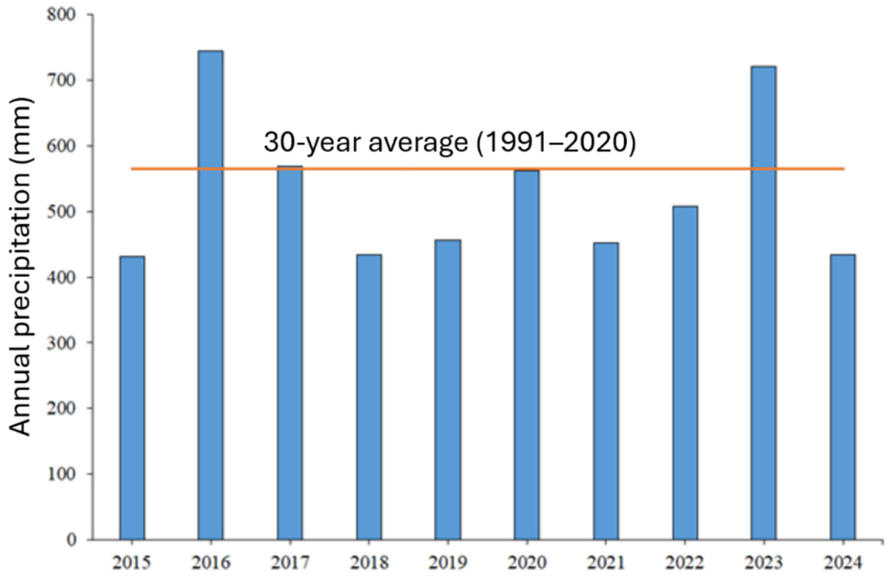

Figure 2: Annual precipitation totals compared to the 30-year average (1991–2020) in the Debrecen region

Source: Authors' analysis based on Hungaromet data

Our experiment employed two UGT Ready-To-Go Lysimeter 800/900 units, each with a 0.5 m² surface area and 0.9 m soil monolith depth (*Figure 3*). Each lysimeter was equipped with load cells for continuous mass measurement. Sensors were installed at depths of 20, 40, and 60 cm; however, because sweet corn has a shallow rooting depth, only data from 20 and 40 cm were used for evaluation. The instrumentation included tensiometers, soil moisture sensors, soil temperature sensors, and one reference tensiometer positioned outside the lysimeters to monitor ambient soil conditions. Rainfall, air temperature, humidity, and global radiation were measured by sensors located 1 m from the lysimeter tanks (*Figure 6*).

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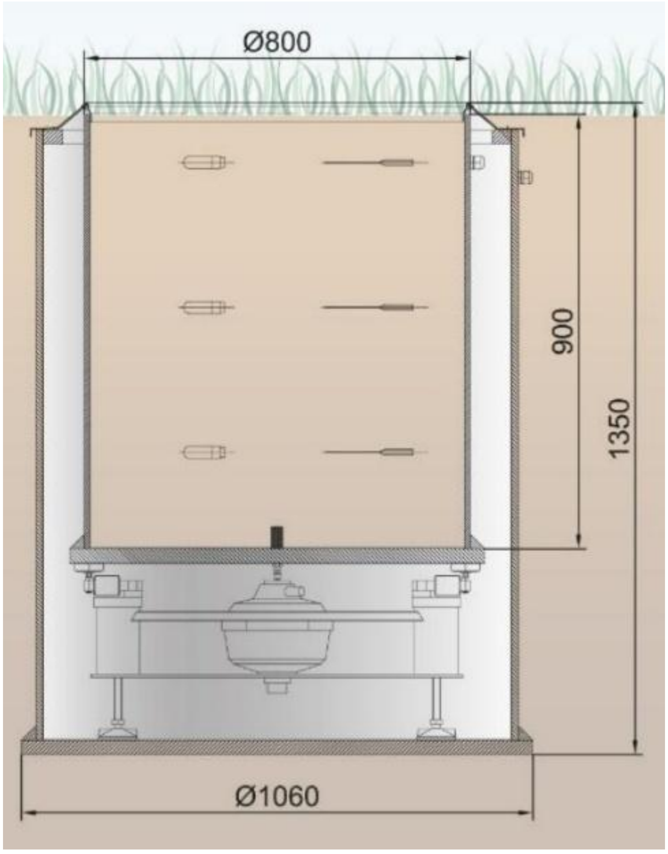

Figure 3: Cross-section of the weighing lysimeter system

Source: Umwelt-Geräte-Technik GmbH., n.d.-b

The variations in soil temperature are shown in *Figure 4a* and *4b*. In both lysimeters, the upper 0-20 cm layer responded rapidly to daily temperature fluctuations, whereas changes in the deeper 20-40 cm layer were attenuated. The highest temperatures occurred in late June and early July, exceeding 28-30 °C.

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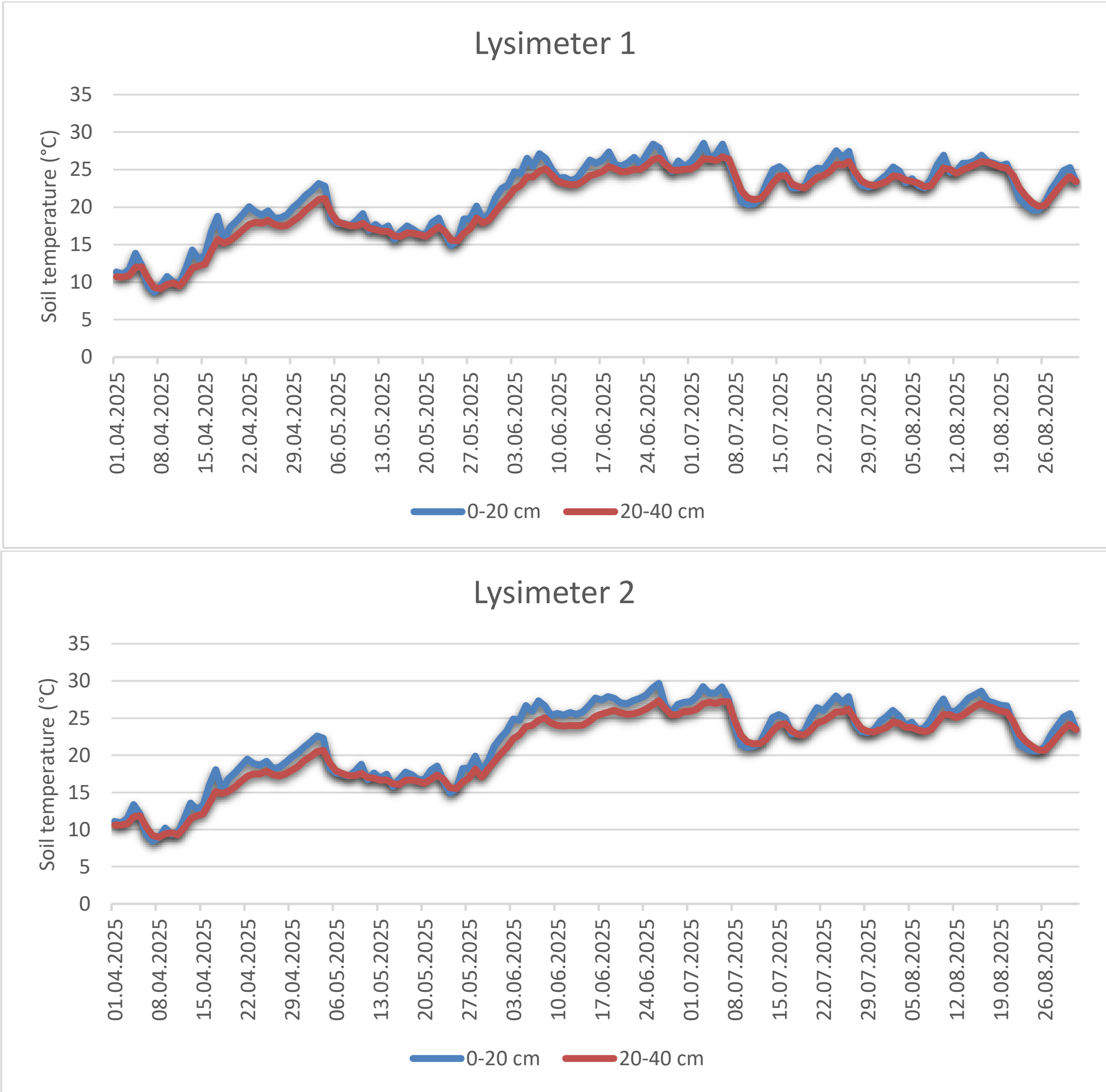

Figure 4a and 4b: Soil temperature variation at different depths in L1 and L2

Source: Authors' data

The lysimeter mass data were recorded continuously at 15-minute intervals. Precipitation was measured using a meteorological station, and irrigation was applied at predetermined doses. Percolating water was collected through drainage outlets at the bottom of the lysimeters and measured directly. Evapotranspiration (ET) was calculated using the water-balance equation, accounting for incoming (precipitation + irrigation) and outgoing (evaporation + percolation) components as well as changes in lysimeter mass over time (*Figure 5*). This approach enabled precise monitoring of water fluxes within the soil-plant system.

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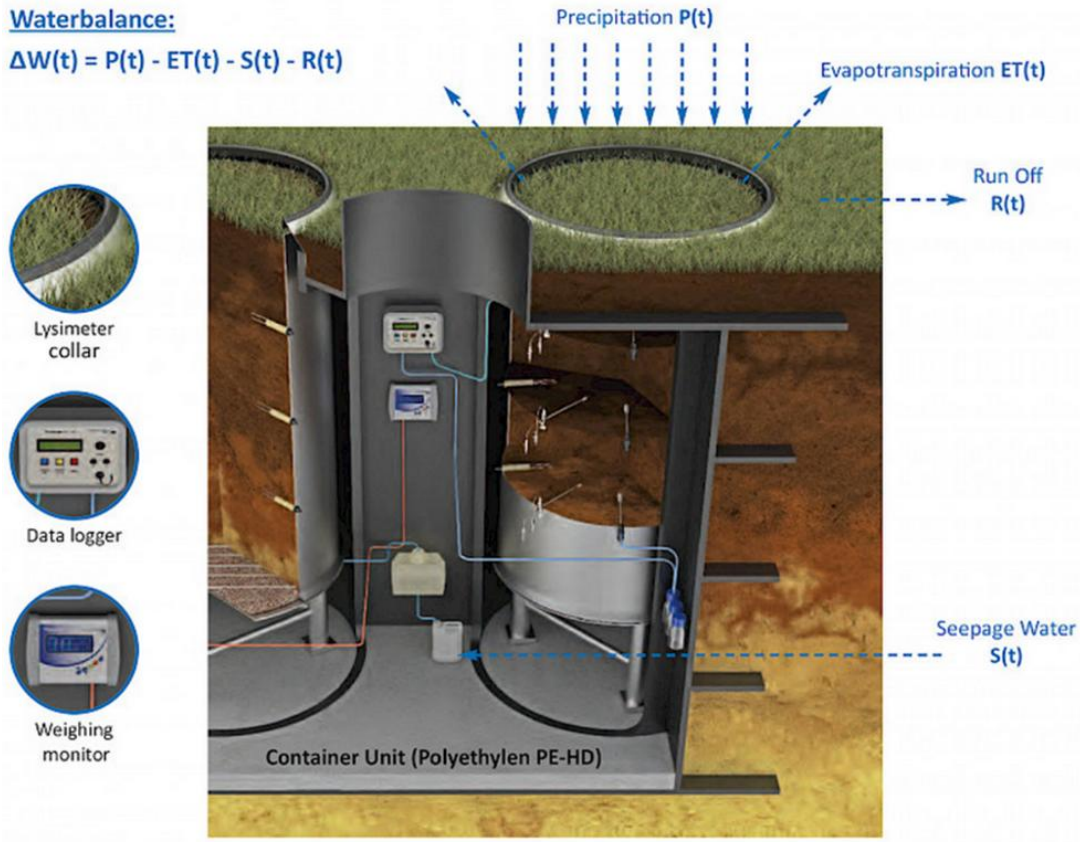

Figure 5: Determination of main water-balance components using a weighing lysimeter

Source: Umwelt-Geräte-Technik GmbH., n.d.-a

Meteorological data were obtained from the Hungaromet automatic station (in .csv format), and time series from the weighing lysimeters and local weather stations (also in .csv format) were compared to determine the individual water balance components. After synchronising the datasets to a unified temporal resolution, verifying time-series consistency, and filtering erroneous records, daily evapotranspiration (ET) and water-use efficiency (WUE) were computed. Data processing, parameter calculation, and graphical visualisation were performed using Microsoft Excel 2024.

The experiment utilised the sweet corn variety *Zea mays* convar. *saccharata* var. MS Erica (*Figure 6*). This medium-maturity hybrid, bred for fresh consumption and industrial processing, develops strong stalks and uniform cobs with 18-20 kernel rows. Owing to its stable yield and favourable water response, it is well-suited for assessing the effects of irrigation. Sowing took place on 16 May 2025, following 25 cm of tillage and loosening. A 10 mm irrigation was applied after sowing to ensure uniform emergence.

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Figure 6. Experimental setup of the sweet corn lysimeter trial and crop stand at the early growth stage

Source: Authors' photo

Two treatments were established: L1 (irrigated) and L2 (rainfed, with only initial irrigation). During the growing period (May-August), total precipitation amounted to 177 mm, indicating a moderately dry season with pronounced monthly variability; most rainfall occurred in July (94 mm), while May and August each received approximately 25 mm (*Figure 7*). In the irrigated treatment (L1), an additional 190 mm of water was applied, whereas the rainfed unit (L2) received only 50 mm of supplementary water during the early growth stage to ensure germination. Irrigation in L1 was applied at 10 mm doses, typically once per week, with irrigation timing determined by crop water demand and prevailing weather conditions. Water applications were concentrated primarily during vegetative development and the reproductive phase, with increased frequency during dry periods (*Figure 8*).

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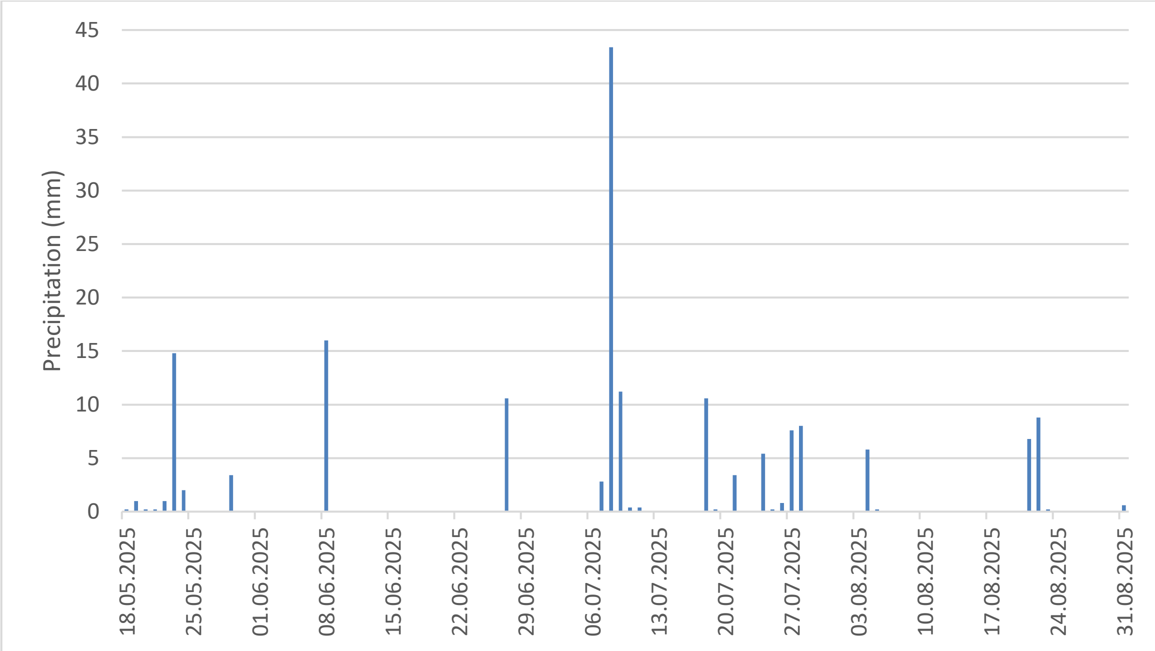

Figure 7: Daily precipitation totals during the experimental period

Source: Authors' data

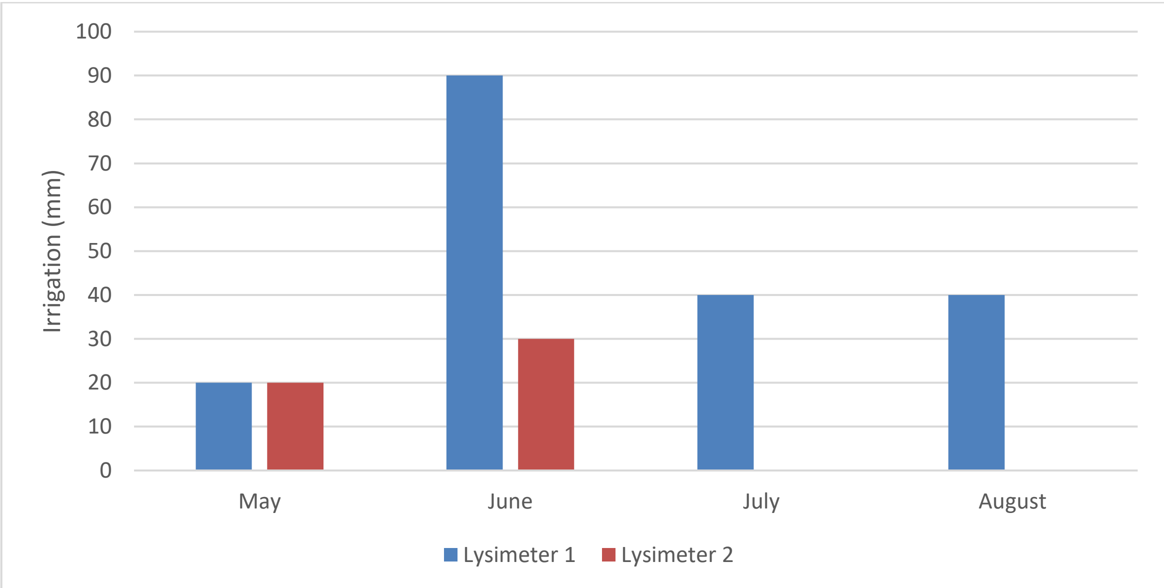

Figure 8: Irrigation schedule and applied water amounts for L1 and L2

Source: Authors' data

The soil water status was evaluated based on tensiometer readings (*Figure 9a* and *9b*). In the irrigated lysimeter (L1), soil water potential values stabilised at low tension levels during the mid-season, reflecting regular replenishment. In contrast, the rainfed L2 unit showed an increasing water deficit in the 20-40 cm layer, reaching 15-20 kPa in July. This difference clearly demonstrates the moisture-stabilising effects of irrigation.

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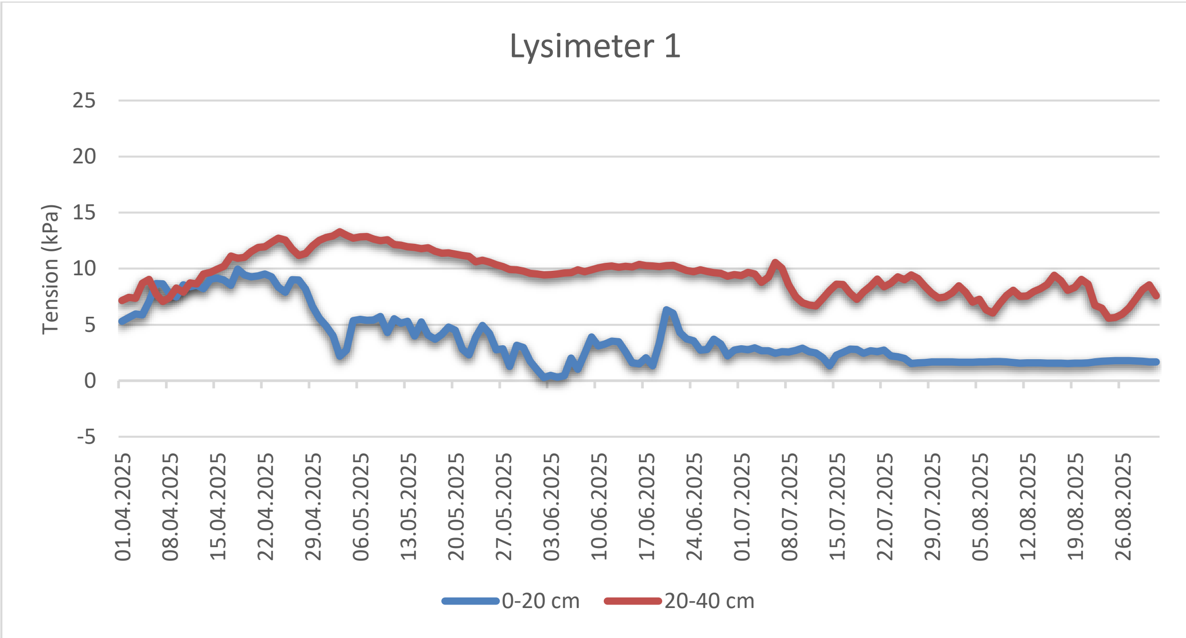

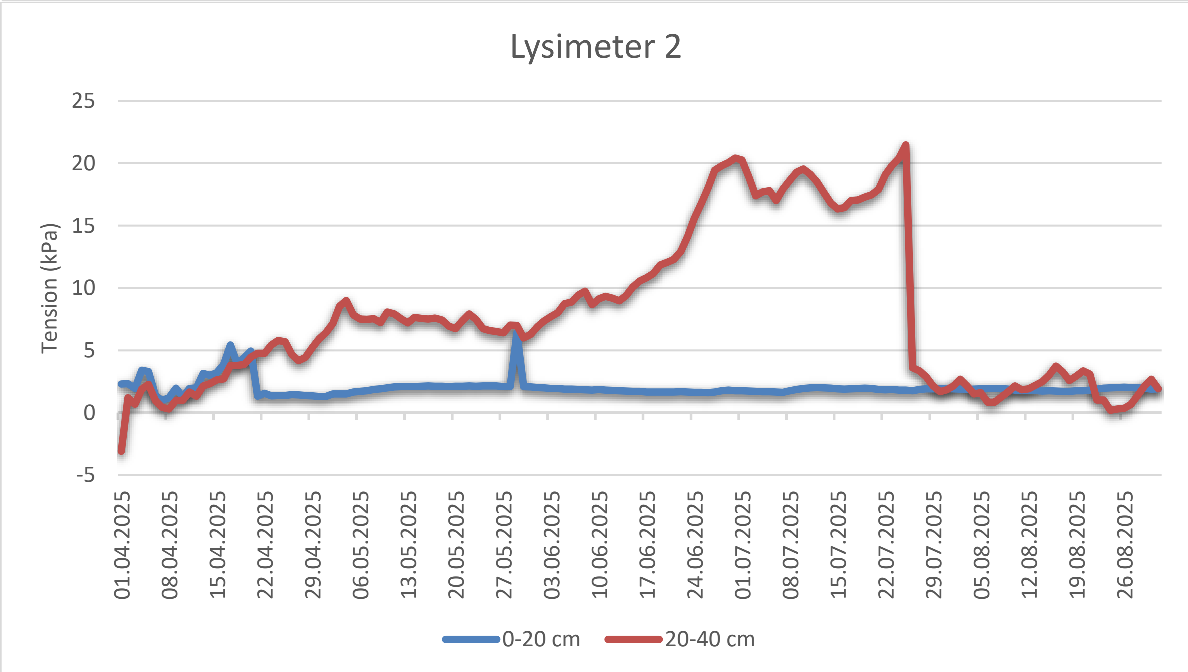

Figure 9a and 9b: Variation of soil-water potential (tension) during the growing season in L1 and L2

Source: Authors' data

Harvesting was conducted in two stages corresponding to full cob maturity. Ear length and mass were measured (*Figure 10a* and *10b*), and dry biomass was determined at the end of the vegetation period for both treatments.

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Figure 10a and 10b. Harvested sweet corn ears at the two sampling dates

Source: Authors' photo

Water-use efficiency (WUE) was calculated as the ratio of dry biomass yield to total water input (precipitation + irrigation) (*Eq. 1*) (Magaia, 2017). This enabled a direct comparison between irrigated and rainfed systems and revealed the relationship between yield increase and water-use efficiency.

$$WUE = \frac{maize\ grain\ yield\ (g\ m-^{2})}{seasonal\ crop\ water\ use\ \ (mm)} \tag{1}$$

3. RESULTS AND DISCUSSION

The daily mass variation curves of the soil monoliths (*Figure 11*) illustrate the balance among precipitation, irrigation, and water loss (evapotranspiration + percolation). Positive peaks corresponded to water input events (irrigation or showers), whereas negative slopes represented storage depletion. During June and July, a sustained mass decrease was observed in both lysimeters. In the irrigated L1 unit, the larger-amplitude recharge peaks clearly followed irrigation events. In early July, several short, sharp positive impulses (rain showers) also appeared in the non-irrigated L2 unit, followed by rapid declines, indicating intensification

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of water stress. By August, daily fluctuations had diminished, and both curves approached equilibrium as crop maturation and reduced evapotranspiration (ET) drove them toward equilibrium.

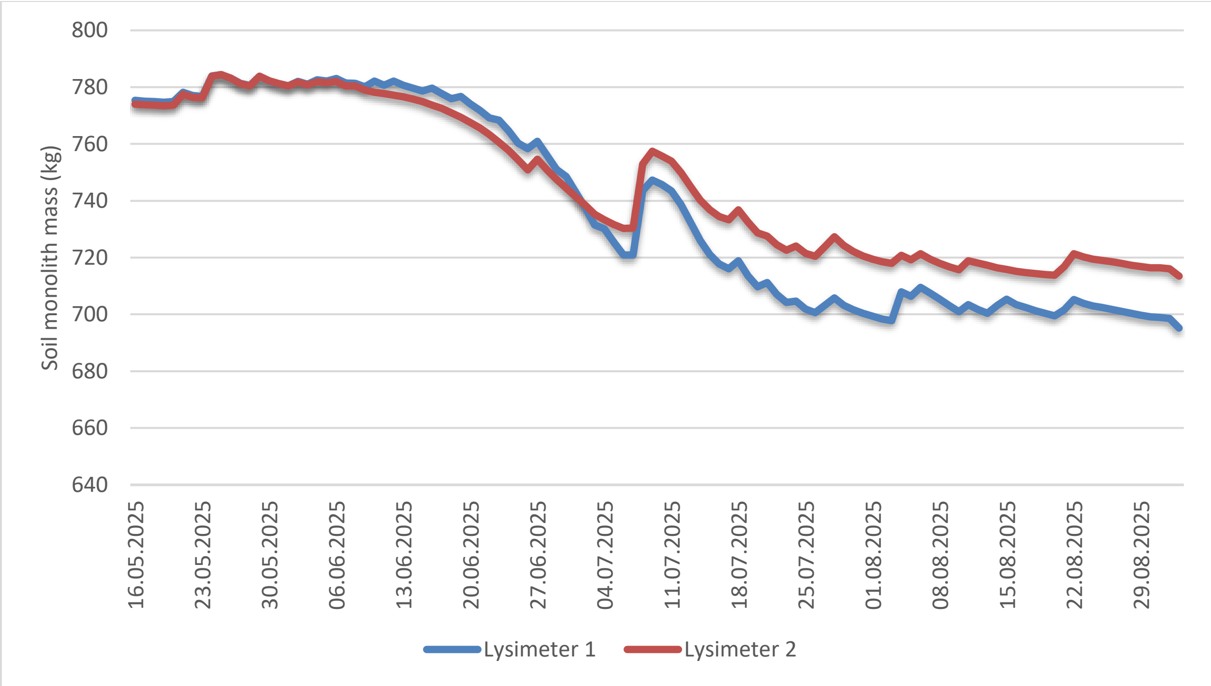

Figure 11. Daily mass variations of the soil monoliths during the growing season in L1 and L2

Source: Authors' data

Based on the combined effects of precipitation and irrigation, the seasonal water balance of the two lysimeters showed marked differences. Total water input (precipitation + irrigation) reached 367 mm in L1 and 227 mm in L2. The contrast was most pronounced in June-July, when the difference between water availability and evaporative demand reached its peak. Seepage water appeared at the beginning of the season in both lysimeters, but in negligible amounts (*Figure 12a* and *12b*).

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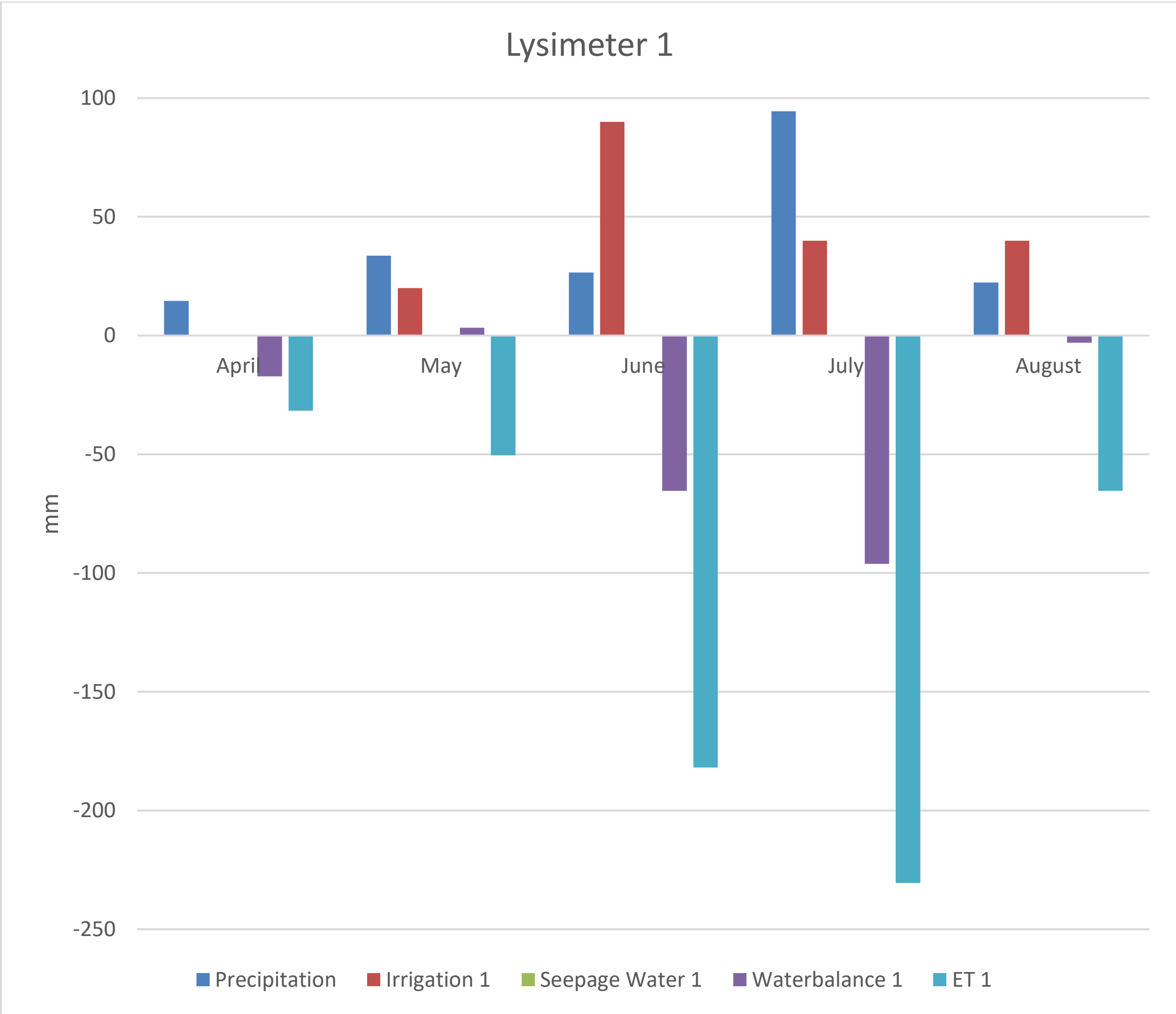

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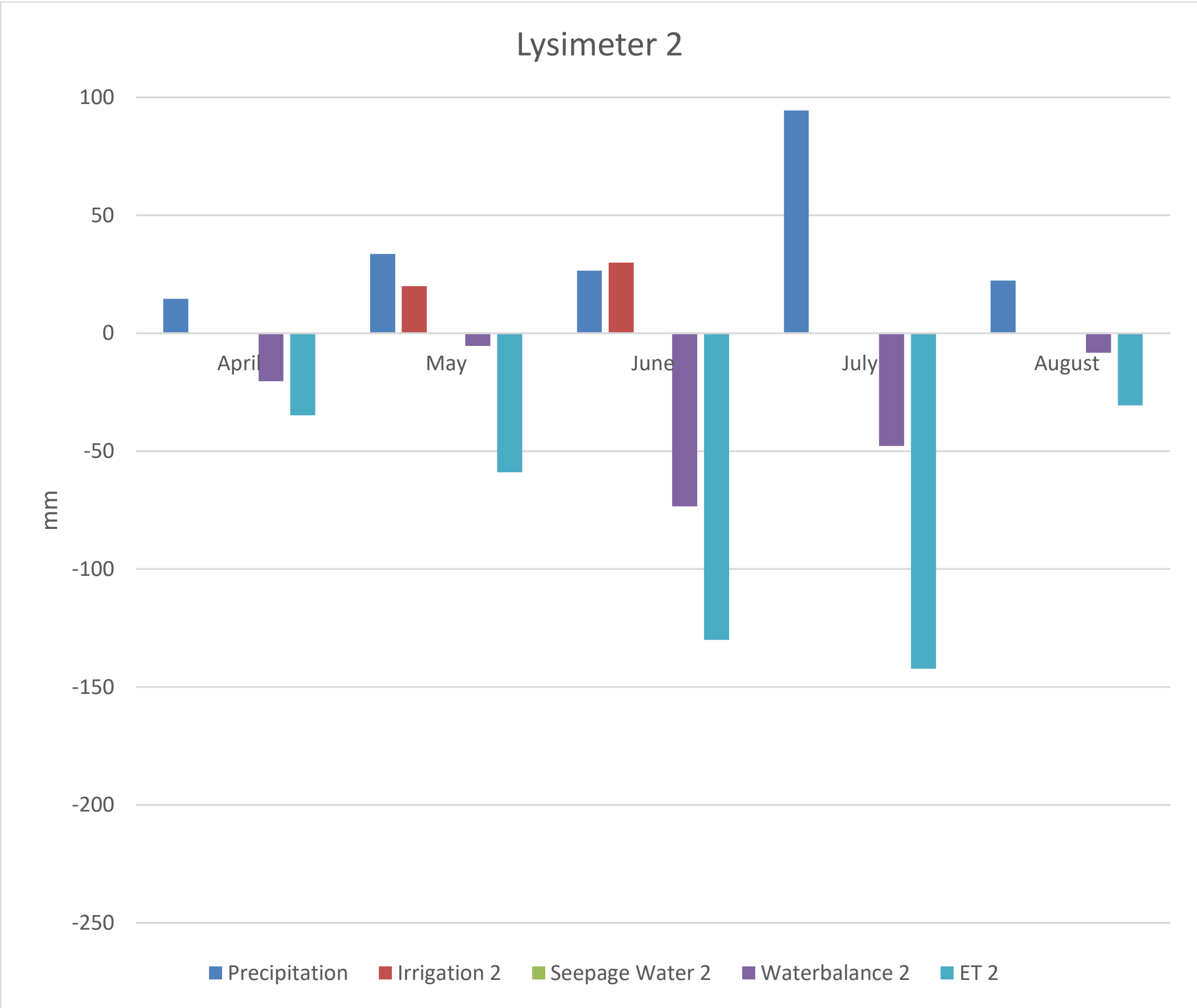

Figure 12: Monthly variation of main water-balance components in L1 and L2

Source: Authors' data

The potential evapotranspiration (PET) and lysimeter-derived actual evapotranspiration (ET) values (*Figure 13a* and *13b*) clearly demonstrate the influence of water supply on crop water use. PET represents the theoretical maximum, determined by meteorological conditions, that the irrigated L1 approached, particularly during the mid-season. In the non-irrigated L2, ET consistently fell below PET, particularly in late June and early July, reflecting the plants' physiological response to water deficit: stomatal closure and reduced transpiration.

The cumulative ET curves highlight the effect of irrigation; ET remained consistently higher in L1 than in L2. By the end of the experiment, cumulative ET reached 447.6 mm in the irrigated treatment and 294.4 mm in the non-irrigated treatment – a 52 % difference.

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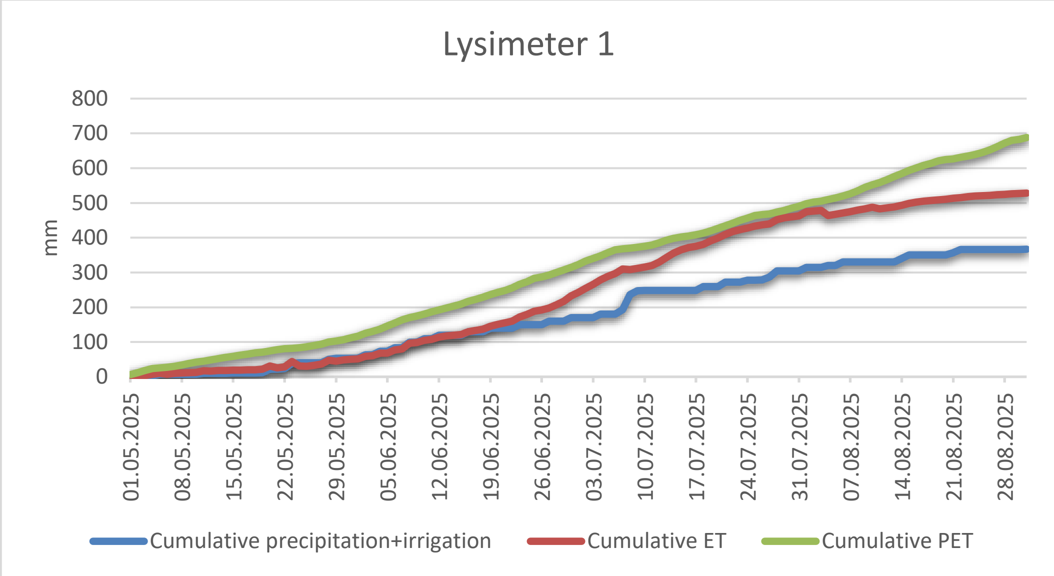

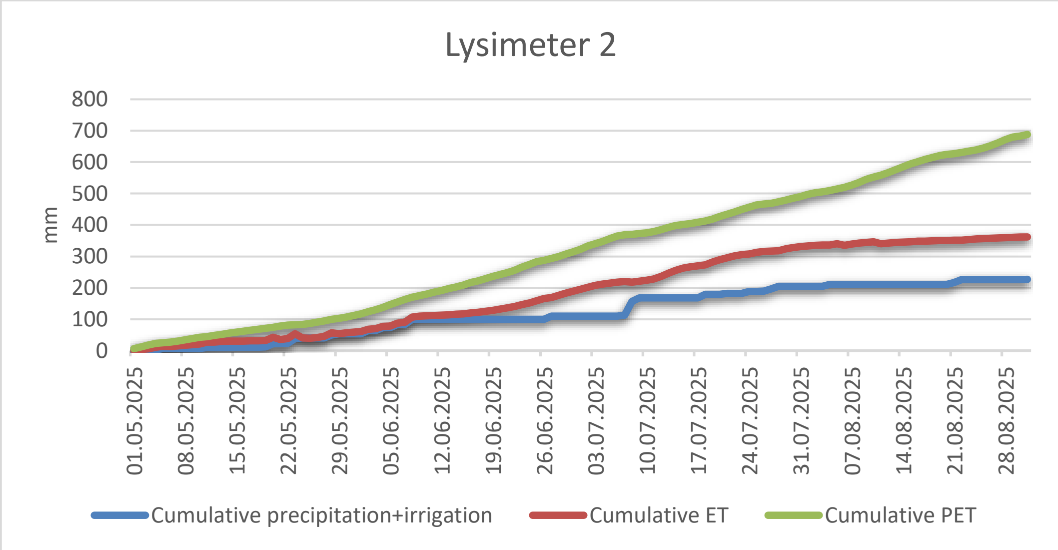

Figure 13a and 13b: Cumulative precipitation, irrigation, ET, and PET during the growing season in L1 and L2

Source: Authors' data

The monthly change in soil water storage (ΔS) reflected the utilisation of soil moisture reserves in both lysimeters (*Figure 14*). In May, a slight increase was observed (L1: +11.8 mm; L2: +14.5 mm), followed by pronounced depletion in June (L1: –65.4 mm; L2: –73.4 mm), consistent with rising ET. The largest drawdown occurred in July, particularly in the irrigated treatment (L1: –96.1 mm), whereas the non-irrigated L2 treatment showed a smaller decline (–47.8 mm) due to reduced transpiration under drought. In August, both systems approached near-equilibrium.

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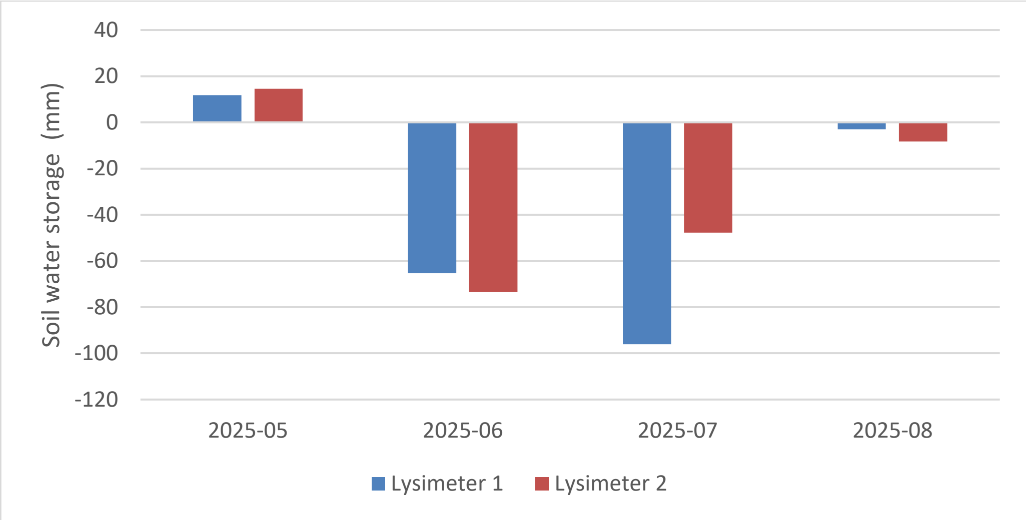
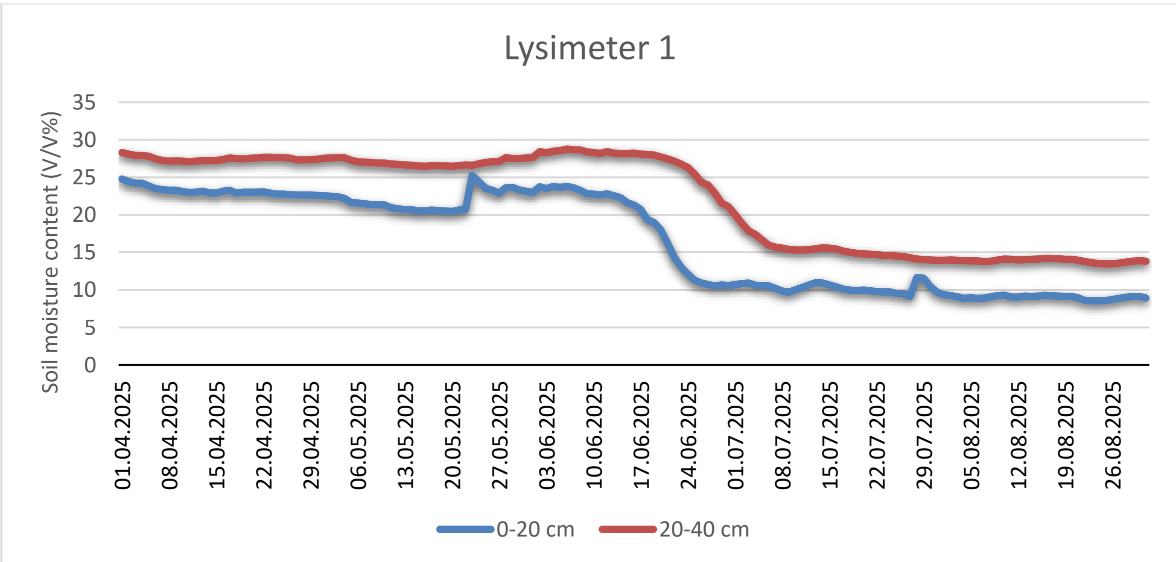


Figure 14: Monthly variation in soil water storage during the vegetation period in L1 and L2

Source: Authors' data

The temporal dynamics of soil moisture (*Figure 15a* and *15b*) also emphasised the differences between treatments. In the irrigated L1, moisture in the upper 0-20 cm layer gradually decreased from late May and then stabilised between 15 and 25 V/V% due to regular irrigation. The 20-40 cm layer responded more slowly but followed the same irrigation pattern. In the non-irrigated L2, the upper layer rapidly dried from late June onward, persistently dropping below 10 V/V%. The deeper layer also declined gradually, showing only short-term recovery after the July rain events. These results confirm that without irrigation, soil water reserves cannot meet crop demand during critical growth stages.



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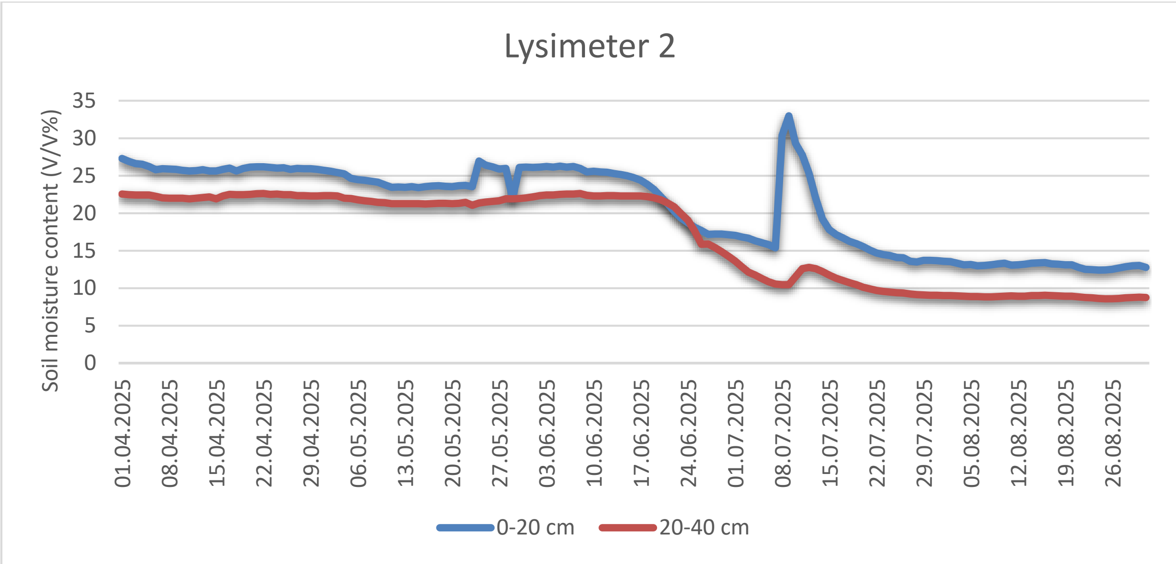

Figure 15a and 15b: Temporal variation of soil moisture at different depths in L1 and L2

Source: Authors' data

Daily ET values (*Figure 16*) reflect the actual water use of the crop canopy. Early in the season (May), both treatments exhibited low ET rates (0-2 mm day^{-1}). From mid-June onward, ET increased markedly, reaching peaks of 6-7 mm day^{-1} in the irrigated L1 and 4-5 mm day^{-1} in the non-irrigated L2. This contrast was most pronounced during hot, dry periods, driven by higher transpiration rates in irrigated plants. Toward the end of July, ET declined in both treatments, marking the closure of the water-use phase by August.

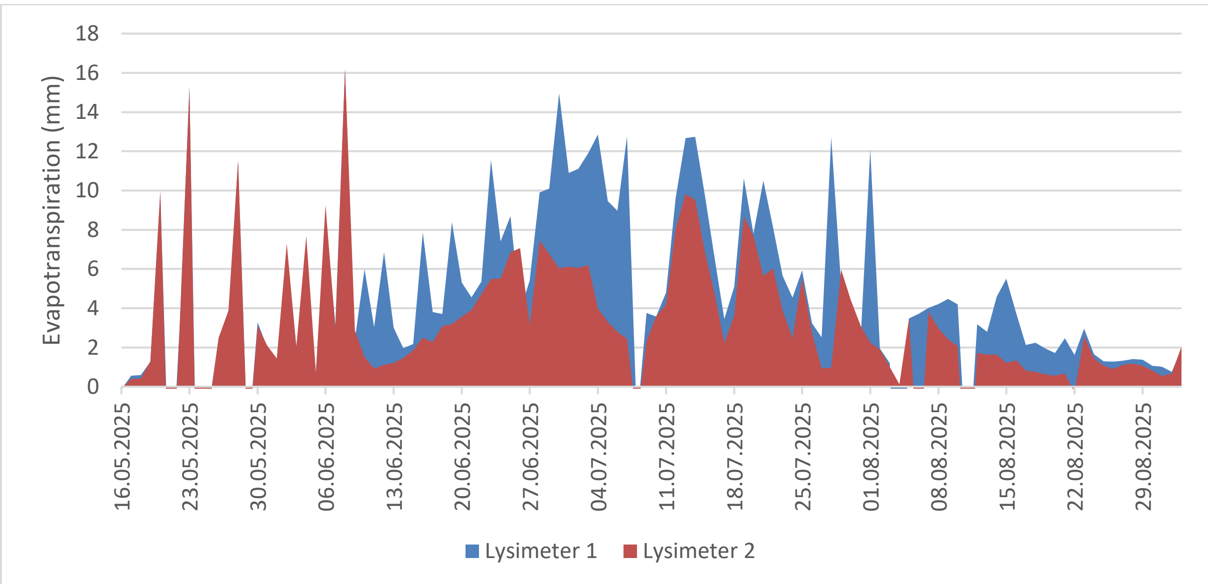

Figure 16: Daily evapotranspiration rates under irrigated and non-irrigated conditions in L1 and L2

Source: Authors' data

Dry biomass production reached 2418 g in the irrigated treatment and 1588 g in the rainfed treatment (*Figure 17*) – a ~52 % difference closely linked to water availability and seasonal ET totals.

Water-use efficiency (WUE) was 6.6 g mm^{-1} in L1 and 7.0 g mm^{-1} in L2, indicating that irrigation increased yield but reduced the biomass produced per unit of water, representing the classical yield–efficiency trade-off.

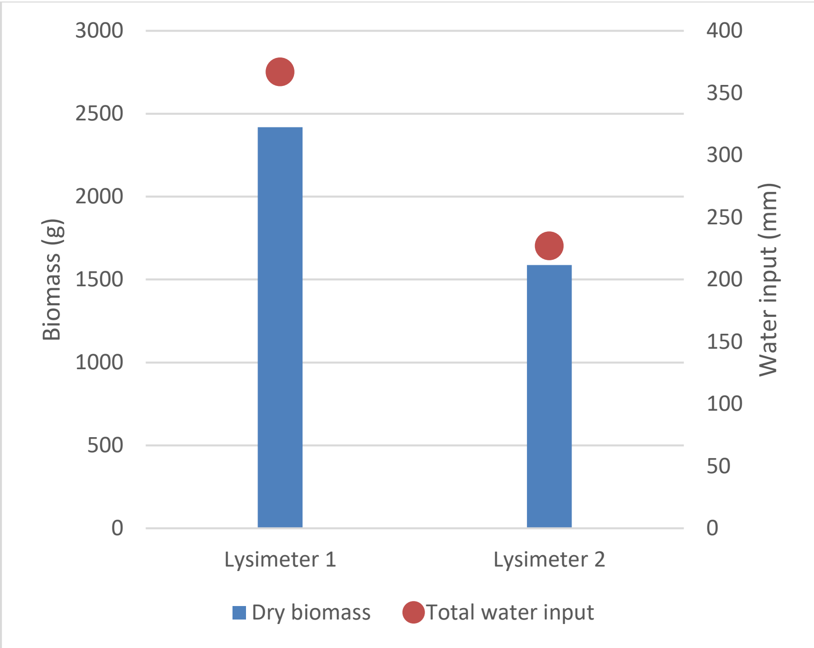

Figure 17: Relationship between dry biomass yield and water supply in L1 and L2

Source: Authors' data

According to the harvest measurements, the mean ear weight was 251 g for L1 and 237 g for L2 (*Figure 18*). The mean ear length was 18.4 cm and 18.1 cm, respectively (*Figure 19*). This irrigation not only enhanced biomass but also slightly improved ear size and uniformity. In the rainfed treatment, smaller ears and lower dry mass reflect the constraining effect of water deficit.

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Figure 18: Average ear weight at the two harvest dates in L1 and L2

Source: Authors' data

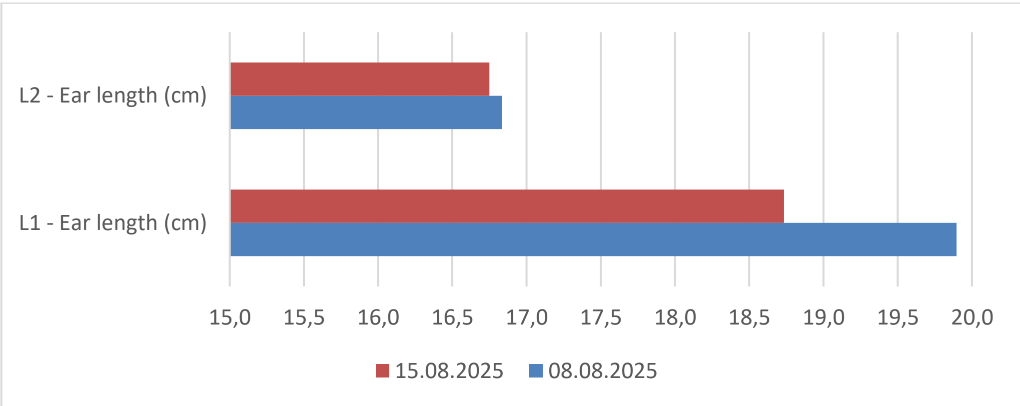

Figure 19: Variation in ear length under irrigated and non-irrigated treatments in L1 and L2

Source: Authors' data

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4. CONCLUSION

The lysimeter experiment highlighted the decisive role of irrigation in regulating water balance and sweet corn yield. In the irrigated L1, cumulative ET reached 447.6 mm, exceeding that in the non-irrigated L2 by 52 %. Irrigation enables the crop to approach potential evapotranspiration and supports greater biomass accumulation.

In the rainfed treatment, water deficit became evident from mid-June onward; the ET/PET ratio fell below 0.65, and daily water use declined due to stomatal closure and reduced transpiration. The soil water storage data showed that the most pronounced depletion occurred in June-July, when water shortages most severely limited uptake.

Biomass production was 52 % higher in the irrigated treatment, confirming a direct relationship between water supply and growth intensity. In contrast, the smaller ears and lower dry mass observed in the non-irrigated system may indicate a water-deficit-induced stress response, potentially associated with premature senescence and incomplete kernel filling.

Water-use efficiency was slightly higher under deficit conditions (7.0 g mm^{-1}) than in the irrigated treatment (6.6 g mm^{-1}), indicating more efficient carbon assimilation per unit of water under limited supply. This yield-efficiency trade-off encapsulates the core dilemma of optimising water use in semi-arid environments.

Overall, irrigation not only increased total water flux but also stabilised crop physiological function. The transpiration reduction observed under rainfed conditions represented a natural water-saving adaptation, whereas the enhanced water use in the irrigated system supported greater biomass production. The significance of lysimeter-based measurements lies in their ability to precisely quantify individual water balance components, providing a robust basis for developing precision irrigation strategies.

Future research should integrate real-time sensor data (tensiometers, soil moisture probes, and temperature probes) and modelling analyses (water-balance simulation and WUE time series) to refine predictions of crop water dynamics and advance sustainable irrigation management under Central European climatic conditions.

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Öntözött és öntözetlen csemegekukorica vízmérlegének vizsgálata súlyliziméterekben

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ÖSSZEFOGLALÁS

A súlyliziméterek alkalmas eszközök a talaj-víz-növény-környezet rendszerek komplex vizsgálatára. A növényi vízigény és a vízhasznosítási hatékonyság (WUE) pontos meghatározása elengedhetetlen az öntözéstervezéshez. 2025-ben Magyarországon a Debreceni Egyetem területén két súlyliziméterts (Lx) állítottunk be a csemegekukorica (*Zea mays convar. saccharata var. MS Erica*) vizsgálatára öntözött (L1) és öntözetlen (L2) körülmények között. Szenzorok mérték a talajnedvességet, a talajhőmérsékletet és a meteorológiai adatokat. Májustól augusztusig a csapadék mennyisége 177 mm volt, míg az öntözés 190 mm (L1), illetve 50 mm (L2) volt. A kumulatív evapotranszspiráció az L1 esetében elérte a 447,6 mm-t, az L2 esetében pedig a 294,4 mm-t, így mindkét kezelés negatív vízmérleget mutatott a vizsgált időszak végére. A száraz biomassza tömege 2418 g (L1) és 1588 g (L2) volt, 6,6 és 7,0 g mm^{-1} WUE-értékek mellett. Az eredmények rávilágítanak a hozamnövekedés és a vízhasznosítás közötti kompromisszumra. A dolgozatban bemutatott kutatás a Széchenyi Terv Plusz program keretében valósult meg, az RRF 2.3.1 21 2022 00008 számú projekt támogatásával.

Kulcsszavak: súlyliziméter, evapotranszspiráció, vízhasznosítási hatékonyság, öntözésirányítás, csemegekukorica

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Consumer acceptance, sensory quality, and techno-functional behaviour of vegetable-based, inulin-enriched ice creams

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ABSTRACT

This study developed and evaluated vegetable-based, inulin-enriched ice creams. A questionnaire (n = 295) was followed by sensory testing (n = 70) of three prototypes – mint-lemon zucchini, orange-carrot, and dark chocolate-sour cherry beetroot – and texture/melting analyses. Willingness to try was high (89 %) despite low awareness (22 %); mango-carrot was the most appealing prospective flavour (63 %). In sensory tests, mint–lemon zucchini achieved the best overall impression (~75 % preference). Overrun ranged 8.7-25.7 %, indicating relatively dense, low-air products. Melting behaviour reflected fibre/solids: beetroot melted slowly with a gel-like residue, carrot melted faster, and zucchini was intermediate. Vegetable-based ice creams thus appear a realistic market alternative – especially for women aged 20-29 – provided that launch strategies emphasise tasting and clear education (inulin as a natural dietary fibre). Technologically, target mouthfeel can be achieved by tuning total solids/fibre/fat and emulsifier–stabiliser levels.

Keywords: vegetable-based ice cream; inulin; consumer acceptance; sensory evaluation; texture analysis; melting behaviour; overrun; functional foods

1. INTRODUCTION

Ice cream symbolises summer, relaxation, and fun for children, but the high sugar and fat content of traditional recipes makes it unsuitable for a health-conscious diet. Given the increasing prevalence of obesity and lifestyle-related chronic diseases, there is a growing urgency to develop innovative desserts that are enjoyable yet nutritious. A growing number of consumers are looking for products that offer added values, whether in terms of fibre intake, micronutrient content, or the more sustainable use of ingredients.

Although vegetables are traditionally used in main courses and side dishes, their use in desserts is still unusual. However, their fibre and micronutrient contents, as well as their low energy density, make them ideal ingredients for developing health-conscious desserts. Developing vegetable-based ice cream presents technological and sensory challenges, such as ensuring the right texture, achieving a harmonious flavour profile, and gaining consumer acceptance, while also benefiting from the favourable dietary properties of vegetables.

This study focuses on three vegetables commonly found in home diets: zucchinis, carrots, and beetroot. The research aims to explore consumers' openness to vegetable-based ice creams, present the sensory perception of the developed products, and evaluate the potential of inulin as a functional fibre-enhancing ingredient. Thus, the work aims to provide a comprehensive picture of the development and consumer perception of vegetable-based ice cream, situated at the intersection of traditional ice cream concepts and health-conscious, innovative product development.

2. LITERATURE REVIEW

In the 21st century, health, special diets, and related functional foods have become a major focus of attention and a primary driver for many product developments. Plant-based ice creams manufactured using soy, almond, or coconut milk have reduced fat content, offer a lactose-free alternative, and can be fortified with probiotics or prebiotics, which have been shown to improve the balance of gut flora (Taspinar et al., 2023; Goktas et al., 2022; Kowalczyk et al., 2021). Several studies have shown that different plant-based beverages, especially soy and coconut-based systems, have favourable emulsifying and foam-stabilising properties, making them technologically suitable as ice cream bases, while consumer acceptance can reach competitive levels compared to traditional dairy ice creams (Acar et al., 2025; El-Sayed, 2025; Taspinar et al., 2023).

Furthermore, ice cream provides a favourable matrix for probiotic microorganisms. Several studies have shown that the bacterial count in ice creams enriched with different strains of *Lactobacillus* is increased (Taspinar et al., 2023; Goktas et al., 2022; Kowalczyk et al., 2021). As demonstrated in the relevant literature, *Lactobacillus*, *Bifidobacterium,* and *Saccharomyces* have been shown to reach the 10^6-10^7 CFU/g range that is considered to be the maximum level at which these organisms can be found in functional foods by the end of storage, without any significant deterioration in sensory quality (Elkot et al., 2022; Goktas et al., 2022; Hanafi et al., 2022; Kowalczyk et al., 2021).

As demonstrated in the relevant literature, dietary fibres, such as inulin and those derived from oats and apples, have been shown to modify the viscosity, melting properties, and texture of ice cream, while also providing nutritional benefits (Tolve et al., 2024; Arslaner & Salik, 2020; Kowalczyk et al., 2021). The incorporation of black rice powder, coconut fibre, or other plant-derived fibre fractions has been demonstrated to enhance the water retention capacity of the system, elevate viscosity, exert a favourable influence on overrun and ice crystal size, and support the viability of probiotics. Consequently, these factors contribute to a creamier, more stable texture (Tang et al., 2025; Elkot et al., 2022; Hanafi et al., 2022). Fibres fulfil dual roles, functioning both technologically (as a fat and sugar replacement, stabiliser) and nutritionally (as a prebiotic), aligning with the rising consumer demand for health-conscious yet pleasurable dessert options. Recent reviews emphasise that developing healthier or functionally enriched ice creams requires formulation and processing strategies that preserve microstructure (e.g. fat partial coalescence and air cell stability) and limit ice recrystallization to avoid iciness and weak body (Chang et al., 2025; Tang et al., 2025).

In recent years, there has been an increasing focus on plant-based desserts, which offer new flavour profiles and can contribute to two key issues of modern society: increasing vegetable consumption

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and reducing food waste (Darko et al., 2024; Nur'Aqilah et al., 2023; Vijayalakshmi & Vijayavahini, 2022). The former would be particularly necessary in Hungary, which, according to the 2024 report by the Organisation for Economic Co-operation and Development (OECD), ranks last in terms of vegetable consumption in the EU. The per capita daily vegetable consumption in Hungary is approximately 165 grams, which is only ~33 % of the recommended intake according to the guidelines set by the Association of Hungarian Dietitians (MDOSZ, 2016).

Consumer studies on plant-based frozen desserts have indicated that non-traditional matrices are frequently penalised for vegetal/off-flavours and texture defects (e.g., grittiness) (Ettinger et al., 2024; Gorman et al., 2023), underscoring the necessity for meticulous ingredient selection and optimisation when introducing plant-derived components. A recent Hungarian consumer survey on plant-based and vegan substitute products indicates a comparable level of receptiveness among consumers to novel and non-traditional food applications (Németh-Torkos et al., 2023).

The use of vegetables in ice cream has a double advantage in this respect. Firstly, they enrich the matrix with natural colouring and flavouring components, fibres, and phytochemicals. Secondly, they can partially replace fat and/or added sugar, which can lead to changes in viscosity, aeration, crystallisation, and melting properties of the ice cream (El-Sayed, 2025; Ateteallah et al., 2019). Conversely, they facilitate the utilisation of vegetable-derived by-products (e.g., beetroot pulp, zucchini residue) for food purposes, thereby promoting the principles of the circular economy and reducing food waste (Darko et al., 2024; Nur'Aqilah et al., 2023).

In accordance with this, recent research has demonstrated that the incorporation of fibre-rich by-products, such as oat okara, into plant-based ice cream can enhance dietary fibre levels and modify rheological and sensory characteristics. This emphasises the technological trade-offs associated with by-product valorisation (Caponio et al., 2025).

The objective of this study is to investigate consumer preferences and interest in vegetable-based ice cream through the implementation of an online questionnaire survey, and to examine the technological and organoleptic characteristics of vegetable-enriched products. A series of three innovative ice creams derived from vegetables (zucchinis, carrots, and beetroot) were developed, accompanied by a sensory evaluation in order to ascertain consumer acceptance and identify the most suitable products for production. Furthermore, physical tests were conducted, encompassing melting rate and composition analysis, to furnish an objective evaluation of the texture and quality of the ice cream. This scientific approach provides a robust foundation for the subsequent development of vegetable-based ice cream products.

3. MATERIALS AND METHODS

The objective of the present study was twofold: firstly, to develop a range of vegetable-based ice creams, and secondly, to evaluate their consumer perception in a complex manner. The primary research comprised five consecutive phases: a questionnaire survey, product development, qualitative interviews, sensory evaluation, and physical (texture and melting) tests. A selection of three vegetable raw materials (zucchinis, carrots, and beetroot) was made on the basis that they would be of use in the production of ice cream. These were then used in combination with fruit to develop inulin-enriched ice cream recipes.

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3.1 Questionnaire survey

A quantitative, cross-sectional, self-completed online questionnaire survey was conducted to explore consumer attitudes and acceptance of vegetable-based ice cream. The questionnaire examined respondents' vegetable consumption habits, interest in vegetable-based ice cream, preferred vegetable and ice cream flavours, and knowledge of inulin. Furthermore, an analysis was conducted to ascertain the influence of demographic characteristics (age, gender, education, and place of residence) on consumers' propensity to adopt innovative products.

The sampling method employed was non-random, namely convenience sampling, with the questionnaire being disseminated primarily through social media platforms. The questionnaire was available on Google Forms from May 2024 to July 2024. Of the 308 completed questionnaires, 295 were found to be assessable (n = 295).

The questionnaire comprised 16 closed questions, 14 of which were mandatory. The survey comprised four questions pertaining to demographic data, five questions relating to ice cream consumption habits, four questions regarding attitudes towards vegetable-based ice creams, and three questions assessing knowledge about inulin. The question types encompassed single-choice, multiple-choice, and scaled (rating) formats.

3.2 Product development

Based on the questionnaire results and practical feasibility (taste harmony and anticipated consumer acceptance), three inulin-enriched vegetable ice cream prototypes were developed: (i) mint-lemon zucchini, (ii) orange-carrot, and (iii) dark chocolate-sour cherry beetroot.

The selected concepts combined a dominant vegetable ingredient with complementary flavour notes (citrus-mint, citrus-carrot, and cocoa-fruit-beetroot) in order to balance freshness, sweetness, and colour appeal.

The formulations (ingredient quantities per batch) are summarised in *Table 1*. Raw materials were prepared as follows: zucchini was washed, peeled, diced, briefly blanched, and blended to a puree together with fresh mint; orange juice was freshly squeezed, and the peel was finely grated; sour cherries were used frozen and were gently heated together with dark chocolate, then cooled and blended with beetroot juice prior to adding the remaining dry ingredients. After homogenisation (hand blender), mixes were matured for 4-5 h at 4-6 °C and frozen in a domestic ice cream machine (Ambiano IM-201/11457, Intertrading GmbH, Hamburg, Germany) with continuous agitation for 30 min; products were then stored at -18 °C. Inulin was included as a dietary fibre and partial sugar replacer; texture-supporting ingredients (a stabiliser/thickener base powder or gel mix, an emulsifier where applicable, and a whipping agent) were used according to each formulation to support aeration and structure.

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Table 1: Formulations of the vegetable-based ice cream prototypes (per batch)

Ingredient (unit)	Mint-lemon zucchini	Orange-carrot	Dark chocolate-sour cherry beetroot
Lemon ice cream base powder (Tutti Ltd., Hungary) [g]	80	-	-
Zucchini puree (blanched) [g]	340	-	-
Fresh mint (chopped) [g]	50	-	-
Carrot juice [mL]	-	500	-
Orange juice (freshly squeezed) [mL]	-	200	-
Orange zest (freshly grated) [g]*	-	approx. 2	-
Beetroot juice [mL]	-	-	375
Sour cherry (frozen) [g]	-	-	300
Dark chocolate [g]	-	-	40
MEC3 Super gel mix (stabiliser/thickener) (MEC3 - OPTIMA S.P.A., Italy) [g]	-	50	37.5
MEC3 softin (emulsifier) (MEC3 - OPTIMA S.P.A., Italy)[g]	8	5	5
Sugar [g]	40	40	30
Inulin [g]	5	5	5
Citric acid [g]	2	3	3

*Orange zest was freshly grated; the amount was approximately 2 g (not weighed).

Note: MEC3 softin functions as an emulsifier; MEC3 Super Gel Mix functions as a stabiliser/thickener.

3.3 Sensory evaluation

Sensory evaluation was conducted in December 2024 at the Széchenyi István University Department of Food Science. Seventy untrained (lay) panellists (students and staff) participated voluntarily.
A structured, descriptive scoring sheet was used. Panellists rated each sample for colour, smell, taste, texture (mouthfeel), and overall appearance/overall impression on a 5-point scale (1 = very poor / dislike very much; 5 = excellent / like very much). After scoring, participants answered an open-ended question to guess the main raw materials (vegetables/fruits) perceived in the product, to capture ingredient recognisability. Samples were served in transparent plastic cups at serving temperature under neutral indoor lighting; samples were coded and served in a balanced order where possible (*Figure 1*). Water was provided for palate cleansing between samples.

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Figure 1: Products tasted during the organoleptic evaluation (A: Mint-lemon zucchini; B: Orange-carrot; C: Dark chocolate-sour cherry beetroot)

Source: own photo

3.4 Texture analysis

Texture analysis was performed using an FRTS Texture Analyzer (IMADA, Inc., Northbrook, USA) to follow softening during controlled melting. Ice cream was portioned into 50 mL measuring cups. Measurements were carried out at 20 ± 2 °C. Immediately after removal from frozen storage (-18 °C), samples were placed in the instrument and tested at 15-min intervals over time (eight time points per product; three replicates).
An ice cream puncture test was used, in which a needle probe penetrated the sample and the instrument recorded force (N) and penetration depth (mm). Hardness was defined as the peak force during puncture; penetration depth was reported as the achieved depth within the 15 mm travel limit under the test settings.
Instrument settings were: penetration speed 1.0 mm/s, return speed 5.0 mm/s, maximum displacement 15.0 mm, single test cycle; the target maximum force limit was 50 N.

3.5 Melting test

To assess melting behaviour (drip loss), three 50 g portions were weighed from each ice cream (three replicates) and placed separately into stainless-steel filters positioned above pre-weighed beakers. The test was performed at 20 ± 2 °C for 90 min; drip loss was recorded every 15 min by weighing the beakers and calculating the cumulative melted mass. Melting rate (g/min) and melting curves were derived from these data.

3.6 Statistical and visualisation methods

Statistical evaluation of the survey data was performed. This used F- and two-sample T-tests. The significance level was set at 95 %. Data processing and basic statistical analyses (calculation of means, standard deviations, and graphical representations) were performed using Microsoft Excel spreadsheet software.

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4. RESULTS

4.1 Questionnaire survey

4.1.1 Demographic characteristics of the sample

A total of 295 responses to the questionnaire were assessable. The vast majority of respondents were women (84 %; 247 respondents), while men accounted for 16 % (48 respondents) (*Table 2*). This proportion is consistent with the observation that women tend to be more interested in health-conscious and innovative food products.

Table 2. Demographic data

Description	Frequency (persons)	Distribution (%)
By gender (n = 295)		
Female	247	84
Male	48	16
Age/year (n = 295)		
under 19	17	6
20-29	145	49
30-39	37	13
40-49	45	15
50-59	34	12
60-69	11	4
70-79	6	2
up to 80	0	0
Place of residence (n = 295)		
County seat, county-level city	75	26
City	93	32
Municipality	82	28
Capital city	45	15
School education (n = 295)		
Elementary school	16	5
Secondary school without a high school diploma, with a vocational certificate	18	6
Secondary school graduation	74	24
Secondary vocational qualification based on secondary school leaving examination	31	10
Higher vocational qualification	11	4
College (BA/BSc)	103	35
University (MA(MSc)	33	11
Doctoral degree	9	3

The largest age group was 20-29 years (49 %), followed by 40-49 years (15 %), 30-39 years (13 %), and 50-59 years (12 %). The number of responses received from participants in the 60+ age group was minimal, and this was further compounded by the scarcity of responses from the 70+ age group. The present sample is predominantly composed of young and middle-aged adults, rendering it well-suited to the investigation of openness to new, functional products.

With regard to the geographical distribution of the sample, the majority of respondents resided in urban areas (32 %) or municipalities (28 %), while 26 % lived in a county town or city with

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county rights, and 15 % resided in the capital. The results of the study indicate the presence of potential consumers of vegetable-based ice cream in all types of municipalities.

The data indicate that almost half of the respondents (48 %) had a tertiary-level education, while a further 40 % had completed secondary education. The proportion of the population with a primary education was 5 %. The sample reflects a population with higher levels of education than average, which may be associated with greater receptiveness to health-conscious thinking and novel food innovations.

4.1.2 Habits and taste preferences relating to ice cream consumption

With regard to seasonality, 74 % of respondents primarily consume ice cream from May to October, while 26 % purchase it regularly throughout the year. About frequency of consumption, 47 % of respondents consume ice cream several times a week or daily, while 53 % consume it monthly or less frequently (*Figure 2*). While the data confirm the classic seasonal increase in ice cream consumption in summer, they also indicate stable demand throughout the year.

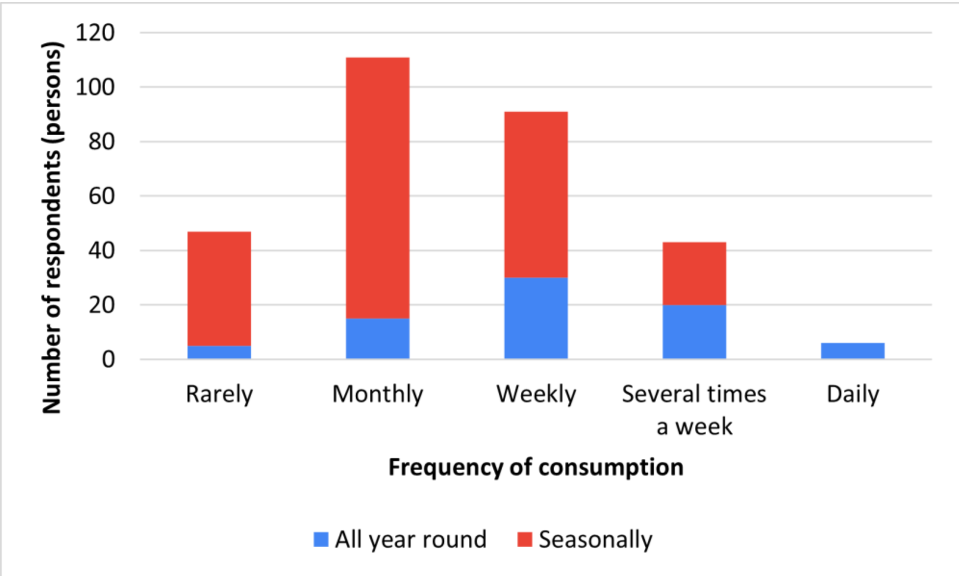

Figure 2: Ice cream consumption by seasonality and frequency (n = 295)

Concerning the preferences of respondents in relation to ice cream, the traditional dairy-based variety was the most popular (168 responses), followed by the fruit-based option (160 responses). Vegetable-based ice creams received only two responses, while sugar-free and dairy-free ice creams received 33 mentions each. This finding indicates that, despite the existence of a demand for alternative ice creams, conventional products continue to dominate the market.

Figure 3 demonstrates that vanilla and chocolate are the most popular traditional flavours, with 55 % of respondents expressing a preference for vanilla and almost 70 % for chocolate-flavoured ice cream. Lemon and orange were less popular, with respondents exhibiting more divergent preferences. The 'other fruit' category was the preferred choice of 74 % of respondents, thereby confirming the widespread popularity of fruit-based ice creams.

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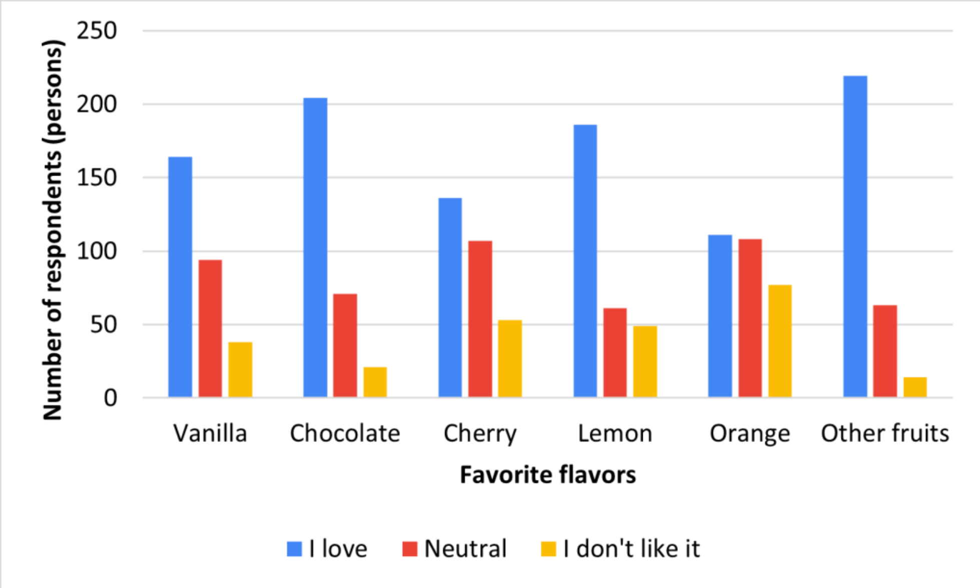

Figure 3: Popularity of ice cream flavors among respondents (n = 295)

4.1.3 Consumption of vegetables and attitudes towards vegetable-based ice creams

As demonstrated by the statistics available for consideration, the consumption of vegetables by the Hungarian population is below the recommended levels. The 2019 data from the Hungarian Central Statistical Office shows that the annual per capita consumption of vegetables is 53.5 kg, which equates to approximately 146 g per day. This is approximately 29 % of the recommended 500 g per day. In line with this, food innovations aimed at increasing vegetable consumption are of particular importance.

Of the vegetables surveyed, carrots and cucumbers proved to be the most popular, with 77 % and 79 % of respondents, respectively, strongly preferring them and only 2 % and 5 % rejecting them, respectively. The results of the survey indicate that 66 % of respondents expressed a positive preference for zucchini, while 22 % consumed it but did not regard it as a preferred choice. Conversely, 12 % of respondents indicated a dislike for zucchini. The perception of beets and pumpkin is more favourable than is generally assumed: The results of the survey indicate that 59 % of respondents expressed a positive preference for beetroot, while 54% indicated a preference for pumpkin. Conversely, 30 % of respondents expressed a dislike for pumpkin. The public's perception of pumpkin is polarised, with 34 % expressing a positive sentiment and 35 % expressing a negative sentiment. The results of the study suggest that several vegetables that could potentially be used for the development of ice creams (in particular carrots, cucumbers and zucchinis) already have an inherently favourable consumer attitude.

However, the awareness of vegetable-based ice creams remains limited, with 78 % of respondents reporting no familiarity with such products and only 22 % having encountered them. Nevertheless, the survey results indicate that 89 % of respondents expressed a willingness to sample vegetable-based ice creams: The data indicates that 46 % of respondents are categorically open to the suggestion, while 43 % are conditionally open. The type of vegetable used was identified as a significant factor in this regard. A mere 5% of respondents expressed a preference for the alternative option, while a further 5 % remained undecided. Consumer attitudes are, in general, favourable towards this practice, although these attitudes are highly dependent on the ingredient image employed.

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The question regarding specific flavour combinations (*Figure 4*) indicates that the combinations of carrot and mango, and beetroot juice and forest fruits, are the most promising, with 63 % of respondents expressing a preference for the former and 55 % for the latter. Furthermore, a significant proportion of the population expressed a strong predilection for orange carrot ice cream, with 55 % of respondents indicating a definite openness to the flavour, and 29 % expressing a willingness to consider its consumption. The results of the survey indicate that 43 % of respondents expressed a desire to sample mint-lemon zucchini ice cream, while 26 % remained undecided and 31 % expressed reluctance. An even more pronounced reluctance to try chocolate zucchini ice cream was observed, with 31 % of respondents indicating acceptance, 33 % undecided, and 36 % reluctant. The combination of chocolate beetroot ice cream and cinnamon-coffee pumpkin ice cream proved to be a divisive one. The products developed (orange carrot, mint-lemon zucchini, dark chocolate beetroot) were selected on the basis of practical considerations (availability of ingredients, ease of production) as well as consumer preferences.

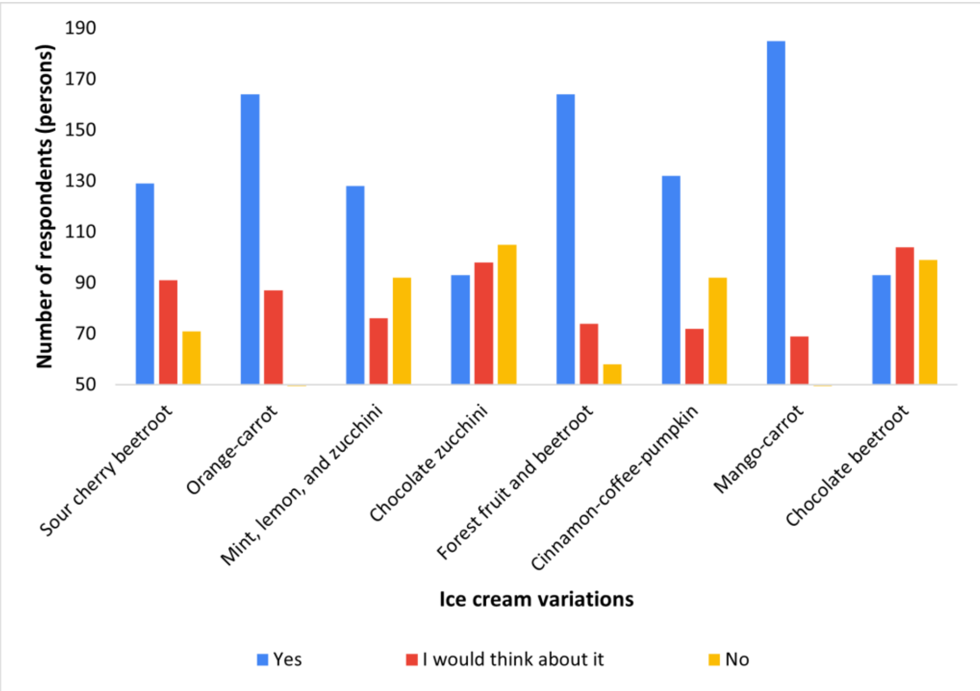

Figure 4: Consumer willingness to try different ice cream flavours (n = 295)

4.1.4 Awareness and perception of inulin

The study revealed a lack of awareness regarding inulin among the study population, with 69 % of respondents expressing a lack of awareness, 28 % indicating awareness but no utilisation, and a mere 3 % reporting both awareness and regular usage.

In the question regarding the properties of inulin, the following statements were identified as accurate: the presence of a sweet taste, the capacity to facilitate digestion, the alleviation of constipation, and the potential for bloating (*Figure 5*). In the survey, 78 % of respondents who used inulin provided at least one correct answer, while 76 % of those who were not familiar with inulin provided only incorrect statements. For example, one statement was, "The group who know but do not use inulin is in an intermediate position: 64 % of respondents who were aware of inulin but did not use it provided correct answers, while 36 % provided incorrect answers.

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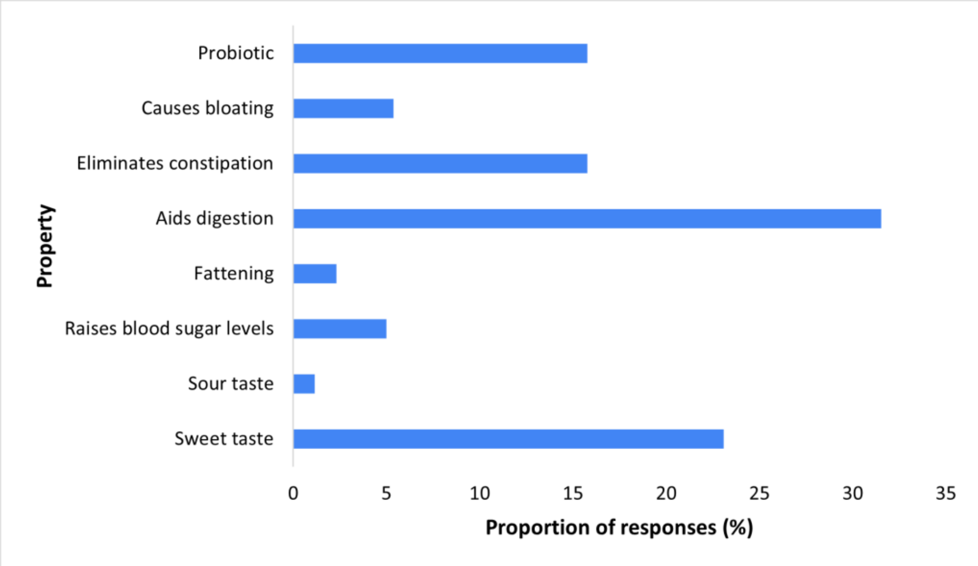

Figure 5: Distribution of responses regarding the properties of inulin (n = 260)

In response to the query regarding the sources of inulin, Jerusalem artichokes, chicory, and onions were identified as the correct responses. However, it is noteworthy that a relatively small proportion of respondents selected these options, with only 50, 3, and 4 respondents, respectively, opting for them. Consumers have limited awareness of inulin, both in terms of its functional properties and its natural sources. This represents a significant opportunity for communication and education in the development of products containing this ingredient.

The results of the study indicate that inulin is generally an 'invisible' functional ingredient in the sample under study: most consumers lack sufficient knowledge of it, yet do not associate it with a particularly negative image. This situation may provide a favourable starting point for communication strategies that link inulin to the 'natural fibre' message, emphasising both its physiological benefits (e.g., aiding digestion, increasing fibre intake) and its sensory benefits (creamier texture, pleasant, sweet sensation).

The responses indicate that the assessment of functional ingredients is predominantly information-driven. Participants with prior knowledge of inulin exhibited a higher propensity to select correct statements, while insufficient knowledge frequently resulted in erroneous categorisation. For instance, one participant stated, “This suggests that consumer education, in the form of straightforward, easily comprehensible messages on labels and online, can be a pivotal component for successful product positioning when launching vegetable-based inulin-enriched ice cream.”.

4.2 Sensory evaluation

The sensory test was completed by 70 participants (60 % of whom were female and 40 % of whom were male), with an average age of 24.3 years. The demographic composition of the sample was dominated by participants in the 19-30 age group, with a proportion of 84 %. This observation is indicative of the fact that the results obtained primarily reflect the consumer perception of young adults.

The results of the five-point rating scale are summarised in *Table 3*. The highest and lowest scores were attributed to dark chocolate and beetroot ice cream, respectively. In terms of aroma and flavour, however, the mint-lemon zucchini ice cream scored the highest, while the other

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two samples scored lower. The texture scores exhibited minimal variation among the three products, indicating comparable properties.

Table 3: Overall results of sensory evaluation

Name of ice cream	Sensory characteristics score (average / mode)				
	Colour	Smell	Taste	Texture	Overall impression
Mint-lemon zucchini	3.83 / 4	4.04 / 5	4.56 / 5	4.59 / 5	4.39 / 5
Orange carrots	4.53 / 5	3.41 / 4	3.31 / 4	4.46 / 5	3.74 / 4
Dark chocolate-sour cherry beetroot	4.76 / 5	3.37 / 3	3.10 / 3	4.50 / 5	3.71 / 3

The colour of the mint-lemon zucchini ice cream was subject to a lower level of approval than that of the orange-carrot and dark chocolate-sour cherry beetroot ice creams. In contrast, the mint-lemon zucchini variant demonstrated superior performance in terms of aroma and flavour compared to the other two products. However, no significant differences were observed between the orange carrot and dark chocolate-sour cherry beetroot ice cream in these attributes.

The overrun values for the vegetable-based ice creams produced during the product development process were as follows: the mint-lemon zucchini ice cream had an overrun value of 25.7 %, the orange carrot had an overrun value of 8.7 %, and the dark chocolate-sour cherry beetroot had an overrun value of 17.4 %. In consideration of the results obtained, it can be concluded that the ice creams were of a high density and low air content. No statistically significant differences were observed in the texture scores.

The mint-lemon zucchini ice cream sample obtained the highest overall score, while the remaining two samples obtained similar but lower overall scores.

The responses to the open-ended questions provide a valuable complement to the quantitative results. In the case of the mint-lemon zucchini ice cream, the tart flavour was noted by several reviewers as being refreshing, while the colour and texture were considered misleading or less homogeneous by some reviewers. Furthermore, the intensity of the sweet flavour was criticised by some. The orange carrot ice cream was judged by the majority of tasters to be a harmonious and interesting combination, with a clearly identifiable carrot flavour, although the intensity of the aroma was considered low by some. In the case of the dark chocolate-sour cherry beetroot ice cream, the chocolate flavour and texture were generally favourable, although the dominant taste of beetroot was mentioned by several reviewers, while the presence of sour cherries was less clear.

The sensory analysis revealed that the incorporation of the vegetable did not necessarily result in a decline in enjoyment; the mint-lemon zucchini ice cream was comparable to, and in some cases superior to, the other two products tested in terms of overall taste. This suggests that, when selected with care and combined in a harmonious manner (for example, a refreshing citrus-mint profile), the vegetable element can be perceived as an enhancement rather than a concession.

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The lower score for colour, however, highlights the potential tension between consumers' visual expectations and the objectives of health-conscious product development. An 'unconventional' ice cream colour (e.g., pale green, yellowish-green) may initially appear unappealing or out of place, despite a positive taste profile. This finding indicates that for vegetable-based ice creams, colour design (e.g., natural colour enhancement, visually appealing decoration) and targeted communication ("green colour = more vegetables") can be important tools to increase consumer acceptance.

The variances observed among the various designs indicate that consumer acceptance is not solely contingent on the vegetable itself but is also influenced by its "culinary context". The combination of carrots with citrus flavours is a more familiar and well-accepted practice in the context of domestic culinary traditions. Conversely, the pairing of beetroot with chocolate or zucchini in the form of ice cream represents a more novel concept, necessitating a higher level of innovative acceptance.

4.3 Texture analysis

The outcomes of the texture (firmness) test demonstrated that, for all products, there was a decrease in firmness with time, whilst there was an increase in penetration depth (*Figure 6*). As demonstrated in *Figure 1*, the probe achieved maximum penetration depth (15 mm) after 30 minutes for the orange carrot ice cream sample. For the dark chocolate-sour cherry beetroot ice cream sample, this was achieved after 45 minutes, and for the mint-lemon zucchini ice cream sample, it was reached after 60 minutes. Consequently, the orange carrot ice cream experienced a more rapid loss of structural firmness, while the dark chocolate-sour cherry beetroot ice cream sample, after 45 minutes, and the mint-lemon zucchini ice cream demonstrated a prolonged retention of their firmer consistency.

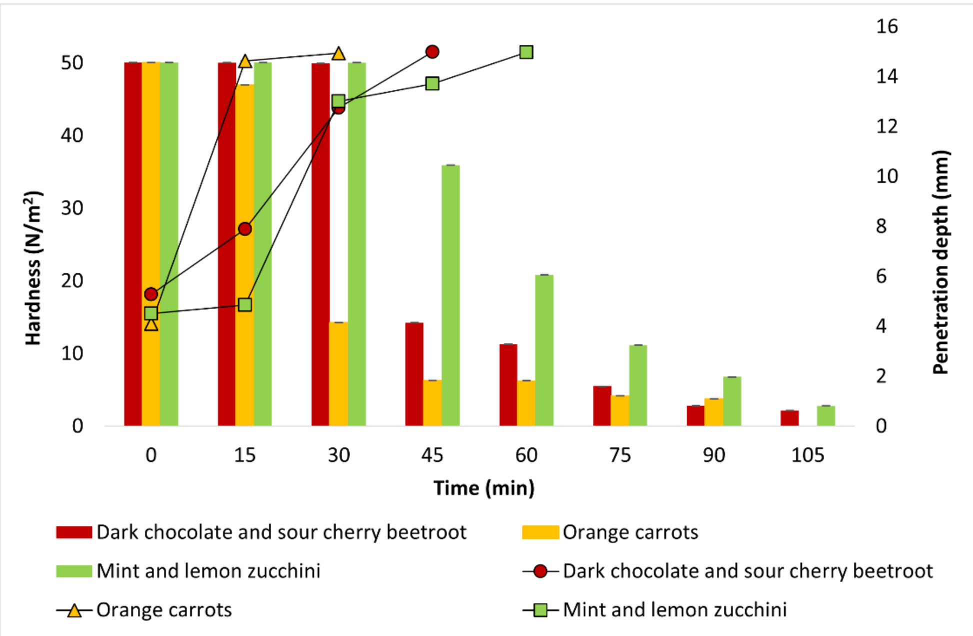

Figure 6: Changes over time in the textural parameters of vegetable-based ice creams

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The slopes of the fitted lines for the change in hardness and penetration depth over time are summarised in *Table 6*. The negative slope values indicate the rate of decrease in hardness over time, while the positive slope values express the rate of increase in penetration depth. A statistically significant ($p < 0.05$) variation was observed in both hardness and penetration depth among the three products.

Table 6: Changes in hardness (N ± SD) and penetration depth (mm ± SD) over time

Name of ice cream	Parameter	
	Hardness (N)	**Penetration depth (mm)**
Dark chocolate- sour cherry beetroot	-0.562 ± 0.003^{a}	0.222 ± 0.003^{a}
Orange carrots	-0.471 ± 0.001^{b}	0.361 ± 0.002^{b}
Zucchini with lemon and mint	-0.538 ± 0.003^{c}	0.202 ± 0.003^{c}

^{abc} Different letters within a column indicate a significant ($p < 0.05$) difference.

The findings of the study indicated that the orange carrot ice cream structure was the least stable, while the mint-lemon zucchini and dark chocolate-sour cherry beetroot ice cream structures demonstrated slower decomposition rates under the test conditions.
The findings from the mechanical tests are consistent with the sensory evaluation, indicating that distinct combinations of vegetable, fruit, and inulin result in varied structural stability. The accelerated structural degradation of the orange carrot ice cream is likely associated with its elevated water content and the comparatively weaker inter-phase network bonding. Conversely, the enhanced dry matter and fibre content, in addition to the presence of cocoa/chocolate components, in dark chocolate-sour cherry beetroot ice creams may have facilitated the maintenance of a more stable structure.
From a technological standpoint, it is imperative to observe that the structural evolution over time and the rate of decrease in hardness exhibited congruence with the outcomes of the melting test. The specimen that exhibited the most rapid 'loosening' also demonstrated the swiftest melting, a factor that is pertinent to practical applications, such as serving time and the anticipated consistency at the time of consumption. The optimization of the texture must incorporate not only sensory parameters but also rheological and melting parameters.

4.4 Melting rate

In the melting test, the orange carrot ice cream was completely melted by the 75th minute, while the mint-lemon zucchini and dark chocolate-sour cherry beetroot ice cream melted by the 90th minute (*Figure 7*). It is noteworthy that the beet ice cream did not fully melt after 90 minutes, with more than half of the sample remaining on the filter and failing to drip off afterwards.

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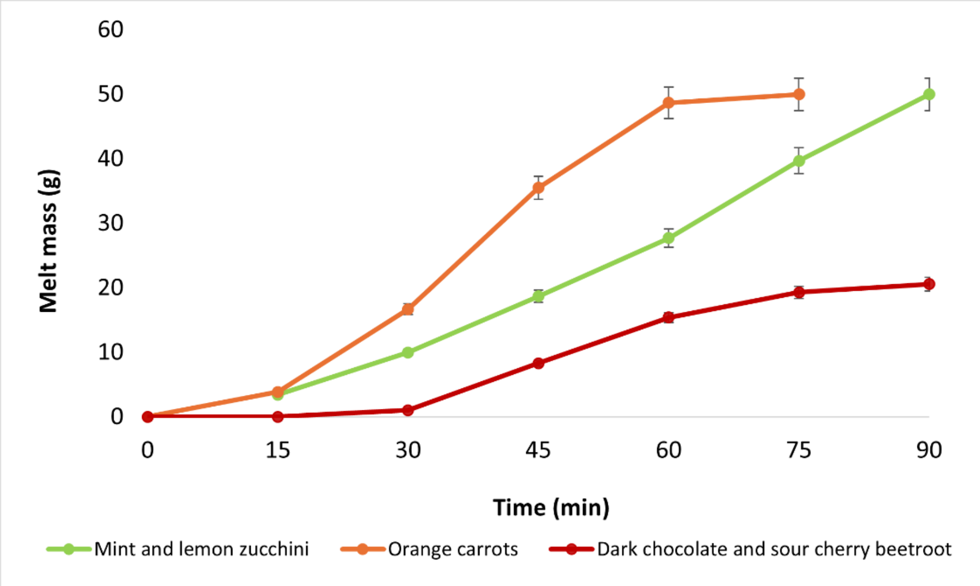

Figure 7: Examination of drip loss in vegetable-based ice creams at 20 ± 2 °C

The mean rate of melting was 0.67 g/min for orange carrot ice cream, 0.55 g/min for mint-lemon zucchini ice cream, and 0.23 g/min for dark chocolate-sour cherry beetroot ice cream. In all cases, the results of the paired comparisons indicated a significant difference ($p < 0.05$) between the melting rates of the three products.
The results demonstrated that orange carrot ice cream exhibited the most rapid melting dynamics, while dark chocolate-sour cherry beetroot ice cream demonstrated the greatest stability in terms of melting resistance. This finding aligns with the observations made in the herd study, suggesting that diverse combinations of vegetables, fruits, and inulin result in varied profiles, manifesting not only in sensory characteristics but also in physico-technological properties.
As demonstrated by the melting profiles, the three ice creams exhibited distinctly divergent technological behaviours. In practice, the rapid melting of orange carrot ice cream results in a reduced time window for aesthetic presentation, thereby increasing the likelihood of consumers encountering a product that has already begun to melt slightly. Conversely, the slower thawing of beet and zucchini varieties is indicative of enhanced heat stability, a trait that may prove particularly advantageous in hotter environments or for extended serving chains, such as in buffet settings or event contexts.
The partially solid phase that remains on the filter after 90 minutes in the case of beetroot pulp indicates that the sample does not melt homogeneously but forms a denser, gel-like residue. This phenomenon can be explained by the higher fibre and dry matter content on the one hand and by the interaction between the chocolate and the vegetable component on the other. In the subsequent phase of product development, it may be advantageous to identify a compromise through the refinement of the recipe (e.g., by adjusting the proportions of inulin, fat, or emulsifiers) to ensure both adequate serveability and a positive sensory experience.

The above results served as the basis for the integrated assessment and further interpretation presented in the Discussion section.

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5. DISCUSSION

5.1 Integrated assessment of results

Taken together, the questionnaire data, sensory ratings, and instrumental measurements of texture and melting behaviour suggest that vegetable-based, inulin-enriched ice creams have realistic market potential, particularly among young, health-conscious consumer groups. A substantial proportion of respondents (89 %) expressed a willingness to sample vegetable-based ice creams, while only 22 % were familiar with such products. This indicates that the main barrier to market expansion is not consumer rejection but limited awareness and availability. Among the proposed flavours, mango–carrot ice cream was the most attractive (63 % preference), confirming that carrot fits well into fruit-forward ice cream concepts. The demographic profile of the sample further suggests that young women (20-29 years) may constitute a key target segment, as they showed high openness to innovative, health-oriented products.

In a broader context, the incorporation of vegetable-derived ingredients into dairy matrices is an area of increasing exploration with a view to enhancing nutritional or functional value. However, the success of the product is dependent on achieving a balance between added bioactive components, sensory acceptance and textural stability (El-Sayed et al., 2025). In related frozen dessert applications, beetroot-based formulations have demonstrated that solids composition and acid-sweetness balance can materially affect colour, melting behaviour, and consumer preference, thereby supporting the importance of formulation-driven optimisation when using pigmented vegetable raw materials (Putradamni & Pramitasari, 2024).

The findings related to inulin point to an information-driven pattern of knowledge. Respondents who had already used inulin demonstrated a clearer understanding of its properties, whereas miscategorisation was more common among those unfamiliar with it. This underlines the importance of targeted consumer education in communicating the functional value of inulin-enriched vegetable-based ice creams (MDOSZ, 2021; Vijayalakshmi & Vijayavahini, 2022).

The sensory evaluation showed that all three developed ice creams were generally well received, with most panellists assigning positive ratings. The mint–lemon zucchini ice cream emerged as the most preferred variant, with approximately 75 % of the judges favouring it based on taste, texture, smell, colour, and overall impression. The mint-lemon zucchini and orange-carrot variants were the most popular in the interviews, while the dark chocolate–sour cherry–beetroot ice cream was sometimes perceived as having an overly dominant beetroot flavour. Nevertheless, the consistency of all products was typically described as creamy and pleasant, reflecting the success of the product development process.

From a technological perspective, the overrun values indicated relatively dense products with low air incorporation (25.7 % for mint–lemon zucchini, 8.7 % for orange-carrot and 17.4 % for dark chocolate–sour cherry beetroot). In light of the literature, which associates higher overrun with lighter, airier textures (Voronin et al., 2021), the developed products can be positioned as ice creams with a more “dense”, rustic texture. The particularly low overrun of the orange–carrot variant is consistent with the composition of the carrot and orange juices, while dark chocolate and sour cherry likely contributed to the thicker texture of the beetroot sample.

Texture measurements revealed a decrease in firmness over time, with the dark chocolate–sour cherry beetroot and orange–carrot ice creams softening more rapidly than the mint–lemon zucchini variant, which retained its firmness for longer. This time-dependent change in consistency has direct implications for serveability and mouthfeel. The melting behaviour was strongly influenced

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by the fibre and water content of the vegetable components. The low fibre content of zucchini (0.8-2.4 g/100 g; Ródler, 2005) resulted in moderate melting, whereas the higher fibre content of beetroot juice (1.2 g/100 ml) likely explains the incomplete melting and fibre residue on the filter (Ceclu & Nistor, 2020; Ródler, 2005). In contrast, the very low fibre content of carrot juice (0.1 g/100 ml) is consistent with the faster melting of the orange–carrot ice cream and reduced water retention. These observations align with previous findings that vegetable fibres substantially influence the texture and melting properties of frozen desserts (Ceclu & Nistor, 2020; Voronin et al., 2021).

5.2 Limitations of the study

However, it is imperative to acknowledge the study's limitations when interpreting the results. The questionnaire survey was not based on random sampling, but rather utilised a convenience sample in which younger female respondents were over-represented. Consequently, the results cannot be considered representative of the population as a whole. The perceptual survey was conducted with a relatively limited number of mostly lay raters at a single location, so the generalisability of the perceptual results is also limited. The product development was constrained to three vegetable species (zucchini, carrot, beetroot) and specific recipe variations; consequently, the conclusions cannot be extrapolated to all vegetable-based ice cream concepts. The physical measurements (stock, melting behaviour) were made for a specific storage period; the effect of longer-term storage or possible technological variations (different dry matter, fat content, or fibre type) was not investigated. Furthermore, the utilisation of rudimentary statistical tests led to the exploratory investigation of relationships, which necessitates the execution of additional, more intricate statistical analyses encompassing a more substantial number of cases.

6. CONCLUSIONS

89 % of respondents expressed a desire to sample vegetable-based ice creams, while only 22 % had previously encountered them; this suggests a considerable propensity to trial them, coupled with a paucity of awareness. The primary target group for this study is women aged 20-29, characterised by high levels of openness.

The consumer screening and sensory judgement results indicated that the mint-lemon zucchini sample was the most preferred option, with an approximate overall impression of 75 %. In contrast, the mango carrot sample demonstrated a higher level of prior interest, with 63 % of respondents expressing a preference. The flavour profile, characterised by the simultaneous presence of chocolate, sour cherry, and beetroot, requires refinement to mitigate the predominance of the latter.

The fibre and dry matter content of the beetroot sample was found to be associated with a slower rate of melting and greater structural stability. In contrast, the low-fibre variants of the carrot sample were found to soften and melt more rapidly. The overrun values (25.7 %, 8.7 %, 17.4 %) indicate a denser, less airy character of the prototypes. It can be posited that the desired mouthfeel can be achieved by targeted tuning of dry matter/fibre/liquid and emulsifier/stabiliser ratios.

The combination of vegetables and pleasure does not constitute a compromise; rather, it is an exciting dessert. Inulin, a natural dietary fibre, has been shown to contribute to fibre intake. The integration of sensory experiences, such as sampling pastries and organizing events, has been identified as a pivotal strategy to enhance acceptance. The explicit communication of the symbolic

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significance of colours, with green signifying a greater emphasis on vegetables, has been shown to mitigate visual resistance.
Potential avenues for future research include: A comparison of more representative samples and a control (classic lemon/chocolate) was conducted, in addition to detailed rheological and microstructural studies. Monitoring of frozen storage stability, as well as nutrient profile and consumer intervention tests (satiety, acceptance after repeated consumption) was also undertaken.

A növényi alapú, inulinnal dúsított jégkrémek fogyasztói elfogadottsága, érzékszervi minősége és technológiai-funkcionális viselkedése

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ÖSSZEFOGLALÁS

A vizsgálat célja zöldségalapú, inulinnal dúsított fagylaltok fejlesztése és fogyasztói/technológiai értékelése volt. Kvantitatív kérdőíves felmérést végeztünk (n = 295), majd három receptúrát (mentás–citromos cukkini; narancsos sárgarépa; étcsokoládés–meggyes cékla) érzékszervileg teszteltünk (n = 70), továbbá állomány- és olvadásvizsgálatokat folytattunk. A válaszadók 89 %-a megkóstolná a zöldségfagylaltokat, ugyanakkor csupán 22 % hallott róluk; a legígéretesebb előzetes ízvariáns a mangós sárgarépa (63 %). Az érzékszervi bírálatban a mentás–citromos cukkini adta a legkedvezőbb összbenyomást (~75 % preferencia). Az overrun értékek 8,7-25,7 % között mozogtak, a prototípusok inkább sűrű, kevéssé levegős profilját jelezve. Az olvadási viselkedést a rost- és szárazanyag-tartalom határozta meg: a céklás minta lassabban olvadt és részben gél-szerű maradékot adott, míg a sárgarépás gyorsabban olvadt; a cukkini köztes profilt mutatott. Következtetésünk szerint a zöldségfagylaltok reális piaci alternatívát jelenthetnek – különöse a 20-29 éves nők körében –, ám a bevezetés kulcsa a kóstoltatás és a célzott edukáció (inulin mint természetes élelmi rost). Technológiailag a kívánt szájérzet a szárazanyag/rost/zsírfázis és az emulgeátor–stabilizátor arány hangolásával optimalizálható.
Kulcsszavak zöldségalapú fagylalt; inulin; fogyasztói elfogadás; érzékszervi bírálat; állományvizsgálat; olvadási viselkedés; overrun; funkcionális élelmiszerek

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The Effect of Plant Conditioner Candidates on the Morphological and Physiological Parameters of the *'Rajnai fürtös'* Cucumber Cultivar

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ABSTRACT

Improving crop tolerance to abiotic stress is increasingly important under changing climatic conditions. This study evaluated three plant conditioner candidates (No. 2, 9 and 10) in the cucumber cultivar '*Rajnai fürtös*' grown under controlled hydroponic conditions. Plants were cultivated either in a complete nutrient solution or in a half-strength solution. Conditioner products were applied as weekly foliar sprays from weeks 4 to 10, and sampling was performed at weeks 6, 8 and 10. Water deprivation stress was imposed by polyethylene glycol (PEG) only prior to the final harvest. Stomatal conductance, net photosynthesis, relative chlorophyll content (SPAD), absolute chlorophyll content and specific leaf area were determined on the fully developed leaf, and shoot/root length, fresh biomass and root volume were also measured. Overall, the tested candidates showed limited efficacy; most traits did not differ significantly from the control under non-stress conditions. For underwater deprivation stress, candidate No. 2 partially mitigated the decline in gas-exchange parameters, whereas candidate No. 9 increased the number of flowers.
Keywords: cucumber, biostimulant, stress, PEG, hydroponics

1. INTRODUCTION

Climate-driven increases in the frequency and intensity of abiotic stress events pose a major constraint to cucumber production, where water deficit can rapidly impair stomatal functioning, photosynthesis and ultimately yield formation. In parallel, the need to improve input efficiency has stimulated interest in plant conditioners/biostimulants as complementary tools to conventional

fertilisation, aiming to enhance plant performance primarily through physiological modulation rather than direct nutrient supply. However, responses to such products are often context-dependent and require cultivar- and condition-specific evaluation.
Therefore, the objective of this study was to assess the effects of three plant conditioner candidates (No. 2, 9 and 10) on the morphological and physiological responses of the cucumber cultivar '*Rajnai fürtös*' under hydroponic cultivation. Emphasis was placed on gas-exchange parameters and leaf traits during vegetative development, and on plant responses following polyethylene glycol (PEG) induced water deprivation as osmotic stress, which was applied before the final sampling. We hypothesised that conditioner treatments would improve baseline growth and/or partially mitigate stress-related declines in photosynthetic performance.

2. LITERATURE REVIEW

With the increasing frequency of extreme weather events and soil depletion, biostimulants are assuming an increasingly important role in sustainable crop production. Neither in Hungary nor at the international level is there a uniformly accepted legal definition of biostimulant products. Numerous studies (Vessey 2003; Calvo et al., 2014; Yakhin et al. 2017; Rouphael & Colla 2020) report on their application and mechanisms of action, based on which the concept can be summarized as follows: biostimulant is a natural or synthetic preparation applied to the seed or foliage of plants, or to the soil, which modifies plant metabolic processes as well as structural and physiological development. As a result, the plant's abiotic stress tolerance may be enhanced, and its growth and development, and, consequently, yield will improve. A further advantage is that its application may allow a reduction in the amount of chemical fertiliser applied.
Since the concept of biostimulants has not yet been precisely delimited in legal and regulatory terms, their classification is based primarily on the practice of researchers, regulators and practitioners. The scientific literature distinguishes several broadly accepted main groups that encompass both substances and microorganisms; these are briefly reviewed in the following sections.
Heterogeneous humic substances (humic acid, fulvic acid) derived from soil organic matter improve nutrient uptake through their effects on the physical, chemical and biological properties of the soil. They increase cation exchange capacity, enhance phosphorus availability, and stimulate plasma membrane H^+-ATPases, thereby promoting nutrient uptake, cell elongation and organ growth. Modulatory effects on stress responses and hormone-like activities are also presumed. The magnitude of their effects strongly depends on their source, environmental conditions and mode of application (Zandonadi et al., 2007; Jindo et al., 2020).
Mixtures of amino acids and peptides obtained by the degradation of plant- and animal-derived proteins, as well as other nitrogen-containing compounds (e.g., betaines, polyamines), directly influence nitrogen (N) uptake and assimilation, the integration of carbon–nitrogen metabolism, and hormonal homeostasis, and–through their chelating capacity–the mobility of micronutrients. Owing to their antioxidant properties, they contribute to stress tolerance. Indirectly, they also enhance soil microbial activity and soil fertility. They frequently exert beneficial effects on yield quantity and quality; however, protein hydrolysates of animal origin raise food chain safety concerns (Jindo et al., 2020; Raidasari et al., 2025).
Extracts of brown and red seaweed contain polysaccharides, nutrients, hormones and characteristic secondary metabolites. In soil, they improve water retention and cation binding and support beneficial microflora; in plants, via their hormonal and nutritional effects, they stimulate

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germination, establishment, growth and stress tolerance. A large part of their hormonal effects is exerted through the regulation of genes involved in plant hormone biosynthesis. Considerably fewer data are available on extracts from other plant sources, but their potential biostimulant role may be based on allelochemical interactions (Stirk et al. 2020; Nanda et al., 2022).
Chitosan ($C_{56}H_{103}N_9O_{39}$), the deacetylated form of chitin, in its various polymer sizes binds to the cell wall, cell membrane, DNA and specific receptors, triggering signal transduction processes similar to those elicited by plant defence elicitors. It induces hydrogen peroxide accumulation, Ca^{2+} signalling and extensive changes in gene expression, which may result in enhanced resistance to pathogens and abiotic stress, as well as improvements in quality parameters (Stasińska-Jakubas and Hawrylak-Nowak, 2022; Molnár et al., 2023).
Certain elements (Al, Co, Na, Se, Si) are not essential for all species but are classified as beneficial elements because, under specific conditions, they can enhance growth and stress tolerance. Their effects range from strengthening the cell wall and supporting osmoregulation to modifying nutrient uptake, antioxidant defence and hormonal regulation (Franzoni et al., 2022). Some inorganic salts (e.g., phosphites) exhibit both fungicidal and biostimulant effects, and their biostimulant role has already been recognised (Gómez-Merino and Trejo-Téllez 2015).
Mycorrhizal fungi (particularly arbuscular mycorrhizal fungi, AMF) live in symbiosis with most plants and improve macro- and micronutrient supply, water relations, and tolerance to both biotic and abiotic stresses (Israel et al. 2022). Hyphal networks linking roots and the soil space may even mediate signalling between plants. Other endophytic fungi (e.g., *Trichoderma spp*., *Piriformospora indica*) can be propagated at least partly independently of the host plant, are able to transfer nutrients to the host, and have significant biocontrol and biostimulant effects (enhanced stress tolerance, growth, and nutrient use efficiency) (Du Jardin 2015; Castiglione et al. 2021).
Bacteria–plant interactions span a broad spectrum from mutualism to parasitism. From a biostimulant perspective, a key group is the *Rhizobium*-type N-fixing endosymbionts and plant growth-promoting rhizobacteria (PGPR) inhabiting the rhizosphere. These bacteria can influence nutrient supply, growth, morphogenesis, stress responses and plant–microbe interactions alike. The success of their practical application depends on strain-specific properties, synergies within bacterial consortia, plant genotype, environmental conditions and product formulation. Despite these challenges, the market for bacterial biostimulants is expanding rapidly, and PGPR are increasingly regarded as “probiotics” for plants (Du Jardin 2015; Choi et al., 2016; Lastochkina et al., 2020).

3. MATERIALS AND METHODS

The plant conditioner candidates were tested on cucumber (Cucumis sativus L.) plants of the ‘*Rajnai fürtös’* cultivar. The plants were grown hydroponically in a climate room under controlled conditions (light intensity 300 µmol m^{-2} s^{-1}, day/night temperature 25/20 °C, day/night hours 16 h/8 h, and relative humidity 65-75 %).
The seeds were germinated between moistened filter paper, and after the hypocotyls had elongated, they were placed in a nutrient solution, with 4 plants in each pot. One part of the pot was filled with a complete nutrient solution, while the other part was filled with a half nutrient solution (containing half the amount of all ingredients). The nutrient solution was prepared according to Treeby et al. (1989), changed every 3 days, and continuously aerated.
For treatment as a foliar fertiliser, we selected plant conditioner candidates 2, 9, and 10 at the concentrations recommended by the manufacturer, using the same amount of each candidate per pot.

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The control plants were sprayed with distilled water in the same amount as the plant conditioner candidates tested on the test plants. There were 3 independent replicates from every treatment. The treatments were performed once a week when the plants were 4-10 weeks old.
Sampling was performed at 6, 8, and 10 weeks of age, using one plant per pot. Three days before the last sampling, the plants were placed in an 8 % polyethylene glycol (PEG) solution to induce water deprivation stress.
During sampling, fresh biomass and shoot- and root-length were measured by thermogravimetry and root volume was determined using the water-displacement method. Stomatal conductance was investigated with an AP4 porometer (Delta-T, UK), while relative chlorophyll content (SPAD) was measured using a SPAD-502Plus meter (Konica Minolta, Japan). Net photosynthesis and stomatal conductance were measured on both young (uppermost fully expanded) and old (third from the bottom) leaves. Absolute chlorophyll content was determined following Moran and Porath (1980) and Wellburn (1994), and specific leaf area (SLA) was quantified on the fully developed leaf according to Garnier et al. (2001). Statistical analyses were performed in SPSS v23.0. Treatment effects were evaluated using one-way analysis of variance (ANOVA) and Student's t-tests, and means were separated using Duncan's multiple range test and Tukey's HSD test. Means annotated with different letters differed significantly at $p \leq 0.05$.

4. RESULTS AND DISCUSSION

Table 1 summarises stomatal conductance and net photosynthesis across the three sampling times for the control and the plant conditioner candidates (No. 2, 9 and 10), with the different letters indicating statistically significant differences among treatments within each sampling date ($p \leq 0.05$).

Table 1: The effect of plant conditioner candidates on the stomatal conductance (mmol H_2O m^{-2} s^{-1}) and net photosynthesis (µmol m^{-2} s^{-1}) of the cucumber variety 'Rajnai fürtös' at different sampling times (1st, 2nd, 3rd). (n = 12; ± S.E.)

	Sampling	Stomatal conductance	Net photosynthesis
Control	1st	177.67 ± 11.26a	21.70 ± 1.69a
2	1st	172.83 ± 14.66a	18.58 ± 2.41a
9	1st	193.17 ± 12.94a	21.53 ± 2.64a
10	1st	211.67 ± 17.37a	17.88 ± 1.26a
Control	2nd	272.00 ± 32.52a	29.54 ± 3.63a
2	2nd	245.50 ± 20.73a	26.18 ± 2.31a
9	2nd	262.58 ± 29.18a	27.48 ± 3.14a
10	2nd	278.17 ± 32.48a	28.02 ± 2.89a
Control	3rd	77.07 ± 11.39a	8.08 ± 1.35a
2	3rd	141.96 ± 13.99b	14.24 ± 1.34b
9	3rd	107.36 ± 20.64ab	11.12 ± 2.21ab
10	3rd	98.27 ± 21.73ab	10.03 ± 2.24ab

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Stomatal conductance and net photosynthesis did not differ significantly among the control and conditioner treatments (No. 2, 9, 10) at the 1st and 2nd sampling, indicating no detectable treatment effect at these time points (*Table 1*). By the 3rd sampling, both parameters declined sharply, consistent with a dominant stress effect. Under these conditions, candidate No. 2 significantly increased stomatal conductance (77.07 ± 11.39 to 141.96 ± 13.99 mmol m^{-2} s^{-1}) and net photosynthesis (8.08 ± 1.35 to 14.24 ± 1.34 μmol m^{-2} s^{-1}) relative to the stress control. Candidates No. 9 and No. 10 showed intermediate responses and were not clearly separable from either the control or candidate No. 2 at the final sampling. Overall, the data suggest that candidate No. 2 partially mitigated the stress-related decline in gas exchange, whereas no consistent benefits were observed under non-stress conditions.

Leaf developmental stage significantly affected gas exchange at the first and second sampling. The fully developed (young) leaves exhibited higher net photosynthesis and stomatal conductance than older leaves ($p \leq 0.05$) (*Table 2*).

Table 2: Net photosynthesis (μmol m^{-2} s^{-1}) and stomatal conductance (mmol m^{-2} s^{-1}) of the cucumber cultivar 'Rajnai fürtös' at different sampling times (1st, 2nd, 3rd), plotted against leaf age (old and young) growing on complete and half nutrient solution (n = 24; ± SE).

1st sampling	**Net photosynthesis**	**Stomatal conductance**	**Nutrient solution**	**Net photosynthesis**	**Stomatal conductance**
Old	17.23 ± 0.70a	167.46 ± 6.58a	Complete	23.48 ± 1.69b	201.13 ± 9.40b
Young	22.61 ± 1.80b	210.21 ± 11.44b	Half	16.36 ± 0.65a	176.54 ± 10.60a
2nd sampling	**Net photosynthesis**	**Stomatal conductance**	**Nutrient solution**	**Net photosynthesis**	**Stomatal conductance**
Old	17.23 ± 0.70a	233.17 ± 14.73a	Complete	33.07 ± 1.98b	316.83 ± 19.94b
Young	22.61 ± 1.80b	295.96 ± 22.85b	Half	22.54 ± 1.60a	212.29 ± 13.77a
3rd sampling	**Net photosynthesis**	**Stomatal conductance**	**Nutrient solution**	**Net photosynthesis**	**Stomatal conductance**
Old	10.62 ± 1.15a	103.65 ± 11.26a	Complete	11.16 ± 1.49a	106.99 ± 14.13a
Young	11.11 ± 1.53a	108.68 ± 14.59a	Half	10.57 ± 1.20a	105.33 ± 11.85a

Nutrient supply also influenced these parameters, as plants grown in the complete nutrient solution showed higher photosynthesis and stomatal conductance than those supplied with the half-strength solution at the first and second sampling. By the third sampling, differences related to leaf age and nutrient solution strength were no longer detectable, suggesting that stress effects at the final harvest overrode these influences.

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Table 3: Effect of plant conditioner candidates (Number 2, 9 and 10) on chlorophyll-a (Chl-a), chlorophyll-b (Chl-b) and carotenoid (Car) content (mg kg-1), specific leaf area (SLA: cm2 g) and relative chlorophyll content (SPAD -index) of the cucumber variety 'Rajnai fürtös' compared to the control (Cont.)

	Chl-a	**Chl-b**	**Car**	**SPAD**	**SLA**
	1st sampling				
Control	14.11 ± 0.43a	5.78 ± 0.43a	1.35 ± 0.06a	43.34 ± 0.99a	165.87 ± 11.21a
2	14.23 ± 0.36a	6.02 ± 0.33a	1.39 ± 0.05a	43.33 ± 1.04a	157.89 ± 10.45a
9	14.29 ± 0.32a	6.02 ± 0.26a	1.37 ± 0.04a	44.05 ± 0.75a	159.81 ± 9.32a
10	14.85 ± 0.39a	6.56 ± 0.36a	1.48 ± 0.05a	44.39 ± 0.91a	167.94 ± 10.66a
	Chl-a	**Chl-b**	**Car**	**SPAD**	**SLA**
	2nd sampling				
Control	14.32 ± 0.44a	6.11 ± 0.36a	1.44 ± 0.06a	43.99 ± 0.89a	146.11 ± 11.10a
2	13.49 ± 0.46a	5.54 ± 0.29a	1.35 ± 0.05a	41.90 ± 1.18a	136.34 ± 9.37a
9	14.19 ± 0.37a	5.86 ± 0.29a	1.39 ± 0.05a	44.46 ± 0.91a	140.06 ± 10.91a
10	13.68 ± 0.55a	5.58 ± 0.36a	1.35 ± 0.07a	42.29 ± 1.55a	147.99 ± 15.29a

Across both sampling dates, none of the measured traits differed significantly between the control and conditioner treatments, as all means share the same letter. Under the applied treatments, candidates No. 2, 9 and 10 did not measurably affect chlorophyll a, chlorophyll b, carotenoid concentration, SPAD index or SLA at either the first or second sampling (*Table 3*). Numerically, pigment contents and SPAD values were broadly similar among treatments at both time points, while SLA tended to be lower at the second sampling relative to the first across all treatments, suggesting a general shift in leaf structure over time rather than a treatment-specific response.
Across traits related to vegetative growth and root development (shoot and root fresh weight, root volume, shoot and root length, number of leaves and lateral shoots), no significant differences were detected between the control and conditioner-treated plants (*Figure 1*).

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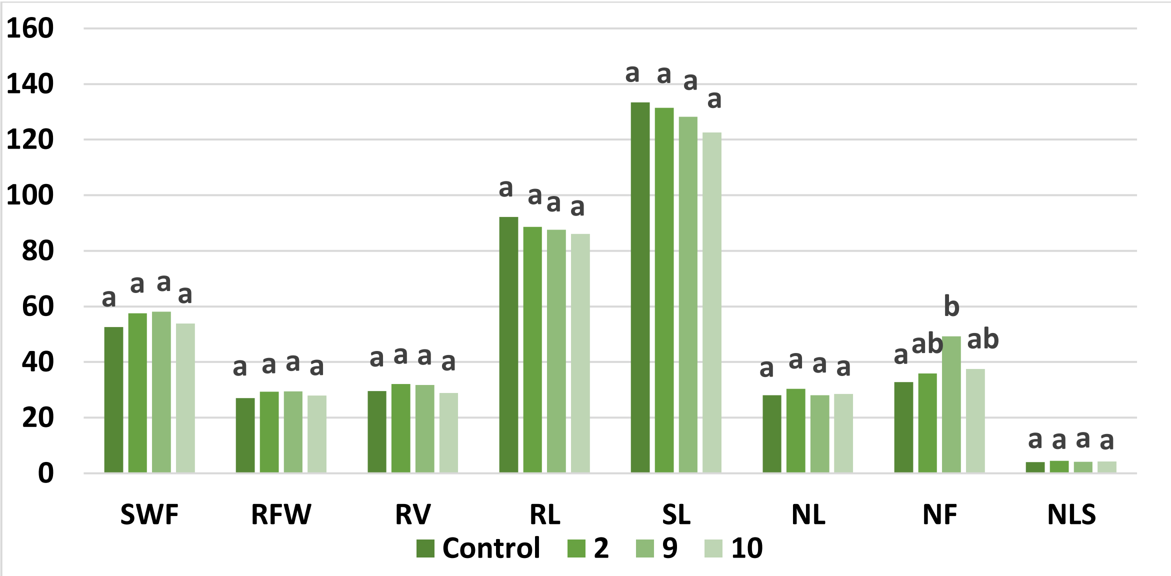

Figure 1: Effect of plant conditioner candidates (Number 2, 9 and 10) on morphological parameters of cucumber cultivar 'Rajnai fürtös' on the average of samplings. (SFW: shoot fresh weight (g); RFW: root fresh weight (g); RV: root volume (cm3); RL: root length (cm); SL: shoot length (cm); NL: number of leaves; NF: number of flowers; NLS: number of lateral shoots) (n = 18; ± SE)

In contrast, the number of flowers (NF) showed a treatment effect: candidate No. 9 resulted in significantly higher flowering compared with the control, while candidates No. 2 and No. 10 exhibited intermediate values. Overall, the conditioner candidates had negligible effects on biomass accumulation and root/shoot architecture under the applied conditions, whereas candidate No. 9 may have promoted reproductive development.

Figure 1 indicates that, when averaged across sampling dates, the plant conditioner candidates (No. 2, 9 and 10) produced no statistically supported changes in most morphological traits (SFW, RFW, RV, RL, SL, NL and NLS), as reflected by the uniform significance groupings. The *Figure 2* comparison of control plants and plants treated with candidate No. 9 supports these findings by revealing broadly similar vegetative growth and root system development, with the most apparent difference being the higher flowering intensity in the candidate No. 9 treatment. The representative phenotypes under PEG-induced water deprivation stress further demonstrate that PEG caused pronounced stress symptoms in all treatments; visually, none of the conditioner candidates fully prevented the development of stress-related damage, consistent with the overall limited treatment effects on morphology, observed in *Figure 3*.

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Figure 2: Control plants (left) and the plants treated with candidate number 9 plant conditioner (right)

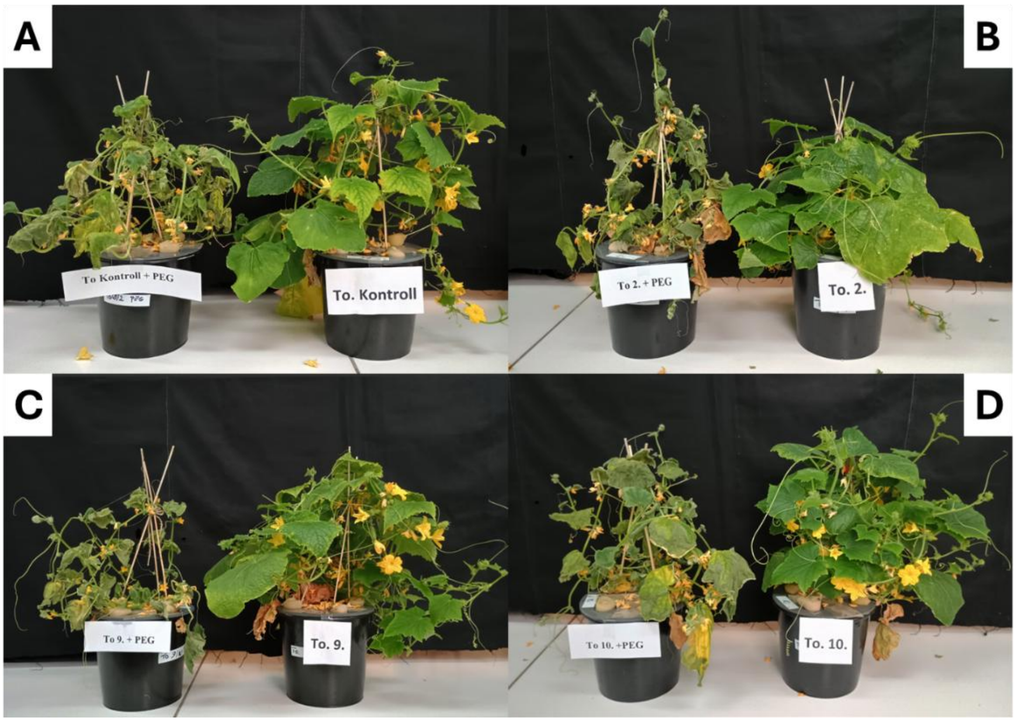

Figure 3: Representative phenotypes of plants treated with plant conditioner candidates under control and PEG-induced osmotic stress conditions. (A) Untreated control and PEG-treated plants. (B) Plants treated with conditioner candidate No. 2 in the absence or presence of PEG. (C) Plants treated with conditioner candidate No. 9 in the absence or presence of PEG. (D) Plants treated with conditioner candidate No. 10 in the absence or presence of PEG

PEG was used to impose osmotic stress. Photographs show representative plants from each treatment.

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There are several possible reasons for these results: the plant conditioner agent candidates do not contain the active ingredient(s) suitable for this purpose, the conditioners are not effective at this growth stage of plants, the applied amount of potential conditioner was not correct, or the degree of water deprivation stress was too severe for the cucumber plants to survive. The plant conditioner agent candidates improved the performance of the tested plants in a few measured parameters compared to the control plants, but it is noteworthy that candidate No. 9 increased the number of flowers. More flowers have the potential to develop into more fruit, which could improve cucumber yield. Candidate No. 2 increased stomatal conductance, implying the possibility of more intense photosynthesis as more carbon dioxide could enter the plant through the open stomata. This increases the efficiency of photosynthesis, a fundamental process in the production of organic matter.

5. CONCLUSION

Under controlled hydroponic conditions, the tested plant conditioner candidates (No. 2, 9 and 10) exerted overall limited and inconsistent effects on the physiological and morphological performance of the cucumber cultivar '*Rajnai fürtös*'. Across the non-stressed sampling dates, none of the candidates produced a consistent improvement in leaf pigment traits, relative chlorophyll content (SPAD) or specific leaf area, indicating that the treatments did not measurably enhance leaf photosynthetic pigment status or leaf structural traits under the applied conditions. Likewise, averaged morphological parameters were only marginally affected, with the most notable qualitative response being an increased flowering tendency in plants treated with candidate No. 9. Following the PEG treatment used to impose water deprivation, plant performance declined markedly across all treatments, and none of the candidates prevented the development of severe stress symptoms. Nevertheless, candidate No. 2 showed a measurable mitigation of stress-related reductions in gas-exchange parameters at the third sampling: stomatal conductance increased from 77.07 to 141.96 mmol m^{-2} s^{-1} and net photosynthesis from 8.08 to 14.24 µmol m^{-2} s^{-1} relative to the PEG-treated control, suggesting a potential capacity to partially sustain stomatal function and photosynthetic activity under stress. In contrast, candidates No. 9 and No. 10 did not yield statistically robust improvements in these parameters under PEG stress.

Overall, the results suggest that the evaluated products, as applied here (weekly foliar sprays and a short-term serious water deprivation), are not sufficient to provide broad-spectrum enhancement of cucumber growth or stress tolerance. Future work should therefore (i) test a graded, less severe water deprivation stress, (ii) include dose–response assessments and application timing optimisation, and (iii) characterise product composition and/or key active fractions to support mechanistic interpretation and reproducibility under practical production conditions.

Acknowledgments

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Növénykondicionáló-jelöltek hatása a „*Rajnai fürtös*” uborkafajta morfológiai és élettani paramétereire

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ÖSSZEFOGLALÁS

A változó éghajlati viszonyok mellett egyre fontosabb a növények abiotikus stresszekkel szembeni tűrőképességének fokozása. Jelen vizsgálatban három növénykondicionáló-jelölt (2., 9. és 10.) hatását értékeltük a „Rajnai fürtös” uborkafajtán kontrollált, hidroponikus körülmények között. A növényeket teljes tápoldatban, illetve fél töménységű tápoldatban neveltük. A készítményeket a 4-10. hetek között hetente egyszer lombpermetezéssel juttattuk ki, a mintavételezés a 6., 8. és 10. héten történt. A vízhiány stresszt polietilén-glikol (PEG) alkalmazásával kizárólag a végső betakarítás előtt idéztük elő (a 3. mintavételt megelőző 3 napban). A sztóma konduktanciát, a nettó fotoszintézist, a relatív klorofilltartalmat (SPAD), az abszolút klorofilltartalmat és a fajlagos levélfelületet az utolsó teljesen kifejlődött levélen határoztuk meg; emellett mértük a hajtás és a gyökér hosszát, friss tömegét, valamint a gyökértérfogatot. Összességében a vizsgált jelöltek hatékonysága korlátozott volt; stresszmentes körülmények között a legtöbb vizsgált tulajdonság szignifikánsan nem különbözött a kontrolltól. PEG-stressz hatására a 2-es jelölt részben mérsékelte a gázcsere-paraméterek csökkenését, míg a 9-es jelölt növelte a virágok számát.

Kulcsszavak: uborka, biostimulator, stress, PEG, hidropónia

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Growth Performance and Water-Use Efficiency of Red Rubin and Genovese Basil Varieties in Aeroponic Cultivation

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ABSTRACT

Our study investigated the growth of two basil varieties – Red Rubin (*Ocimum basilicum* var. *purpurascens*) and Genovese (*Ocimum basilicum* var. *Genovese*) – under aeroponic conditions at the Institute of Water and Environmental Management, University of Debrecen. Growth dynamics were monitored using morphological parameters (plant height and leaf number), manual LiDAR measurements, and yield analysis. The aim was to evaluate the performance of these varieties in terms of growth characteristics and productivity under controlled light, climate, and nutrient conditions, with particular emphasis on water-use efficiency. The results revealed differences in growth patterns between the two varieties, as well as in their responses to nutrient availability and environmental factors. This research offers valuable insights for optimizing aeroponic basil cultivation and supports sustainable, resource-efficient agricultural practices, especially in urban and vertical farming systems. The research presented in the article was carried out within the framework of the Széchenyi Terv Plusz programme, with support from the RRF-2.3.1-21-2022-00008 project.
Keywords: aeroponics, basil, soilless cultivation, water use efficiency

1. INTRODUCTION

The agricultural sector currently faces numerous global challenges. Climate change, which has already caused adverse effects for several decades, is expected to intensify and lead to even more profound disruptions in the coming years. At the same time, the reduction of arable land due to urbanisation and industrial expansion – combined with soil degradation through salinisation, nutrient depletion, erosion, and contamination with pesticides or heavy metals – poses an increasing threat to global food production. Plants have inherent limitations in rapidly adapting to rapidly changing conditions, resulting in reduced yields, lower crop quality, and greater vulnerability to pests and diseases. Together, these factors create significant risks to food security and economic stability.

At the same time, market demand for fresh, high-quality herbs – particularly basil – is steadily increasing due to the growth of the food industry and gastronomy, as well as the rising popularity of functional foods rich in bioactive compounds. However, basil is highly sensitive to environmental fluctuations, and traditional field cultivation often fails to deliver stable yields and uniform quality. This has made controlled environment agriculture (CEA) increasingly important for producing consistent, contamination-free plant material with predictable growth characteristics (Gomez et al., 2019).

Soilless cultivation technologies offer promising solutions to these challenges. Among them, aeroponics stands out as one of the most innovative and efficient plant production systems (Kumar, 2024). By suspending plant roots in air and delivering a nutrient-rich mist directly to the rhizosphere, aeroponics provides optimal root-zone oxygenation, precise nutrient delivery, and significantly reduced water consumption. Its closed-loop design minimises water losses from evaporation or leaching, making it particularly suitable for regions facing water scarcity. In addition, aeroponics eliminates exposure to soil-borne pathogens and enables pesticide-free production, thereby supporting sustainable horticultural practices.

Recent developments in digital phenotyping, including LiDAR-based morphological monitoring, further enhance the potential of aeroponics (Gano et al., 2024). These technologies enable high-resolution, non-destructive tracking of plant development, offering valuable insights into genotype-specific growth responses and supporting data-driven optimisation of cultivation protocols.

Given these technological advancements and the increasing need for sustainable, water-efficient crop production, evaluating the performance of different basil varieties under aeroponic conditions is both timely and relevant. Understanding how varietal traits interact with controlled environmental parameters can help refine production strategies and improve the overall efficiency of urban and vertical farming systems.

2. LITERATURE REVIEW

Aeroponics has emerged as an innovative and highly efficient plant production method, attracting growing attention for its ability to reduce water use and enhance growth rates (Garzón et al., 2023; Lakhiar, 2018). In this system, roots are suspended in air and supplied with water and nutrients as a fine mist (Blok et al., 2017), promoting optimal plant development while minimising resource consumption. As a closed production technology, aeroponics enables precise environmental control and reduces pathogen pressure, thereby eliminating soil-borne diseases and supporting pesticide-free cultivation (Scortichini, 2022). The beneficial effects of aeroponic cultivation have been successfully demonstrated in tomatoes (Tafesse et al., 2021), cucumbers (Jamshidi et al., 2020), leafy

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greens (Chandra et al., 2014; Lim, 1996), potatoes (Farran & Mingo-Castel, 2006; Tunio et al., 2020), and herbs and medicinal plants (Hayden, 2006). Positive results have also been observed with lettuce (Kovács et al., 2025a) and seed potatoes (Kovács et al., 2025b).

Basil (*Ocimum basilicum*) is a widely used culinary and economically important herb, valued for both fresh consumption and its essential oils, which have applications in the food, pharmaceutical, and cosmetic sectors. Its short production cycle, high market demand, and sensitivity to environmental fluctuations make it particularly suited to controlled environment agriculture. Aeroponic production is especially advantageous for basil, which requires a tightly regulated nutrient and water supply (Khater et al., 2021; Salachas et al., 2015). Environmental factors such as light, nutrients, and water availability strongly influence its growth and essential-oil profile (Stagnari et al., 2018), while the species responds well to precise nutrient delivery and a highly oxygenated root zone.

Studies consistently show that basil grown aeroponically develops faster and produces greater biomass and more refined root systems than when grown under hydroponic or soil-based conditions (Mourantian et al., 2023; Pasch et al., 2021; Salachas et al., 2015). Improved oxygenation enhances enzyme activity, nutrient transport, and stress tolerance, while water-use efficiency (WUE) – shaped by transpiration, leaf area expansion, and biomass-to-water ratios – also tends to increase. Aeroponics' pulsed water delivery creates alternating wet-dry cycles that can stimulate water uptake and nutrient efficiency, thereby increasing chlorophyll content, accelerating canopy development, and enhancing essential-oil synthesis. Overall, the resource-efficient, year-round production enabled by closed systems positions aeroponics as a key technology for meeting the growing global demand for high-quality basil.

This study aimed to evaluate the performance of these basil varieties in terms of growth characteristics and productivity under controlled light, climate, and nutrient conditions, with particular emphasis on water-use efficiency.

3. MATERIALS AND METHODS

We conducted the experiments in the Aeroponics Laboratory of the Institute of Water and Environmental Management, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen. The closed climate chamber enabled controlled conditions for up to 80 plants by regulating temperature, relative humidity, and light cycles.

3.1 The two basil varieties used in the experiment

"Red Rubin" (*Ocimum basilicum* var. *purpurascens*) is a red-leaved basil variety characterised by medium plant height, a strong clove-like aroma, vigorous stems, and dense foliage. Under optimal conditions, plants typically reach 40-60 cm in height.

The traditional sweet basil variety "Genovese" (*Ocimum basilicum* var. *Genovese*) is widely cultivated for fresh consumption and pesto production. It features large, bright-green leaves, a strong aroma, and high yield potential, making it well-suited to hydroponic and aeroponic cultivation systems (Biksa, 2022). It is considered the standard cultivar for Italian-style basil production (Gardenia, 2025).

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3.2 Description of the experiment

Basil seeds were germinated on 3.6 × 3.6 cm rockwool cubes (*Figure 1*). Seedling cultivation took place in a Mammoth Lite 80+ indoor growing tent equipped with a SANLIGHT Q5W GEN2 grow lamp capable of emitting light in the 400-780 nm wavelength range.

Figure 1: The seedling nursery tent (left) and the pre-grown seedlings (right) in the cotton cubes

Source: The authors

At sowing, four basil seeds were placed in each rockwool cube, and a thin layer of perlite was added. Two-week-old pre-grown seedlings were then transplanted into the Aeroponics Laboratory. In each of the four growing units (each with a surface area of 1 m²), ten seedlings per variety were planted. The climate chamber contained four aeroponic growing units, each connected to its own nutrient storage tank via a pipe system. Plants were placed in basket-shaped growing pots filled with clay pellets as the inert growth medium.

The aeroponic nozzles were adjusted to deliver a fine nutrient mist evenly onto the suspended plant roots. Pumps were equipped with timers, and nutrient delivery was set to 10 min every hour throughout the experiment.

Data-collecting sensors were installed in the climate chamber, connected to a central computer, and continuously recorded temperature and humidity. *Figure 2* shows the variation in temperature and relative humidity over the 111-day experimental period in the aeroponic system. During the first 60 days, the temperature fluctuated between 15 °C and 25 °C with noticeable variation before stabilising at approximately 20 °C to meet the plants' developmental requirements. Relative humidity initially ranged widely between 60 % and 90 %, then stabilised at around 70 % from day 40 onward.

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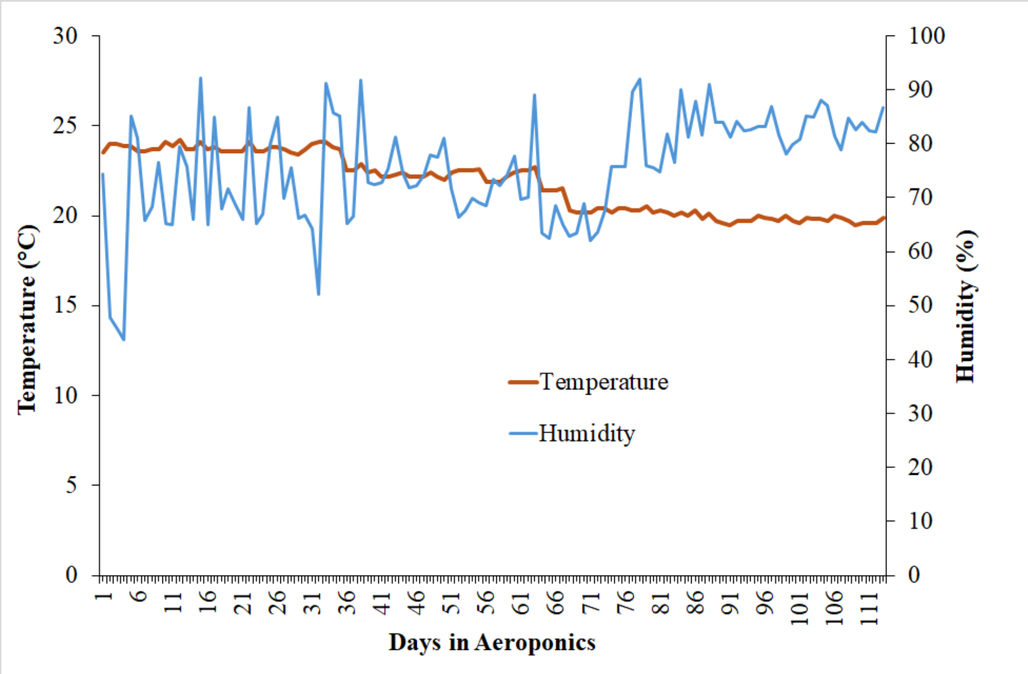

Figure 2: The temperature and humidity changes during the experiment in the Aeroponics

Source: The authors' data

The plants were illuminated using Research Top Light full-spectrum, high-intensity, four-channel horticultural LED grow lamps controlled by the Hungarian "Power Grow" software developed by Tungsram. The lighting system operated fully automatically throughout the experiment.

During the early seedling stage, basil does not require far-red light; therefore, far-red wavelengths were omitted from the spectrum. After the vegetative expansion stage, far-red light becomes necessary. Incorporating far-red light into the spectrum provides significant benefits for biomass production and resource-use efficiency. Far-red (FR) light treatments are associated with increased carbohydrate reserves, more efficient stachyose production, and potentially improved phloem loading in intermediary cells through enhanced sucrose homeostasis. The combination of higher biomass yield, increased resource-use efficiency, and elevated leaf carbohydrate concentrations in response to FR light supplementation offers promising opportunities for commercial crop production in controlled environment agriculture (Driesen et al., 2023). *Figure 3* shows the light intensity and spectrum applied before and after the addition of far-red light.

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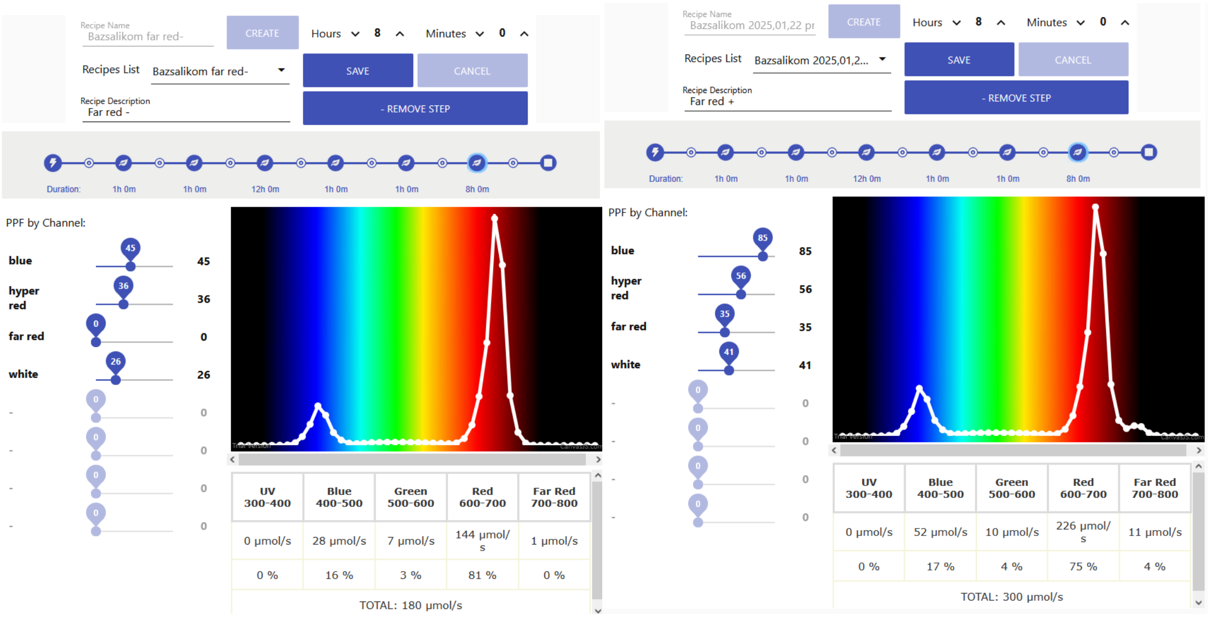

Figure 3: The applied light protocol before and after the use of far-red light

Source: The authors

During the experiment, four growing units were available in the laboratory, each capable of accommodating 20 plants. Each unit was supplied by its own nutrient solution tank, allowing independent adjustment of nutrient replenishment according to specific requirements. The nutrient solution was prepared in accordance with the manufacturer's recommendations using GHE–Terra Aquatica TriPart Grow and Micro concentrates. *Table 1* summarises the nutrients supplied to each unit over the entire experiment, along with the total amount of water replenished.

Table 1: Nutrient solution and water replenished throughout the experiment

***Ocimum basilicum* var. *purpurascens* (1)**			***Ocimum basilicum* var. *Genovese* (2)**			***Ocimum basilicum* var. *purpurascens* (3)**			***Ocimum basilicum* var. *Genovese* (4)**		
Grow (ml)	**Micro (ml)**	**Water (L)**	**Grow (ml)**	**Micro (ml)**	**Water (L)**	**Grow (ml)**	**Micro (ml)**	**Water (L)**	**Grow (ml)**	**Micro (ml)**	**Water (L)**
164	57	90	180	65	100	136	68	85	144	72	90

Source: The authors' data

The slight differences in the amount of nutrient solution supplied to each unit were mainly due to operational adjustments during the cultivation period. Since the primary experimental objective was to assess varietal performance rather than nutrient treatment effects, the results were evaluated on a variety basis by averaging the data from the two corresponding units.

During the experiment, plant height (*Figure 4*) and leaf number were measured weekly. On day 42, regular pruning of the basil plants began, with larger leaves removed. For each unit, the fresh weight of all harvested leaves was recorded. The leaves were then dried to determine their dry weight. At final harvest, the total fresh mass of the plants (including shoots and roots) was measured, followed by drying to determine dry matter content. At the end of the experiment, the total volume of water used during cultivation was quantified to calculate the water-use efficiency (WUE) index.

Water-use efficiency (WUE) is a measure of how efficiently plants utilise water. It was calculated as the ratio of produced biomass (g) to total water consumption (L). A high WUE indicates that plants produced more biomass per unit of water, whereas a low WUE suggests that water consumption did not result in proportionally greater growth.

Figure 4: The two basil varieties in the growing units

Source: The authors

In this experiment, basil plants (*Ocimum basilicum* L.) were grown in an aeroponic system inside a closed climate chamber. Throughout cultivation and measurement procedures, the temperature was maintained at 25 °C, and the relative humidity was kept near 70 %. The developmental stages of the plants were recorded across the entire vegetation period at all major phenophases.

To survey the plant stand, we employed an X120GO handheld 3D LiDAR scanner, which operates on an active remote-sensing principle and produces high-density 3D point clouds. The device has a maximum range of 120 m, a minimum measurement distance of 0.5 m, and a relative accuracy of 6 mm under controlled conditions. It features 16 vertical channels, operates at a sampling frequency of 320,000 points per second, and has a 360° × 270° field of view with a class 1 laser source. The integrated camera system consists of three RGB cameras, each with a resolution of 5 megapixels (total 15 megapixels), providing a 200° × 100° field of view for capturing hemispherical colourised point clouds. Measurement data were stored in the scanner's 32 GB expandable memory. At the same time, real-time visualisation was performed on an Android-based device, and post-processing was carried out using the manufacturer's GOpost software.

During data acquisition, the operator slowly walked through the climate chamber between rows of plants while holding the scanner. Three-dimensional point clouds were generated from raw LiDAR data and subsequently cleaned using noise filtering and erroneous-point removal procedures. From the denoised point clouds, we derived plant height, canopy volume, and other geometric characteristics. Based on the resulting 3D canopy structure information, established modelling approaches can be applied to estimate leaf area and biomass, providing a basis for further water and energy balance analyses. Our objective was to extract quantitative plant parameters from the point clouds – including plant height, leaf area, leaf count, and leaf orientation – and to monitor their temporal dynamics.

The data were organised, analysed, and plotted using Microsoft Excel spreadsheets. One-way analysis of variance (ANOVA) was used to identify significant differences between groups.

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4. RESULTS

Averaged data for the two basil varieties (*Figure 5*) show that growth was gradual in both, but Genovese (green) grew significantly faster and reached a higher height by day 70. In contrast, Purpurascens (purple) exhibited slower growth, with final plant height reaching only about half to two-thirds that of Genovese. Error bars (representing standard deviations or standard errors) indicate measurement variability, which increased over time – particularly for the Genovese variety. After day 42, when weekly pruning began, Genovese growth slowed and the height curve levelled off.

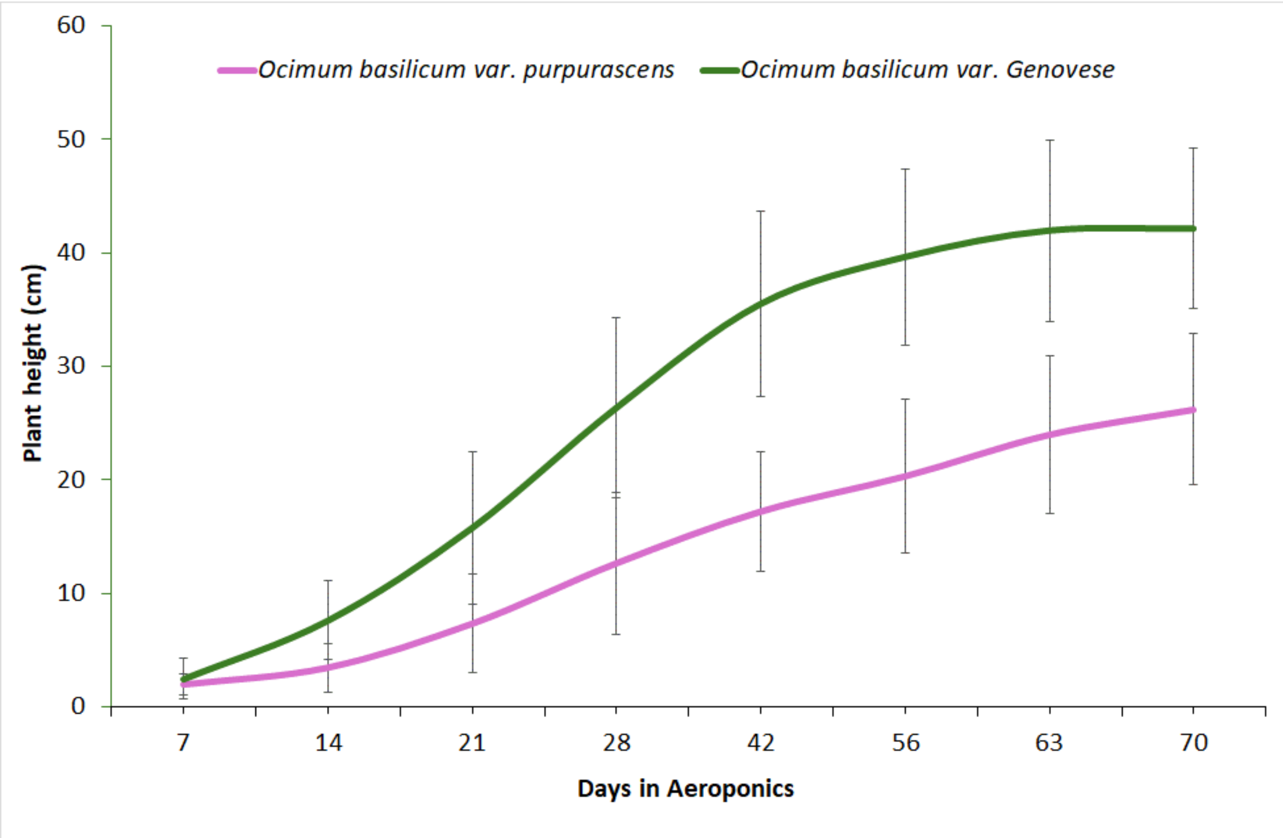

Figure 5: The development of plant height of the two basil varieties during the experiment

Source: The authors' data

Although the height development of the two basil varieties differed markedly, one-way ANOVA indicated that this difference was not statistically significant at the 5 % probability level ($P = 0.08$). The high variance reduced statistical confidence in the result. Nevertheless, the observed differences in plant height development suggest distinct growth strategies between the two varieties under controlled aeroponic conditions. Genovese exhibited more intensive vertical growth, likely associated with its genetic characteristics and the strong vegetative vigour commonly reported in commercial sweet basil cultivars. In contrast, Purpurascens showed slower height growth, a trait typical of red-leaved basil types that often allocate more resources to leaf pigmentation and structural tissues. The increasing variance in later stages suggests that individual plant responses became more heterogeneous as plant size increased and regular pruning influenced canopy architecture.

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Leaf number development was also examined in each unit throughout the experiment. *Figure 6* shows the average leaf number for the two varieties over time. After regular pruning began on day 42, leaf numbers changed rapidly, and no significant difference was observed between the varieties for this parameter. Leaf counts were recorded at regular intervals (days 7, 14, 21, 28, 42, 56, 63, and 70). Both varieties showed a steady increase in leaf number during the early cultivation period. From day 28 onward, Purpurascens generally had a slightly higher leaf count than Genovese, with the difference becoming more pronounced in the later stages (days 63-70). Error bars represent standard deviations, reflecting variability among individual plants. These data suggest that, while both varieties perform well under aeroponic conditions, Purpurascens may achieve a higher leaf number in the later growth stages.

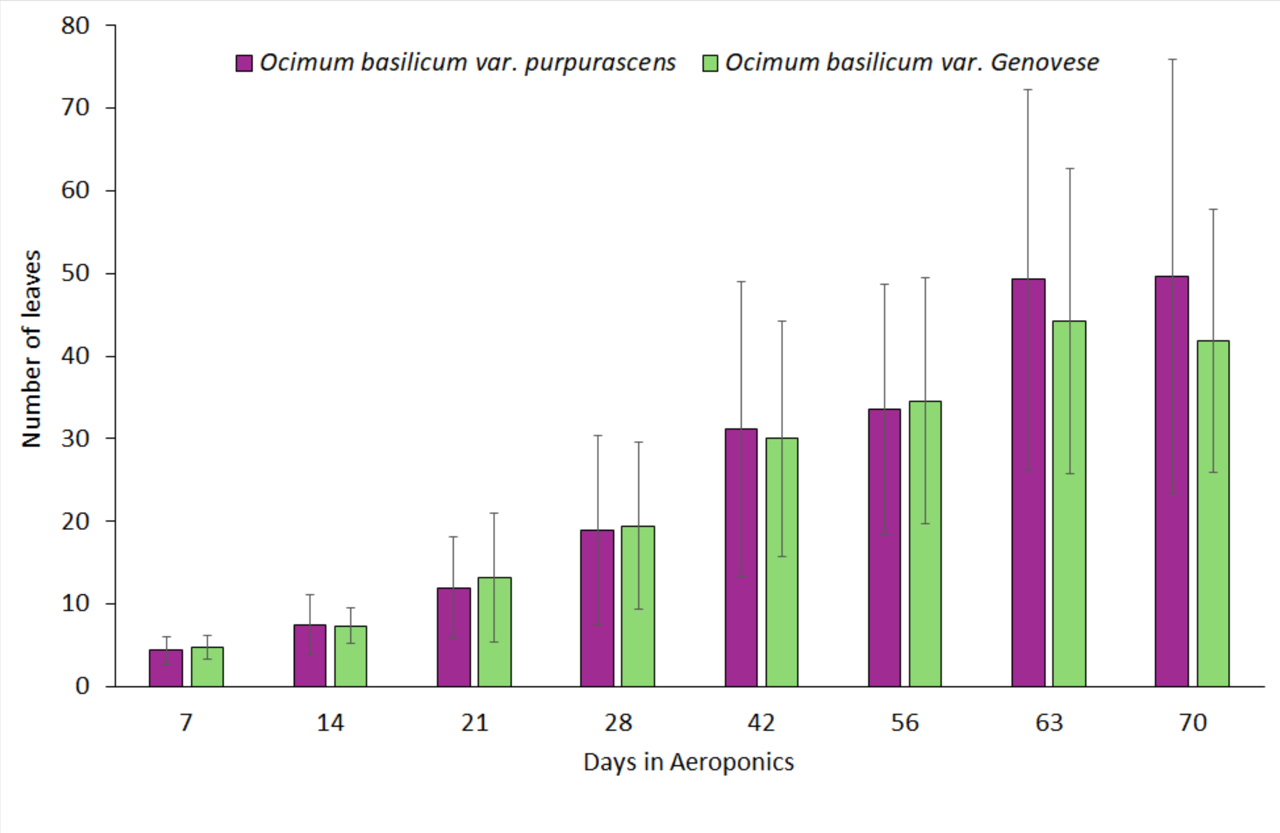

Figure 6: The development of leaf number of the two basil varieties during the experiment

Source: The authors' data

The dynamics of leaf number development provide additional insight into the morphological differences between the two varieties. Although Genovese showed more pronounced vertical growth, Purpurascens tended to maintain a slightly higher leaf number in the later stages of cultivation. This suggests that the varieties may differ in canopy architecture and biomass allocation patterns. The pruning practices introduced during the experiment likely influenced lateral shoot development and leaf production, which may account for the rapid fluctuations in leaf number after day 42. Such responses are typical in basil cultivation, where regular harvesting or pruning stimulates new leaf formation and branching.

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Basil plants grown in the aeroponic system were continuously monitored using LiDAR to track real-time growth dynamics and morphological changes across all phenological phases (*Figure 7*). The aim was to quantitatively extract plant parameters, including height, leaf area, leaf count, and leaf angle. However, the controlled conditions in the climate chamber – particularly the high relative humidity of 70 % maintained alongside a stable temperature of 25 °C – significantly affected the quality of the LiDAR scans. Due to the elevated humidity, the raw point clouds were extremely noisy. Although effective de-noising algorithms were applied, this processing inevitably reduced point density and, consequently, the level of detail captured in the point clouds. *Figure 7* presents RGB-coloured, denoised point clouds from three different phenological phases to visually illustrate the growth pattern of basil plants.

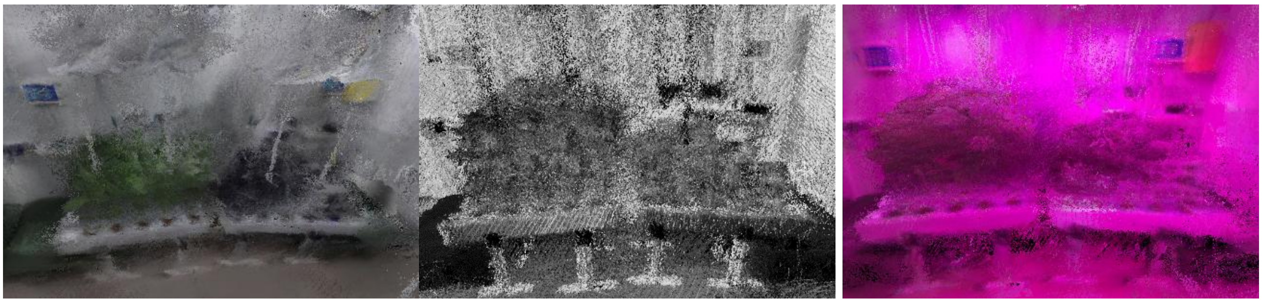

Figure 7: Monitoring morphological parameters with a LiDAR camera

Source: The authors

The application of LiDAR-based monitoring demonstrated the potential of three-dimensional plant phenotyping methods in controlled-environment agriculture. Although the high humidity in the climate chamber reduced the quality of the raw point clouds, the processed data still provided valuable visual information on canopy structure and plant development. Such non-destructive monitoring techniques can support detailed analysis of plant growth dynamics and may contribute to the optimisation of cultivation strategies in future studies.

Water-use efficiency (*Figure 8*) was much higher for the Genovese variety than for Purpurascens (9.39 g L^{-1} vs. 4.83 g L^{-1}), representing nearly a twofold difference. The relatively small standard deviations indicate low measurement variation and confirm the reliability of the results. Genovese not only grew faster but also demonstrated greater water-use efficiency under aeroponic cultivation compared with Purpurascens.

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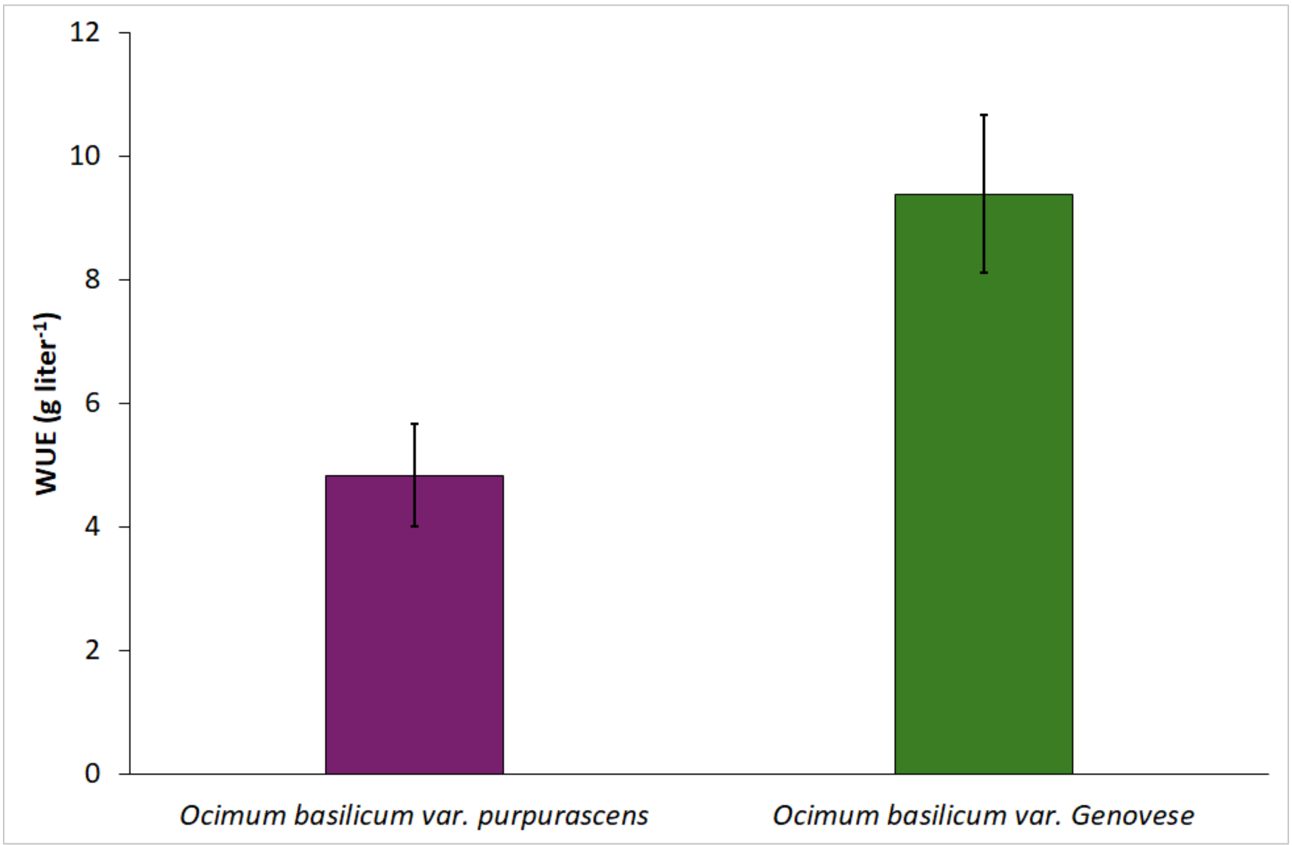

Figure 8: The development of water use efficiency of the two basil varieties during the experiment

Source: The authors' data

The observed differences in water-use efficiency underscore the importance of varietal traits in determining plant performance under controlled cultivation systems. The higher WUE values recorded for Genovese indicate that this cultivar converted supplied water into biomass more efficiently than Purpurascens under the experimental conditions. This difference may be linked to Genovese's faster growth rate and larger canopy development, which enhance photosynthetic activity and biomass accumulation. Similar varietal differences in water-use efficiency have been reported in controlled-environment basil cultivation, where genotype-specific responses to water and nutrient availability influence overall productivity.

5. CONCLUSION

The results demonstrate that the aeroponic system provided a favourable cultivation environment for both tested basil varieties, although each responded differently to environmental factors and modifications in the light programme. The inclusion of far-red light proved particularly significant, accelerating vegetative growth, increasing canopy biomass, and improving photosynthetic efficiency.

The varietal differences highlight the importance of defining clear cultivation objectives. Genovese is ideal when the goal is high yield and efficient water use. In contrast, Purpurascens is advantageous when the aim is to produce plants with a distinctive appearance, unique pigmentation, and strong aromatic qualities.

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The findings also indicate that minor adjustments to environmental parameters – such as light intensity, spectral composition, or nutrient concentration – affect plant development to varying degrees. Future studies should explore further fine-tuning of the light spectrum and test different microclimate scenarios. In addition, clarifying the role of genetic factors – particularly in biomass accumulation and water-use efficiency (WUE) – would justify broader comparative trials. Overall, the present experiment confirmed that the aeroponic system is a controllable cultivation method enabling efficient plant development and water use under controlled environmental conditions.

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Bazsalikomfajták növekedésének vizsgálata biztonságos és víz-hatékony aeroponikus körülmények között

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ÖSSZEFOGLALÁS

Kutatásunk két bazsalikomfajta – Red Rubin (*Ocimum basilicum* var. *purpurascens*) és Genovese (*Ocimum basilicum* var. *Genovese*) – növekedését vizsgálta aeroponikus körülmények között a Debreceni Egyetem MÉK Víz- és Környezetgazdálkodási Intézetében. A két fajta növekedési dinamikáját különböző morfológiai paraméterek (növény magassága, levelek száma), manuális LiDAR-mérések és hozamelemzés segítségével követtük nyomon. A cél az volt, hogy értékeljük ezen bazsalikomfajták teljesítményét növekedési jellemzőik és termékenységük alapján, kontrollált fény-, éghajlat- és tápanyagkörülmények mellett, a vízhatékonyság figyelembevételével. Az eredmények különbségeket mutattak a két fajta növekedési mintázatai között, valamint azok válaszát a tápanyagellátottságra és a környezeti tényezőkre. A kutatás értékes információkat nyújt a bazsalikom aeroponikus termesztésének optimalizálásához, különösen a fenntartható, erőforráshatékony mezőgazdasági gyakorlatokhoz, amelyek a városi és vertikális gazdálkodási rendszerekben is alkalmazhatók. A dolgozatban bemutatott kutatás a Széchenyi Terv Plusz program keretében valósult meg az RRF-2.3.1-21-2022-00008 számú projekt támogatásával.
Kulcsszavak: aeropónia, bazsalikom, talaj nélküli termesztés, vízfelhasználás

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Farmers' Participation Motivations and Sustainability Attitudes in the Context of the Agro-Ecological Programme

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ABSTRACT

The Agro-Ecological Programme, launched in 2023, is one of the most important instruments of the European Union's new Common Agricultural Policy. It aims to encourage environmentally friendly farming practices. This study analyses responses from 80 Hungarian farmers regarding their participation in the programme, motivations, and attitudes towards sustainability. The research employed quantitative methods, with particular attention to farm size, income level, and environmental awareness. The results indicate that participation decisions are motivated not only by economic considerations but also increasingly by sustainability values, especially among younger and more highly educated farmers. The study is primarily recommended for agricultural policy makers, professional agricultural organisations, and agricultural advisors, as its empirical findings contribute to the more effective design and targeted development of agri-environmental programmes, particularly the Agro-Ecological Programme. It may also prove useful to researchers in agricultural economics and rural development, as well as to students at higher education institutions, who examine the connections between sustainable agriculture, agroecology, and farmer decision-making in the context of the new Common Agricultural Policy.

Keywords: agroecology, sustainability, motivations, environmental awareness, agricultural policy

1. INTRODUCTION

The environmental and economic challenges facing European agriculture in the 21st century – including the impacts of climate change, biodiversity loss, soil degradation, and market and income uncertainties – create a complex adaptation imperative that requires a comprehensive transformation of production systems. The European Union's new Common Agricultural Policy (CAP) for 2023-2027 accordingly focuses on sustainability, the preservation of ecosystem services, and the implementation of climate considerations. One of the key elements of the CAP reform is the Agro-Ecological Programme (Agro-ökológiai Program, AÖP), which supports farming practices such as soil conservation, the maintenance of landscape elements, biodiversity-enhancing interventions, and the reduction of plant protection loads. The aim of this programme is twofold: on the one hand, to reduce environmental burdens through financial incentives and, on the other hand, to promote wider social and professional acceptance of the agroecological approach.

However, for policy instruments to effectively support the agroecological transition, a deep understanding of the factors shaping farmers' decision-making processes is essential. International research increasingly shows that farmers' participation in environmental programmes is not solely determined by economic incentives: personal values, attitudes, risk perceptions, professional experience, and community norms also influence the adoption of sustainability innovations. These factors are particularly significant in Central and Eastern Europe, where agricultural structures are diverse, and farms exhibit significant heterogeneity in terms of size, capital endowment, technological development, and environmental awareness.

Empirical research on farmers' motivations and attitudes can therefore provide important insights for improving the effectiveness of agri-environmental policy instruments. Understanding how socio-economic characteristics, environmental awareness, and previous programme participation influence farmers' decisions may help policymakers design more targeted and accessible support schemes. Such knowledge is particularly valuable in the context of newly introduced programmes like the AÖP, where long-term success depends on both participation rates and genuine behavioural change. Consequently, examining farmers' perceptions and sustainability orientations is essential for evaluating the programme's early impacts and future development potential.

2. LITERATURE REVIEW

2.1 The EU Common Agricultural Policy (CAP) and the context of agroecological measures

The Common Agricultural Policy of the European Union has been given a strong environmental and sustainability dimension in the framework of the 2023-2027 reform, in which agroecological and agri-environmental instruments (e.g., eco-schemes and agri-environmental schemes) play a key role in the sustainable transformation of agricultural practices (European Commission, 2024). The CAP strategic plans are supported by eco-schemes, which aim to encourage farmers to modify their agricultural practices in line with environmental and climate protection goals (Nagy, 2024; Nagy & Soós, 2025). The CAP is closely linked to the objectives of the EU European Green Deal (e.g., Biodiversity Strategy and Farm to Fork) and its strategic environmental objectives (Lámfalussy et al., 2023).

Agroecological programmes – such as the Hungarian AÖP – represent a specific form of agri-environmental incentives based on voluntary environmental and climate-conscious practices. These are similar to the previous Agri-Environmental Management (AEM) measures but are integrated into the 2023 CAP strategy (Csizmady et al., 2024). The aim is to protect soil and water, increase biodiversity, and support climate-friendly practices.

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2.2 Farmers' motivations and participation decisions in agri-environmental schemes

According to the scientific literature, the motivations that influence farmers' participation decisions are multidimensional and are not limited to economic incentives:

a) Economic and income factors

Most research shows that economic incentives, such as financial compensation or income stability, significantly influence participation in schemes (Makszim, 2011; Szabó, 2013). The "fairness" of the compensation rate – i.e., the balance between sacrifice and benefit – is a key factor for farmers. This is particularly important in the case of agri-environmental measures, where income disadvantages may also occur in the initial period of implementing environmentally friendly practices (Lastra et al., 2015).

b) Demographic and social factors

The literature emphasises that demographic characteristics, such as age, education, and experience, influence farmers' attitudes and motivations. Younger and more educated farmers often have stronger environmental awareness and commitment to sustainability, which increases their willingness to participate (Makszim, 2021; Zsóka et al., 2011). This includes a positive attitude towards sustainable agricultural practices and a higher likelihood of adopting innovations (Podruzsik & Fertő, 2024).

c) Behavioural and institutional factors

Participation is influenced by behavioural factors such as farmers' environmental values, risk tolerance, and trust in the programme. Furthermore, institutional frameworks – such as participation conditions, administrative burdens, and local support structures – play a crucial role in the programme's effectiveness. The literature also highlights the importance of contextual differences – for example, regional or economic size-dependent – that determine which factors affect participation (Szilárd & Imre, 2024).

2.3 Sustainability and Agroecological Practices

Agroecology as a professional and practical direction emphasises the enhancement of ecosystem services, biodiversity goals, and the sustainable use of natural resources (Kosztyuné et al., 2024; Magyar & Macher, 2023). Agricultural systems thus serve not only productivity goals but also integrate ecological and social sustainability (Van Cauwenbergh et al., 2007). Agroecological frameworks (as a science and a practical approach) aim to develop agricultural practices in harmonious cooperation with natural systems, preserving biodiversity and maintaining natural capital in the long term (Szilágyi et al., 2018).

The CAP reform partly reflects a shift towards these principles: greening and agri-environmental incentives aim to promote agricultural practices that contribute to climate protection and biodiversity objectives (Kopasz, 2005). This includes promoting soil and water protection, as well as sustainable plant protection practices.

2.4 Hungarian specificities in agri-environmental and agroecological programmes

Historical institutional development, landholding structures, farmer attitudes, and domestic agricultural policy adaptation processes fundamentally determine the specifics of Hungarian agri-environmental and agroecological measures. Hungary had been implementing environmentally friendly agricultural support programmes even before EU accession, which were integrated into the AEM system of the Common Agricultural Policy upon accession (Baráth & Fertő, 2017).

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Differences arising from the structure of Hungarian agriculture – especially the high proportion of large farms in Central and Eastern Europe – create a distinct motivational pattern regarding agri-environmental measures.

In Western Europe, agri-environmental participation is largely characteristic of smaller, family-run farms (often motivated by a combination of environmental values, low opportunity costs, and stewardship norms) (Burton & Schwarz, 2013). In Hungary, however, due to the significant territorial weight of large farms, undertaking these measures more often appears as a strategic, income-stabilising decision (Fertő & Szabó, 2020). In the case of large-scale farm structures, however, the costs of adapting to environmental regulations and management capacities may differ, which affects the uptake of agroecological practices (Popp et al., 2018).

Farmers' participation decisions in Hungary are particularly strongly determined by their trust in the predictability of agricultural policy. Previous studies by Szabó et al. (2011) have shown that farmers are often cautious about new programmes, primarily due to the variability of programme conditions, the complexity of support systems, and administrative costs. This trust dimension is also clearly evident in the introduction of the AÖP in 2023: although the programme promised flexibility and a simpler set of conditions, uncertainties emerged among farmers regarding scoring, practice monitoring, and the predictability of payments (AKI, 2023).

Regional differences play a specific role in Hungary. Research consistently shows that while in the regions of Western Hungary – where the average size of farms is smaller, the state of the environment is more favourable, and rural social networks are stronger – there is a greater willingness to undertake environmentally friendly measures, in the Great Plain the dominance of large-scale production, water scarcity, and the income exposure of farms reduce the motivation to participate (Nagy, 2007; Vincze & Tóth, 2019). The system of agricultural advisory services also contributes to regional differences: the expertise and accessibility of advisors significantly impact farmers' decisions.

When evaluating Hungarian agri-environmental and agroecological measures, the literature agrees that environmental effectiveness has been mixed to date. Although the programmes have contributed to improvements in certain ecological indicators – such as grassland biodiversity and soil conservation practices (Batáry et al., 2015) – the measures are often insufficiently targeted or do not always reflect local ecological needs. This is also in line with the European literature, which finds that CAP-based measures are often too general, thereby limiting their effectiveness in protecting biodiversity (Pe'er et al., 2020).

Several authors examine the limitations and opportunities of domestic adaptation of agroecology from the perspectives of social acceptance and farmer identity. The agroecological transition is not merely a technical or agronomic issue, but a "social innovation process" in which cooperation between farmers, knowledge sharing, and rural communities play a decisive role. In Hungary, these networks are developing but do not yet reach the strength of Western European agroecological movements (Wezel et al., 2018).

Overall, the specificities of Hungarian agri-environmental and agroecological programmes show a complex institutional and structural pattern. Economic motivations, political trust, land tenure structure, and regional ecological and social factors simultaneously influence the willingness to participate. These specificities determine the extent to which the AÖP introduced in the new CAP period can promote the spread of truly sustainable, agroecological-based farming practices in Hungary.

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3. MATERIALS AND METHODS

During the study, 80 farmers were interviewed using a questionnaire. The questionnaire included eight ordinal variables:

- educational level,
- farm size,
- years of farming experience,
- net sales,
- frequency of integrating environmental awareness into agricultural activities,
- degree of actively striving for sustainability in agricultural activities,
- extent to which respondents felt they had become more environmentally conscious through participation in the AÖP,
- level of agreement that the AÖP significantly contributes to more sustainable farming practices and improved environmental health in Hungary.

It also included two binary (nominal) variables:

- current participation in an environmental support programme (yes/no),
- previous participation in an environmental support programme (yes/no).

All ordinal-ordinal and nominal-ordinal variable pairs were analysed for correlations. Spearman's rank correlation coefficient was used to explore relationships between ordinal variables, while the χ^2 test and Cramer's V were used to examine associations between nominal and ordinal variables (Makszim, 2023). The sample size was 80.

Spearman's rank correlation coefficient was chosen because the variables were measured on an ordinal scale, a normal distribution could not be assumed, the method reduces the influence of outliers, and it allows detection of monotonic (but not necessarily linear) relationships.

Statistical analyses were performed using Jamovi software (Version 2.7.6; https://www.jamovi.org). Based on the Spearman correlation matrix, significant relationships were found among the variables in four cases, all with $P < .05$. These results highlight significant relationships between certain farmer characteristics and their sustainability aspirations, as well as their perceptions of the Programme's impacts.

4. RESULTS

The results of the questionnaire survey show significant correlations between farmers' sustainability attitudes and their experiences with the AÖP at several points. These correlations are consistent with previous research, which indicates that the adoption of sustainable agricultural practices is often associated with education, farming approach, and participation in previous environmental programmes (Zachariou et al., 2025).

A significant positive relationship was found between educational level and the degree of active sustainability efforts (Spearman's $\rho = 0.309$, $P = 0.005$). This correlation supports the literature finding that farmers with higher levels of education are more open to adopting innovative, environmentally friendly solutions (Knowler & Bradshaw, 2007).

There was also a significant, moderately strong positive relationship between active sustainability efforts and the frequency of integrating environmentally conscious practices (Spearman's $\rho = 0.437$, $P < .001$). This suggests that farmers who consciously strive for sustainability more consistently integrate environmentally friendly procedures into their daily activities—a pattern also confirmed by previous European studies (Swart et al., 2023).

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A similar relationship was observed between active sustainability efforts and environmentally conscious thinking promoted by the AÖP (Spearman's ρ = 0.442, P < .001). The programme, therefore, appears to have an impact, especially on those who are already more fundamentally committed to sustainability, consistent with previous studies examining the mechanisms by which environmental protection programmes affect behaviour (Wilson & Hart, 2000).
In addition, a significant positive relationship was identified between perceptions of the programme's benefits and the strengthening of environmentally conscious thinking (Spearman's ρ = 0.432, P < .001). Farmers who considered the programme effective reported a greater attitude-shaping effect, consistent with Padel and Lampkin's (2007) findings on the role of support systems in shaping attitudes.
Examination of the nominal variables revealed that current participation in an environmental support programme was significantly related to environmentally conscious thinking associated with the AÖP ($\chi^2(4)$ = 12.1, P = .017, Cramér's V = 0.389). This suggests that farmers participating in such programmes are more open to accepting new environmental approaches – a pattern also highlighted by other research (Burton et al., 2008).
Previous participation in environmental programmes was also moderately associated with the degree of active sustainability efforts ($\chi^2(3)$ = 11.1, P = .011, Cramér's V = 0.373). Past participation, therefore, appears to have a positive long-term effect on farmers' behaviour, which aligns with the literature's findings that programme membership has cumulative learning and attitude-shaping effects (Burton & Schwarz, 2013).
Overall, the results indicate that the impact of the AÖP is most significant for farmers who already have an environmental commitment, although the programme also contributes to attitude formation. This supports research lines that emphasise the dual economic and attitude-shaping role of support systems in the sustainable agricultural transition (Darnhofer, 2020).

5. CONCLUSION

5.1 Conclusions based on the correlation matrix

The research revealed four significant positive correlations among the ordinal variables:
1) Educational level and the degree of active sustainability efforts in agricultural activities showed a significant positive correlation (Spearman's ρ = 0.309, P = 0.005, df = 78). This suggests that farmers with higher education are moderately more likely to apply sustainable practices.
2) The degree of active sustainability efforts and the frequency of integrating environmental awareness into agricultural activities were even more strongly correlated (Spearman's ρ = 0.437, P < .001, df = 78). This indicates that farmers who are more committed to sustainability tend to integrate environmentally conscious practices into their operations more regularly.
3) Active sustainability efforts and the level of environmentally conscious thinking developed through use of the AÖP correlated the most strongly of the group (Spearman's ρ = 0.442, P < .001, df = 78). This implies that farmers who are more actively committed to sustainability tend to develop a greater degree of environmentally conscious thinking through the programme.
4) Finally, farmers who perceived the AÖP as contributing meaningfully to sustainable farming and environmental health in Hungary also reported greater attitude change through the programme (ρ = 0.432, P < .001, df = 78), reinforcing the notion that positive perceptions and pre-existing commitment reinforce each other.

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5.2 Conclusion based on associations

The study showed a significant association between current participation in an environmental support programme and the degree of environmentally conscious thinking developed through the AÖP ($\chi^2(4) = 12.1$, $P = .017$, Cramér's V = 0.389), as also shown in *Table 1* and *Table 2*. Among the 67 participants currently in the programme, the majority were environmentally aware before participation and indicated higher levels of environmental awareness (scores 3-5).

In contrast, the 13 non-participants typically showed lower levels of environmental awareness (scores 1-4). Overall, participation in such programmes is associated with higher levels of environmental awareness. Cramér's V indicates a medium-strength association, suggesting that farmers who participate in these programmes tend to develop more environmentally conscious attitudes as a result of the AÖP. This finding is important because it demonstrates that such programmes not only provide practical support but also contribute to the long-term strengthening of sustainable thinking among farmers (Apáti & Makszim, 2025). In the long term, this is particularly relevant because changing climatic conditions increasingly necessitate transforming traditional farming methods, for which an environmentally conscious attitude provides an indispensable foundation (Kosztyuné et al., 2023; Soós & Makszim, 2024).

Table 1: Independence review results

	Become more environmentally conscious by using the AÖP					
Now participating	**1**	**2**	**3**	**4**	**5**	**Total**
No	2	3	3	4	1	13
Yes	0	10	30	23	4	67
Total	2	13	33	27	5	80

χ^2 Tests			
	Value	**df**	**p**
χ^2	12.1	4	0.017
N	80		

Table 2: Cramer's association coefficient

Nominal	
	Value
Phi-coefficient	NaN
Cramer's V	0.389

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Table 3 clearly shows that those who had previously participated in environmental support programmes (n = 51) exhibited higher levels of aspiration (scores 4-5), whereas non-participants (n = 29) tended to report lower or medium levels of aspiration (scores 2-4). This suggests that previous participation in such programmes is associated with higher aspiration or goal orientation.

Table 3: Level of aspiration in relation to previous participation in the program

	Aspiration				
Previously participated	**2**	**3**	**4**	**5**	**Total**
No	4	12	13	0	29
Yes	1	13	28	9	51
Total	5	25	41	9	80

The study revealed a significant association between previous participation in environmental support programmes and the degree of active sustainability efforts in agricultural activities ($\chi^2(3) = 11.1$, $p = .011$, Cramér's V = 0.373). Cramér's V indicates a medium-strength association, suggesting that farmers who have previously participated in such programmes typically strive to achieve greater sustainability in their activities.

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Gazdálkodók részvételi motivációi és fenntarthatósági attitűdjei az Agro-Ökológiai Program kontextusában

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ÖSSZEFOGLALÁS

A 2023-ban indult Agro-ökológiai Program az Európai Unió új Közös Agrárpolitikájának egyik legfontosabb eszköze, amelynek célja a környezetbarát gazdálkodási gyakorlatok ösztönzése. Ez a tanulmány 80 magyar gazdálkodó programban való részvételükkel, motivációikkal és a fenntarthatósághoz való hozzáállásukkal kapcsolatos válaszait elemzi. A kutatás kvantitatív módszereket alkalmazott, különös figyelmet fordítva a gazdaság méretére, a jövedelmi szintre és a környezettudatosságra. Az eredmények azt mutatják, hogy a részvételi döntéseket nemcsak gazdasági megfontolások, hanem egyre inkább a fenntarthatósági értékek is motiválják, különösen a fiatalabb és magasabban képzett gazdálkodók körében. A tanulmány elsősorban agrárpolitikai döntéshozóknak, mezőgazdasági szakmai szervezeteknek és mezőgazdasági tanácsadóknak ajánlott, mivel empirikus eredményei hozzájárulnak az agrár-környezetvédelmi programok, különösen az Agroökológiai Program hatékonyabb megtervezéséhez és célzottabb fejlesztéséhez. Hasznos lehet az agrárgazdasági és vidékfejlesztési kutatók, valamint a felsőoktatási intézmények hallgatói számára is, akik az új Közös Agrárpolitika kontextusában vizsgálják a fenntartható mezőgazdaság, az agroökológia és a gazdálkodói döntéshozatal közötti összefüggéseket.
Kulcsszavak: agroökológia, fenntarthatóság, motivációk, környezettudatosság, agrárpolitika

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The Potential of Natural Deep Eutectic Solvents for the Extraction of Phenolic Compounds and Caffeine from Green Coffee (*Coffea arabica*) Beans

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ABSTRACT

A natural deep eutectic solvent (NDES) mixture was studied for extracting phenolic compounds from green coffee beans (GCB) (*Coffea arabica*). Dehydrated, finely ground GCBs were extracted with water, 50 % aqueous ethanol, and NDES (glucose and glycerin, 1:1 M) at 30 ˚C for 30, 60, and 90 min using a shaking incubation method. The process was repeated at 50 °C for 30 min. Total phenolic content (TPC) was measured via the Folin-Ciocalteu test. Chlorogenic acids (3-, 4-, and 5-caffeoylquinic acid) and caffeine were quantified by HPLC-PDA. At 30 °C, the highest TPC (48.7 ± 0.6 mg GAE/g) was found in the NDES 30-min extract, comparable ($P > 0.05$) to NDES 60-min (47.4 ± 0.1 mg GAE/g) and 90-min (48.6 ± 1.1 mg GAE/g) extracts. The highest chlorogenic acid content (52.4 ± 0.6 mg/g) was in 50 % ethanol, 30-min extraction, similar ($P > 0.05$) to other ethanolic extracts and NDES 60- and 90-min extracts. Caffeine content (12.1 ± 0.2 mg/g) peaked in 50 % ethanol, 30-min extract, similar ($P > 0.05$) to most other extracts except NDES 30-min (11.3 ± 0.3 mg/g). NDES at 50 °C gave 46.9 ± 0.5 mg/g TPC, 48.6 ± 0.7 mg/g chlorogenic acid, and 11.1 ± 0.2 mg/g caffeine, not significantly different from 30 °C. These results indicate glucose–glycerin NDES is a promising, eco-friendly solvent for extracting phenolic compounds from GCBs, providing an alternative to 50 % ethanol.
Keywords: chlorogenic acid, deep eutectic solvents, green coffee beans, phenolic compounds

1. INTRODUCTION

Green coffee bean (GCB) has received much attention in recent studies for its potential health benefits in weight management, heart health, neurological conditions, and blood sugar regulation, due to its profile rich in several bioactive compounds, such as caffeine, diterpenes, chlorogenic acids, ferulic acid, caffeic acid, p-coumaric acid, and trigonelline. Therefore, GCB extracts are widely

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used as supplements to treat or prevent several non-communicable diseases, such as type 2 diabetes, high blood pressure, and cardiovascular disease (Munyendo et al., 2021; Khalili-Moghadam et al., 2023). Caffeine, which is an alkaloid, is responsible for 1-2.5 % of coffee dry matter composition. Additionally, caffeoylquinic acids (CQA), such as *3*-CQA, *4*-CQA, and *5*-CQA, that belong to the group of chlorogenic acids, are responsible for 4-12 % of the dry matter coffee composition (Farah et al., 2005). Amongst these phytochemicals, *5*-CQA is the main phenolic compound with redox properties that accumulates in coffee beans during the maturation process (Acidri et al., 2020; Tripathi et al., 2024). Previous animal-based and human clinical studies have shown that GCB extracts exhibit anti-obesity and anti-diabetic properties, attributed to the lipid-lowering and insulin-sensitivity-improving effects of *5*-CQA (Sudeep & Prasad, 2021; Khalili-Moghadam et al., 2023; Chandimala & Ajtony, 2025). However, as coffee is typically consumed after roasting, a considerable amount of these phytochemicals is degraded. For example, Acidri et al. (2020) reported that roasting GCBs resulted in a 66 % decline of their initial phytochemical content. However, the negative impact of roasting on caffeine and trigonelline was lower than that of *5*-CQA. Therefore, when developing extracts to generate health benefits, GCB extracts are more imperative and beneficial than roasted coffee extracts.

Solvent extraction is the most studied method for isolating phytochemicals with antioxidant potential from plant sources. A range of factors, such as temperature, time, and solvent concentration and polarity, influence the extraction and purification of bioactive compounds from plant materials. The type and concentration of bioactive compounds in the extract mainly depend on the chemical composition of the solvent system. Overall, solvents with medium polarity, such as ethanol, methanol, and acetone, have been shown to give higher yields of total phenolics and antioxidant activity in GCB extracts (Tripathi et al., 2024).

Recent developments in green chemistry have encouraged the creation of new organic solvent systems, such as natural deep eutectic solvents (NDES), as safer alternatives to harmful organic solvents. NDES are made by mixing hydrogen bond donors (e.g., organic acids, sugars) with hydrogen bond acceptors (e.g., choline chloride). The NDES mixture usually has a freezing point lower than that of its components (Loukri et al., 2022). NDES are considered environmentally friendly solvents because they are derived from non-toxic and biodegradable natural ingredients like sugars, salts, amino acids, and organic acids. Their ability to dissolve a wide range of biomolecules with excellent solubility and thermal stability, coupled with low toxicity and cost, makes them a promising green solvent for extracting phytochemicals from various plant materials (Ruesgas-Ramón et al., 2017; Okeke et al., 2025). However, research on the extraction of GCB phenolic compounds using NDES and their food applications remains limited in the current literature. For example, aqueous ethanolic extracts of GCB are the most commonly used for food applications, such as enhancing the microbial and oxidative stability of meat products (Atondo-Echeagaray et al., 2025). Therefore, this study focused on preparing GCB extracts using an NDES mixture with a shaking incubation extraction method and on comparing the phenolic content, *5*-CQA, *3*-CQA, *4*-CQA, and caffeine levels with ethanolic and water extracts. Based on previous studies involving NDES in plant extracts (Rumiyati et al., 2024; Sik et al., 2024), a mixture of glucose (hydrogen bond donor) and glycerin (hydrogen bond acceptor) was selected as the NDES system for this research.

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2. MATERIALS AND METHODS

2.1 Materials and equipment

Commercial GCB (*Coffea arabica*) samples used for the measurements were purchased from Gourmet Kave, Hungary. The Folin-Ciocalteu reagent and gallic acid were purchased from Merck (Germany). Anhydrous sodium carbonate and d-(+)-glucose anhydrate were purchased from Riel-de Haan (Germany). Glycerol was purchased from Sigma Aldrich, Hungary. Moreover, absolute ethanol was purchased from VWR chemicals (France). The standard *5*-CQA and caffeine (purity ≥ 95 %) were purchased from Merck Science Life Ltd. (Budapest, Hungary). For the HPLC analysis, acetonitrile of HPLC grade (Fisher Scientific, UK) and ortho-phosphoric acid of analytical grade (Lachner, Hungary) were used.

A 70 M model food dehydrator (Precision Scientific, United States) was used for drying GCBs. Dried coffee beans were ground into fine particles with a coffee grinder (Aroma, Hungary). The extraction of phenolic compounds from GCBs was carried out using a shaking incubator (GFL 3032, Germany). The samples were centrifuged using a Z206A laboratory centrifuge (Hermle, Germany). For the experiments, deionized ultra-pure water was obtained from an ultra-pure water system (Milli Q-SQ 2 series, Germany). Spectrophotometric analysis was implemented using a Spectroquant Pharo 100 spectrophotometer (Merck, Germany). The instrumental analysis of the *5*-CQA and caffeine was performed using an HPLC-PDA system (Jasco, Japan) equipped with a 4-line degasser (Jasco DG-2080-54), intelligent HPLC pump (Jasco PU-980), ternary gradient unit (Jasco LG-980-02), intelligent sampler (Jasco AS-2055), column thermostat (Phenomenex TS-130), and column compartment. ChromeNAV software (Jasco, Japan) was used for data acquisition.

2.2 Methodology

2.2.1 NDES preparation

The NDES mixture was prepared according to Sik et al. (2024). Glucose and glycerin were mixed at a 1:1 M ratio with 10 mL of water and stirred at 500 rpm (approximately 3 h) at a temperature of 90 °C until a viscous, colorless liquid was obtained. The resulting solvent was mixed with 50 % (w/w) high-purity deionized water, cooled down to room temperature, and used for the extraction.

2.2.2 Extraction conditions

A 0.25 g powdered GCB sample was mixed with 5 mL of glucose-glycerin-based NDES. Then, samples were placed in a shaking incubator set to 30 °C at 150 rpm for varying times: 30, 60, and 90 min. Additionally, the effect of using a higher temperature-short time extraction was tested by applying a 50 °C temperature at 150 rpm for 30 min, following the same procedure. After extraction, the samples were diluted fivefold with deionized water and centrifuged at 6000 rpm for 10 min, and the filtered supernatants were used for the spectrophotometric/HPLC analysis. Solvent volume and dilution were selected after pre-trials. To facilitate comparisons, water extracts and 50 % (v/v) ethanolic extracts were prepared under the same extraction conditions.

2.2.3 Determination of total phenolic content (TPC)

The TPC of the extracts was measured by the Folin-Ciocalteu method as described by Sik et al. (2024) with slight modifications. A 100 µL sample was mixed with 1.5 mL of deionized water, 10 % (v/v) Folin-Ciocalteu reagent, and 2 mL of sodium carbonate solution (7.5 g/100 mL), respectively. After

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90 min of incubation at room temperature, the absorbance was measured at 725 nm versus the blank. A standard curve was developed by plotting gallic acid concentration (ranging from 0-1000 µg/mL) versus absorbance based on spectrophotometric analysis. The regression equation for TPC was y = 1.3005x + 0.0152, with a high correlation coefficient (0.999). The standard curve met the standards, with a 0.0261 standard error of slope, a 0.056 mg/mL LOD, and a 0.171 mg/mL LOQ, and was used to calculate TPC yields for each extract. TPCs were expressed as mg of gallic acid equivalents per gram of dry plant material (mg GAE/g).

2.2.4 Determination of chlorogenic acid and caffeine contents

Working standard solutions of 5-CQA and caffeine with concentrations ranging from 0 to 1000 µg/mL and 0 to 500 µg/mL, respectively, were prepared and injected into the HPLC system under specified conditions to develop calibration curves for 5-CQA and caffeine by plotting concentration against peak area. Separation was achieved using an InertSustain Phenyl column with 5 µm pore size, 3 mm diameter, and 150 mm length, maintained at 35 ˚C. The mobile phase consisted of 7 % acetonitrile and 93 % water containing 0.1 v/v% phosphoric acid. The flow rate and injection volume were set at 0.8 mL/min and 5 µL, respectively. Identification of 5-CQA and caffeine was performed by comparing their retention times with those of the respective standards and by spiking samples with small amounts of the appropriate standards. Quantification in each extract was conducted using the regression equation of the best-fit line from the calibration curves. Due to the unavailability of 3-CQA and 4-CQA standards in our lab, their quantification was based on the area of the 5-CQA standard combined with the molar extinction coefficients of the respective CQA, as previously described by Farah et al. (2005).

2.2.5 Research design and statistical analysis

All experiments were conducted using a one-factor-at-a-time (OFAT) approach, with three replicates per factor. All data were presented as the mean ± standard deviation of triplicate analyses. Minitab®19 statistical software was used for the analysis of variance (ANOVA) at a 95 % confidence level to determine the significance of differences. All tested parameters followed normal distribution based on designed probability plots ($P > 0.05$, Anderson-Darling value < 0.75), and Tukey's HSD test was used to compare all possible pairs of means to determine whether the differences were statistically significant.

3. RESULTS

3.1 Total phenolic content in GCB extracts

TPC values detected in the three solvent systems – water, 50 % ethanol, and a glucose-glycerin-based NDES mixture – are shown in *Figure 1*. The highest TPC yield (48.7 ± 0.6 mg GAE/g) was observed in the NDES extract with a 30-min extraction time, followed by the NDES extract with a 90-min (48.6 ± 0.6 mg GAE/g) extraction. However, the TPC yield was similar ($P > 0.05$) in all tested extraction times for the NDES. According to the one-way ANOVA test, NDES yielded significantly higher levels than 50 % ethanol (45.8 ± 1.1 mg GAE/g) at a 30-min extraction time ($P < 0.05$). Similarly, NDES yielded significantly higher amounts than water (41.9 ± 1.1 mg GAE/g) at 30 min ($P < 0.05$). These results suggest that glucose-glycerin-based NDES can effectively replace water and organic solvents, such as ethanol, for the extraction of phenolic compounds from GCBs.

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Overall, the TPC content observed in all solvent extracts in this study (4.0-4.8 %) exceeds the previously reported TPC yield in water extracts (3.8 %) of GCBs (Priftis et al., 2015).

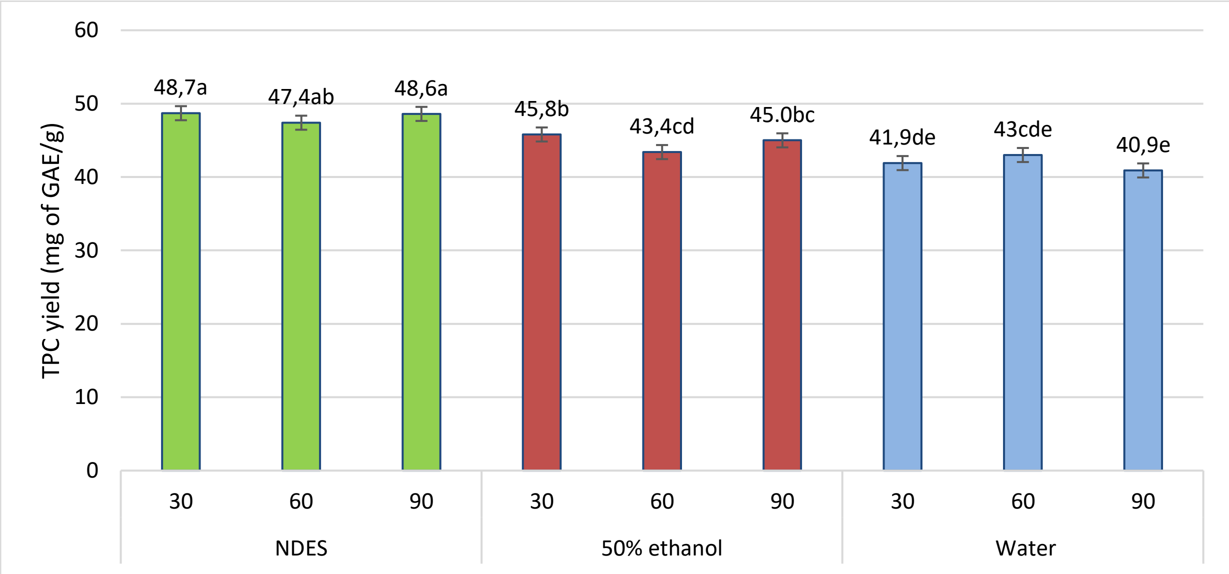

Figure 1: Total phenolic content of GCB extracts at 30 °C temperature

Values denote the mean of the three replicates. Means followed by the same letter are not significantly different at a 95 % confidence level according to Tukey's HSD test. Letters are assigned from a to e in descending order of the mean values.

3.2 Chlorogenic acid concentration in GCB extracts

Figure 2 depicts the representative base-peak chromatogram of the NDES extract for 30 min, analyzed with the InertSustain Phenyl HPLC column. When the phenyl column was used for the analysis at the occupied wavelength of 325 nm, peak 2 was identified as *5*-CQA by comparing it with the standard *5*-CQA spectra. Based on the literature on peak shape and peak purity when analyzing UV spectra, peaks 1 and 3 were identified as *3*-CQA and *4*-CQA, respectively. All three peaks had a peak purity level of above 99.9 %, confirming that peaks 1 and 3 are isomers of *5*-CQA. Peak 4 also showed a purity above 90 %, although it was not identified in this study due to a lack of a standard and information in the literature.

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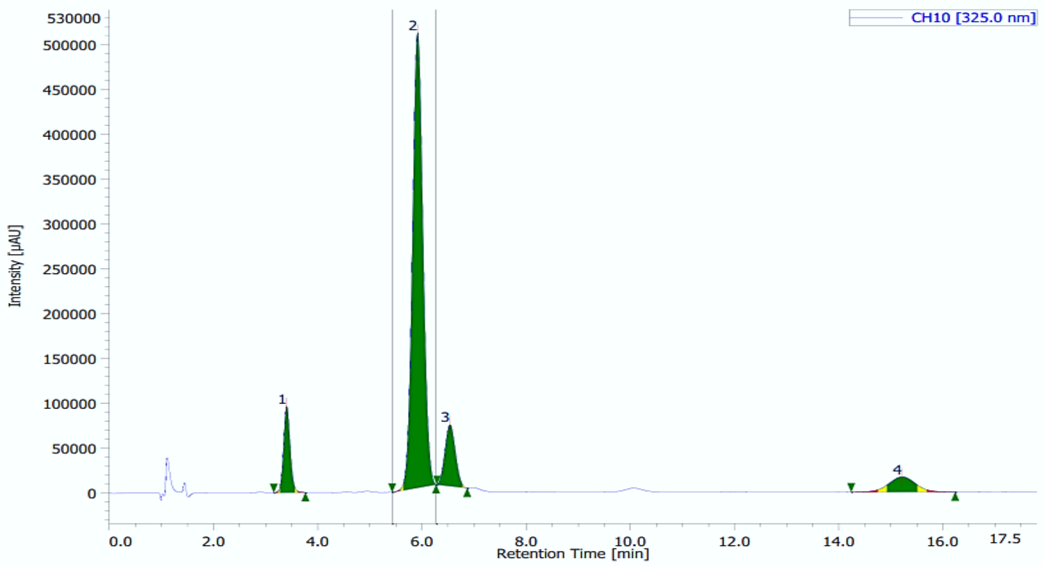

Figure 2: Elution order of CQA isomers in an NDES extract (30 °C for 30 min) of GCBs with InertSustain phenyl column at detector wavelength of 325 nm

Peaks 1, 2, 3, and 4 represent 3-CQA, 5-CQA, 4-CQA, and unidentified, respectively. The mobile phase contained 7 % acetonitrile and 0.1 % phosphoric acid. Flow rate was 0.8 mL/min. The purity of 1-3 peaks was > 99.9 %. The green color represents high purity at the peak's top position.

Concentrations of 5-CQA, 3-CQA, and 4-CQA in GCB extracts at 30 °C temperature are represented in *Figure 3*. The highest 5-CQA concentration (41.5 ± 0.5 mg/g) was observed in ethanolic extraction for 30 min. However, there was no significant difference ($P > 0.05$) in the 5-CQA content among all ethanolic extracts and NDES extracts at 60 and 90 min. NDES extraction for 30 min indicated 38.9 ± 0.9 mg/g of 5-CQA yield, which was significantly lower ($P < 0.05$) than the ethanolic extraction for 30 min. Water extracts yielded the lowest 5-CQA levels (34.3-34.8 mg/g). A similar pattern was observed for 4-CQA as well. The highest 4-CQA yield (6.2 ± 0.1 mg/g) was observed with ethanolic extraction for 30 min, which was not significantly different from the NDES extraction yields at 60 and 90 min. NDES extraction for 30 min indicated 5.8 ± 0.2 mg/g of 4-CQA yield. Water extracts yielded the lowest 4-CQA content (5.2 mg/g). Regarding 3-CQA concentration, there was no significant difference ($P > 0.05$) between all ethanolic (5.1-5.2 mg/g) and NDES extracts (5.0 mg/g). However, in all water extracts (4.4 mg/g), the 3-CQA yield was significantly lower than the above.

Overall, the highest chlorogenic acid concentration was observed in ethanolic extraction for 30 min (52.4 ± 0.6 mg/g). This value was similar ($P > 0.05$) to other ethanolic extraction yields and NDES extraction for 60 and 90 min. NDES extraction for 30 min indicated 49.7 ± 1.2 mg/g of total chlorogenic acid yield, which was significantly lower ($P < 0.05$) than the ethanolic extraction for 30 min. Water extracts yielded the lowest total chlorogenic acid (43.9-44.4 mg/g). These values align with the documented range of 3 % to 6 % of CQAs in C. arabica dry matter (Farah & Donangelo, 2006). The present study reveals that 5-CQA is the predominant phenolic compound in NDES, ethanolic, and water extracts of GCBs.

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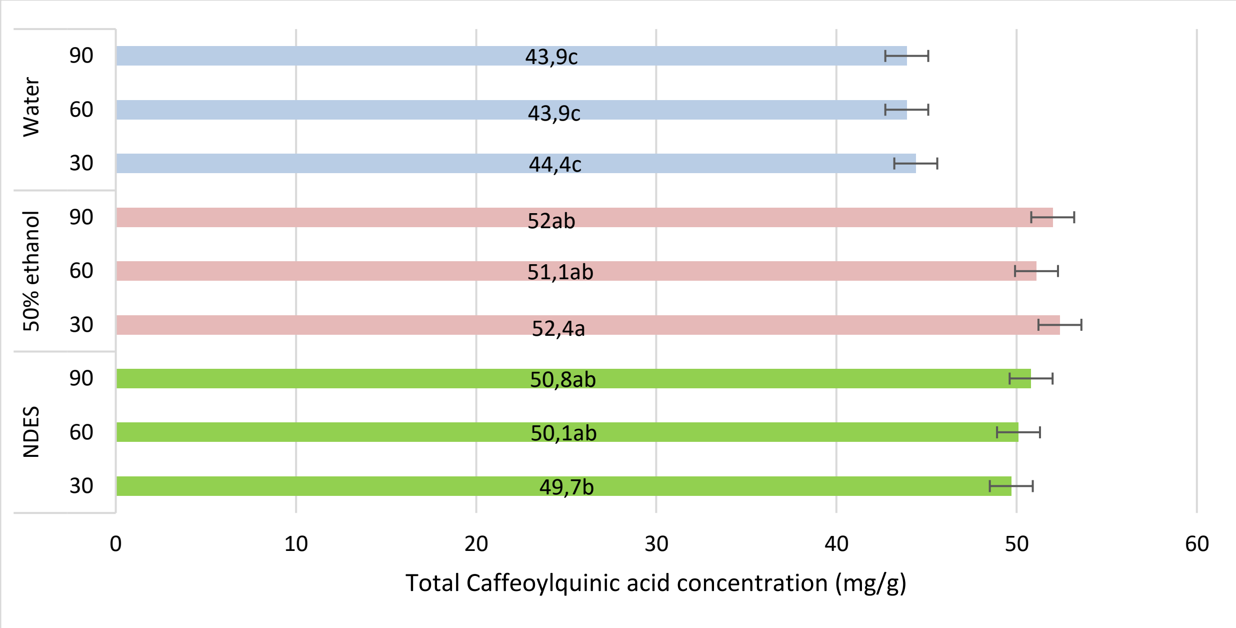

Figure 3: Total caffeoylquinic acid concentration in green coffee bean extracts

Values denote the mean of the three replicates. Means followed by the same letter are not significantly different at a 95 % confidence level according to Tukey's HSD test. Letters are assigned from a-c based on the descending order of their mean values, respectively.

3.3 Caffeine concentration in GCB extracts

There was no significant difference ($P > 0.05$) between the water extracts and NDES extracts for the caffeine yield. The highest caffeine content (12.1 ± 0.2 mg/g) was observed in 50 % ethanol 30-min extraction. Ethanolic extracts showed comparatively higher caffeine yields than other extracts. However, only the NDES extraction for 30 min showed a significantly lower yield than the 50 % ethanol extraction for 30 min (*Figure 4*).

In a study, Loukri et al. (2022) reported higher caffeine yields from coffee pulp using choline chloride and glycerin-based NDES solvent systems compared with the aqueous ethanolic system. In contrast, in the present study, ethanolic extraction for 30 min yielded significantly higher caffeine than all NDES extracts.

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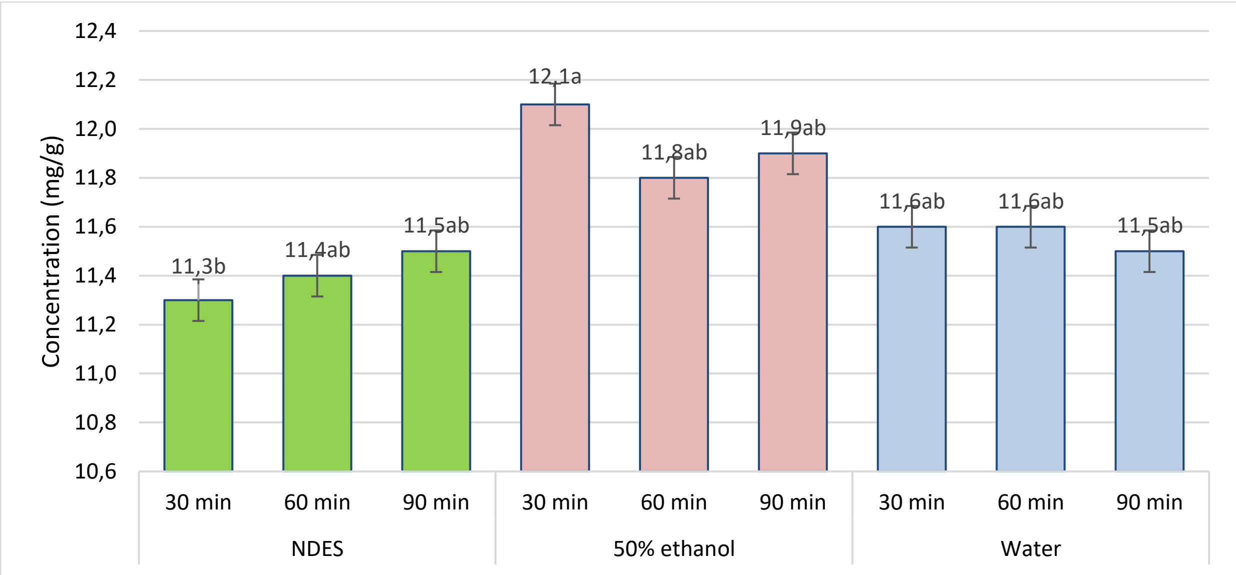

Figure 4: Caffeine content of GCB extracts at 30 °C temperature

Values denote the mean of the three replicates. Means followed by the same letter are not significantly different at a 95 % confidence level according to Tukey's HSD test.

3.4 Effect of temperature on the concentration of phenolic compounds and caffeine

The effect of using a higher temperature (50 °C) for a 30-min extraction was also examined in this study. The TPC, total CQA and caffeine yields compared to 30 °C are shown in *Figure 5*. According to the results, the TPC yield tends to decrease at 50 °C compared to 30 °C in NDES and ethanol extracts, although a slight increase was observed in water extracts, which was not significant ($P > 0.05$). The total CQA yield also slightly decreased in NDES extracts when the temperature was raised from 30 °C to 50 °C. However, water and ethanolic extracts showed an increase in total CQA yields with increasing temperature. This increase was not significant in ethanol, whereas it was significant in water extracts. Furthermore, *Figure 5* illustrates that the total CQA concentration exceeds the total phenolic concentration in all GCB extracts, regardless of the extraction temperature. The difference between TPC and CQA is more prominent in ethanolic extracts than in NDES and water extracts. Moreover, the figure underscores that the yield of caffeine, an alkaloid, is significantly lower than the yields of phenolics in all GCB extracts. Additionally, caffeine yield was lower at higher temperatures across all solvent types used in this study.

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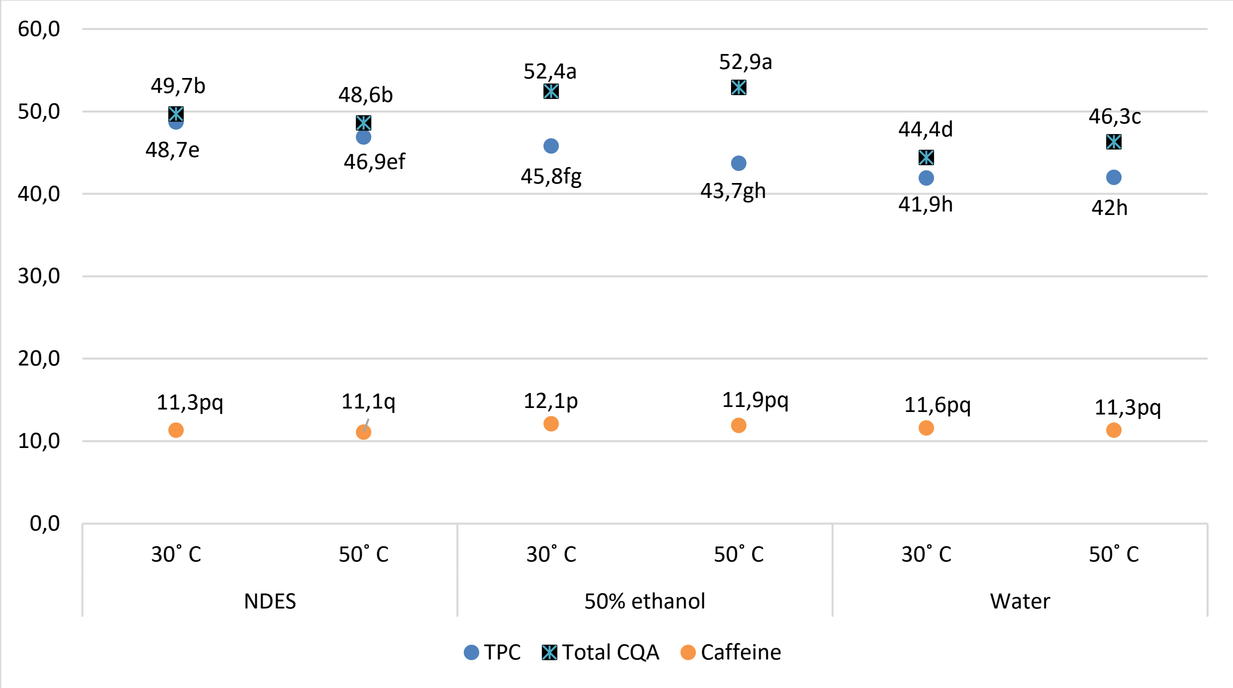

Figure 5: The effect of temperature increase (from 30 °C to 50 °C) on TPC, total CQA and caffeine content of GCB extracts (30 min extraction time)

Values denote the mean of the three replicates based on one-way ANOVA. Means followed by the same letter are not significantly different at a 95 % confidence level according to Tukey's HSD test.

A summary of TPC, chlorogenic acids, and caffeine in glucose-glycerin-based NDES, 50 % ethanol, and water extracts at 30 °C for 30, 60, and 90 min, and at 50 °C for 30 min, is shown in *Table 1*.

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Table 1: Summary of phenolic compounds, caffeine content in NDES, ethanol and water extracts of GCBs

Solvent	Sample Mass (g)	Solvent Volume (mL)	Dilution	Extraction Temperature (°C)	Extraction Time (min)	TPC (mg GAE/g)	5-CQA (mg/g)	3-CQA (mg/g)	4-CQA (mg/g)	Caffeine (mg/g)
NDES (glucose-glycerin)	0.25	5	5	30	30	48.7 ± 0.6^{a}	38.9 ± 0.9^{b}	5.0 ± 0.1^{a}	5.8 ± 0.2^{b}	11.3 ± 0.3^{b}
					60	47.4 ± 0.1^{ab}	39.2 ± 0.6^{ab}	5.0 ± 0.1^{a}	5.9 ± 0.2^{ab}	11.4 ± 0.2^{ab}
					90	48.6 ± 1.1^{a}	39.8 ± 0.4^{ab}	5.0 ± 0.1^{a}	6.0 ± 0.1^{ab}	11.5 ± 0.2^{ab}
				50	30	46.9 ± 0.5^{ab}	38.1 ± 0.6^{b}	4.8 ± 0.1^{a}	5.7 ± 0.1^{b}	11.1 ± 0.2^{b}
50 % ethanol	0.25	5	5	30	30	45.8 ± 1.1^{b}	41.0 ± 0.5^{a}	5.2 ± 0.1^{a}	6.2 ± 0.1a	12.1 ± 0.2^{a}
					60	43.4 ± 0.8^{cd}	40.1 ± 0.6^{ab}	5.1 ± 0.1^{a}	6.0 ± 0.1^{ab}	11.8 ± 0.2^{ab}
					90	45.0 ± 0.5^{bc}	40.8 ± 0.6^{ab}	5.2 ± 0.1^{a}	6.1 ± 0.1^{a}	11.9 ± 0.2^{ab}
				50	30	43.7 ± 0.5^{cd}	41.5 ± 0.9^{a}	5.2 ± 0.1^{a}	6.2 ± 0.1^{a}	11.9 ± 0.2^{ab}
Water	0.25	5	5	30	30	41.9 ± 1.1^{de}	34.8 ± 1.1^{c}	4.4 ± 0.1^{b}	5.2 ± 0.2^{c}	11.6 ± 0.4^{ab}
					60	43.0 ± 0.8^{de}	34.4 ± 0.6^{c}	4.4 ± 0.1^{b}	5.2 ± 0.1^{c}	11.6 ± 0.2^{ab}
					90	40.9 ± 0.8^{e}	34.3 ± 0.7^{c}	4.4 ± 0.1^{b}	5.2 ± 0.1^{c}	11.5 ± 0.2^{ab}
				50	30	42.0 ± 1.3^{de}	36.2 ± 0.2^{bc}	4.6 ± 0.1^{ab}	5.5 ± 1.0^{c}	11.3 ± 0.3^{b}

Values denote the mean ± SD of the three replicates based on one-way ANOVA. Means followed by the same superscript letter within the same column are not significantly different at a 95 % confidence level according to Tukey's HSD test.

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4. DISCUSSION

The solubility of phenolic compounds mainly depends on their chemical structure. For example, the balance between the molecule’s polar hydroxyl groups and non-polar aromatic ring determines its solubility. Chemical modifications, such as esterification or glycosylation, can alter the solubility of phenolics (Taheri & Jafari, 2019). Additionally, factors such as temperature, extraction time, pH, and the presence of salts or cosolutes affect their solubility (Furia et al., 2021; Chandimala et al., 2025). Previous studies using COSMO-SAC modelling have shown that phenolic compounds, such as chlorogenic acids, have limited regions available for hydrogen bonding. Likewise, various NDES mixtures exhibit more hydrogen-bonding regions than alcohol (Hijo et al., 2022). The higher TPC yields observed in NDES mixtures compared to those in other solvents may be due to the greater availability of hydrogen-bonding regions in NDES than in water or ethanol. Studies also show that NDES can extract more phenolic compounds due to their higher hydrogen-bonding capacity and improved solute–solvent electrostatic interactions compared to water or pure alcohols (Hijo et al., 2022). Sik et al. (2024) also found that glucose-glycerin-based NDES is more effective than conventional organic solvents (80 % (v/v) ethanol) in extracting phenolic compounds from cornelian cherry. The current study indicated that the highest TPC yield is obtained at 30 min of extraction time. Additionally, TPC yield was lower at 50 °C. These results suggest that a short extraction time at room temperature (~30 °C) is the most suitable for isolating phenolics from GCBs using glucose-glycerin-based NDES.

However, the chlorogenic acid yields in glucose-glycerin-based NDES were comparatively lower than those of ethanol extracts. This can be due to the specific NDES composition used in this study. As a polar molecule, chlorogenic acid shows greater affinity for 50 % aqueous ethanol, which is more polar than the glucose-glycerin mixture. The observed higher caffeine yields in ethanolic extracts may also be due to the higher polarity of 50 % ethanol compared to the specific NDES composition used in this study. In preparing NDES solvent, the ratio of hydrogen bond donors to hydrogen bond acceptors, as well as the addition of water, directly influence the system's polarity and hydrogen bonding capacity, thereby affecting extraction efficiency. Adding water not only reduces viscosity but also improves mass transfer properties and increases polarity, thereby enhancing phenolic yield (Hijo et al., 2022; Loukri et al., 2022). Increasing the solvent volume can also improve plant matrix penetration, but further increases become inefficient. Identifying the ideal solvent volume and dilution level tailored to the NDES and plant material is essential for enhancing extraction efficiency (Taweekayujan et al., 2023). Overall, optimizing glucose-glycerin concentrations in the NDES mixture is crucial to maximize hydrogen bonding, enhancing polarity and phenolic extraction. In the present study, pre-trials conducted with different volumes of a glucose-glycerin mixture (5, 10, and 20 mL) and dilutions (five-fold and ten-fold) revealed that 5 mL of solvent with five-fold dilution yielded the highest TPC. Moreover, heating and stirring NDES components at 90 °C with 50 % water until a clear solution is obtained was found to be the most suitable method for preparing glucose-glycerin-based NDES. Further experiments with other NDES systems, such as choline chloride-glycerin and glucose-lactic acid/citric acid, should be performed to assess their effectiveness in extracting phenolic compounds, including chlorogenic acids, from GCBs.

Further, in this study, total CQA yields exceeded TPC yields in all extracts. This may be because TPC measurements are not specific to all phenolic compounds and include a broad range of phenolics, which may be degraded during extraction. Additionally, the extraction efficiency of different phenolic compounds may vary with the extraction method and conditions used (Platzer et al., 2021).

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5. CONCLUSION

This study was conducted to evaluate the potential of using glucose-glycerin-based NDES for extracting phenolics from GCBs. It found that a glucose-glycerin mixture (1:1 M) with 50 % water is more effective than 50 % ethanol or pure water for isolating phenolics from GCBs, shaking incubation at 30 °C. GCBs extracted with NDES for 30 min yielded the highest TPC (48.7 ± 0.6 mg GAE/g), which was statistically similar to other NDES extracts. NDES for 30 min yielded 49.7 ± 1.2 mg/g of chlorogenic acids and 11.3 ± 0.3 mg/g of caffeine. Chlorogenic acid contents ranged from 43.9 to 44.4 mg/g, 51.1 to 52.4 mg/g, and 49.7 to 50.8 mg/g, in water, ethanolic and NDES extracts, respectively. In NDES for 30 min extract, increasing the extraction temperature to 50 °C resulted in comparatively lower yields of TPC (46.9 ± 0.5 mg GAE/g), *5*-CQA (38.1 ± 0.6 mg/g), *3*-CQA (4.8 ± 0.1 mg/g), *4*-CQA (5.7 ± 0.1 mg/g), and caffeine (11.1 ± 0.2 mg/g). These findings indicate that a short extraction time at room temperature (~30 °C) is most suitable for extracting phenolics from GCBs using glucose-glycerin-based NDES.

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A glükóz-glicerin alapú természetes eutektikus oldószerek alkalmazhatóságának vizsgálata fenolos vegyületek és koffein extrakciójára zöld kávé (*Coffea arabica*) babból

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ÖSSZEFOGLALÁS

Zöld kávébabból (*Coffea arabica*) származó fenolos vegyületek kinyerésére természetes mélyeutektikus oldószer (NDES) keveréket vizsgáltak. A dehidratált, finomra őrölt GCB-ket vízzel, 50 %-os vizes etanollal és NDES-sel (glükóz és glicerin, 1:1 M) extrahálták 30 °C-on 30, 60 és 90 percig rázós inkubációs módszerrel. A folyamatot 50 °C-on 30 percig megismételték. A teljes fenoltartalmat (TPC) Folin-Ciocalteu-teszttel mérték. A klorogénsavak (3-, 4- és 5-koffeoilkinsav) és a koffein mennyiségét HPLC-PDA-val határozták meg. 30 °C-on a legmagasabb TPC-értéket (48,7 ± 0,6 mg GAE/g) a NDES 30 perces kivonatában mérték, ami összehasonlítható ($P > 0,05$) a NDES 60 perces (47,4 ± 0,1 mg GAE/g) és 90 perces (48,6 ± 1,1 mg GAE/g) kivonataival. A legmagasabb klorogénsav-tartalom (52,4 ± 0,6 mg/g) az 50 %-os etanolos, 30 perces extrakcióban volt, ami hasonló ($P > 0,05$) más etanolos kivonatokhoz, valamint a NDES 60 és 90 perces kivonatokhoz. A koffeintartalom (12,1 ± 0,2 mg/g) az 50 %-os etanolos, 30 perces kivonatban érte el a csúcsot, ami hasonló ($P > 0,05$) a legtöbb más kivonathoz, kivéve a NDES 30 perces kivonatot (11,3 ± 0,3 mg/g). Az 50 °C-on végzett NDES 46,9 ± 0,5 mg/g TPC-t, 48,6 ± 0,7 mg/g klorogénsavat és 11,1 ± 0,2 mg/g koffeint eredményezett, ami nem különbözött szignifikánsan a 30 °C-on kapott eredményektől. Ezek az eredmények azt jelzik, hogy a glükóz-glicerin NDES egy ígéretes, környezetbarát oldószer a fenolos vegyületek GCB-kből történő extrakciójához, alternatívát kínálva az 50 %-os etanollal szemben.

Kulcsszavak: klorogénsav, mély eutektikus oldószerek, zöld kávébab, fenolos vegyületek

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Investigation of the Applicability of Stinging Nettle (*Urtica dioica* L.) for the Production of Functional Bakery Products

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ABSTRACT

The demand for health-promoting foods with exceptional nutritional and biological qualities is increasing. Medicinal herbs are rich in antioxidants and polyphenols and often possess favourable organoleptic properties. Therefore, this study aimed to develop a novel functional bakery product enriched with stinging nettle (*Urtica dioica* L.). The functional food consisted of crackers supplemented with nettle leaves and nettle seeds. The objectives were to demonstrate that nettle leaves and seeds are excellent sources of bioactive compounds and that these compounds are retained during food production, and to evaluate consumer acceptance of nettle-enriched crackers through organoleptic testing. The results showed that dried nettle leaves had significantly higher values than nettle seeds for both parameters tested (TAC: 108.1 ± 7.7 mg AAE/g; TPC: 46.6 ± 5.2 mg GAE/g). Among the cracker samples, the baked crackers enriched with nettle seeds exhibited the highest polyphenol content (7.7 ± 0.4 mg GAE/g) and antioxidant content (17.4 ± 1.9 mg AAE/g). These samples were also the most preferred by consumers. From both organoleptic and nutritional perspectives, nettle seeds proved to be the superior choice for enhancing crackers.
Keywords: stinging nettle, functional food, antioxidants, spectrophotometry, consumer acceptance

1. INTRODUCTION

Stinging nettle (*Urtica dioica* L.) is a wild-growing medicinal herb commonly found in temperate regions. It is native to Europe, Asia, North America, and North Africa (Đurović et al., 2020; Kutlu et al., 2020). Although it originated in Eurasia, it is now widely distributed across Europe (especially Northern Europe), northern Africa, Asia, and North and South America (Said et al., 2015).

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The above-ground parts of nettle contain 2.5-3.6 % crude fat, 18-34 % crude protein, 9 % crude fibre, 16 % total ash, and 37 % carbohydrates on a dry matter basis (Tarasevičienė et al., 2023).
In addition, nettle is a rich source of bioactive compounds, including various phenolic compounds (mainly the flavonoids quercetin, kaempferol, and rutin), vitamins (B-group, K, and C), minerals (especially iron), essential amino acids, terpenoids (the main components of nettle essential oil), fatty acids (palmitic, linoleic, and linolenic acids), tannins, carotenoids (such as β-carotene, lutein, and lycopene), chlorophyll, sterols, and isolectins (Đurović et al., 2017; Đurović et al., 2022; Zeković et al., 2017).
Previous studies have shown that the chemical composition, nutritional value, and bioactive properties of nettles and their extracts vary depending on several factors, including plant part used, geographic origin, harvest time, collection site, and extraction method (Devkota et al., 2022; Opačić et al., 2022). Due to its excellent biological properties, nettle has been incorporated into various formulations to develop functional foods with health-promoting effects. Despite the considerable market potential of nettle-enriched foods, most such products remain at the laboratory scale rather than reaching large-scale industrial production. This is mainly attributed to inadequate cultivation and post-harvest processing methods for the plant (Jeannin et al., 2020).
Numerous studies have investigated the incorporation of various plants and plant parts into baked goods, such as cakes and cookies, to enhance their nutritional value and health-promoting properties—an approach that is increasingly demanded by modern consumers (Mitrović et al., 2022). For example, Đurović et al. (2020) reported a significant increase in phenolic content and antioxidant activity in bread when enriched with freeze-dried nettle leaves.
The present study aimed to develop crackers enriched with nettle leaves and nettle seeds and to confirm the positive physiological effects of this enrichment through analytical measurements. In addition, organoleptic (sensory) evaluation was performed to determine whether nettle enrichment improves consumer perception and acceptance of the crackers.

2. MATERIALS AND METHODS

2.1 Sample collection and preparation

The seeds and leaves of wild-grown stinging nettle (*Urtica dioica* L.) were collected in early autumn in Hegyeshalom the plain in Northwestern Hungary with coordinates N47°55’28.4”, E17°11’49.1” Latitude 47.924564, Longitude 17.196272. Both the leaves and stems are covered with erect, bristly, glandular hairs containing acetylcholine, formic acid, 5-hydroxytryptamine, and histamine. Therefore, the fresh green plant can cause skin irritation if touched without protective gloves (Asgarpanah & Mohajerani, 2012).
The leaves and seeds were separated from the stems, and the cleaned plant parts were dried in a drying oven at 40 °C until constant weight was reached. The dry matter content of the nettle samples was determined using a gravimetric method. For further analysis, the dried seeds and leaves were ground to a particle size of < 1 mm using a kitchen grinder (Sencor, SCG 2050RD, Budapest, Hungary).

2.2 Chemicals

The chemicals used for the determination of total polyphenol and total antioxidant content were: anhydrous sodium carbonate (99 %, Riedel-de Haën, Seelze, Germany), Folin-Ciocalteu reagent (98 %, Sigma-Aldrich, Budapest, Hungary), 2,4,6-tripyridyl-s-triazine (TPTZ)

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(98 %, Sigma-Aldrich, Budapest, Hungary), acetic acid (96 %, Reanal, Budapest, Hungary), anhydrous iron(III) chloride (98 %, Merck, Budapest, Hungary), ascorbic acid (96 %, Sigma-Aldrich, Budapest, Hungary), and gallic acid (98 %, Sigma-Aldrich, Budapest, Hungary).

2.3 Cracker baking process

The ingredients and their quantities used to prepare the control, nettle seed-enriched, and nettle leaf-enriched crackers are listed in *Table 1*. The total flour base was 250 g (125 g white flour + 125 g whole flour), and the dough was prepared with oil and water as liquid ingredients.

Table 1: Ingredients used to make crackers

Cracker type	Ingredients [g]						
	White flour	Whole flour	Baking soda	Water	Salt	Seed	Leaf
Control	125	125	1.92	120	4	None	None
Enriched with nettle seeds	125	125	1.92	120	4	25	None
Enriched with nettle leaves	125	125	1.92	120	4	None	25

Note: The amounts of oil (40 g) and water (120 g) were selected to achieve a homogeneous, kneadable dough consistency suitable for rolling to 0.5 cm thickness. These quantities are based on standard cracker dough formulations for a 250 g flour base.

The amount of the ingredients needed to make the crackers was weighed using a tare balance (GM series, GMB5002, Budapest, Hungary). To prepare the control cracker, the dry ingredients (flours, baking soda, and salt) were first placed in the mixing bowl. The oil was then poured into the dry mixture and mixed with a few quick movements. Water was gradually added while kneading until the dough reached the appropriate consistency and became homogeneous. For the nettle-enriched doughs, the previously dried and ground nettle seeds or leaves were added together with the dry ingredients. Samples of the prepared raw dough were taken for further analysis. The dough was rolled out on a floured surface to a thickness of 0.5 cm and then cut into 2 × 2 cm squares. The shaped raw dough pieces were placed on a baking tray lined with baking paper and baked in a preheated oven at 180 °C for 15 minutes.

2.4 Sample preparation for the determination of total antioxidant (TAC) and polyphenol (TPC) content

For the determination of total antioxidant capacity and total polyphenol content, 0.5 g of dried and ground nettle leaves or seeds was weighed into 250 mL Erlenmeyer flasks using an analytical balance (Sartorius, TE214SE, Budakeszi, Hungary). Then, 100 mL of the extractant, consisting of methanol and high-purity water (80:20, v/v), was added.

For the cracker samples, 1 g of raw dough or baked cracker was weighed into 100 mL Erlenmeyer flasks using an analytical balance, and 20 mL of the same methanol: high-purity water mixture (80:20, v/v) was added. The samples were extracted in a shaking thermostat (Bartelt, 3032, Graz, Austria) for 2 hours at 50 °C. After extraction, the mixtures were transferred into centrifuge tubes

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and centrifuged (Hermle, Z 206 A, Wehingen, Germany) at 6000 rpm for 20 minutes. The supernatant was collected for further analysis.

2.5 Determination of total antioxidant content by FRAP assay

The FRAP assay was performed according to the method described by Benzie and Strain (1996). Briefly, 200 µL of supernatant and 3 mL of FRAP reagent were pipetted into a test tube. The mixtures were kept in the dark for 5 min, after which the absorbance was measured at 593 nm against the blank using a Spectroquant Pharo 100 spectrophotometer (Merck, Darmstadt, Germany). Ascorbic acid (40-500 mg/L) was used as the standard, and the results were expressed as milligrams of ascorbic acid equivalents (mg AAE) per gram of dry matter.

2.6 Determination of total polyphenol content by Folin-Ciocalteu assay

Total polyphenol content was determined according to the Folin-Ciocalteu method described by Singleton et al. (1999). Briefly, 200 µL of supernatant was mixed with 1.5 mL of high-purity water. Then, 2.5 mL of 10 % Folin-Ciocalteu reagent was added, followed by 2 mL of 7.5 % Na_2CO_3 solution. The mixtures were kept in the dark for 90 min, after which the absorbance was measured at 725 nm against the blank using a spectrophotometer. Gallic acid (25-1000 mg/L) was used as the standard, and the results were expressed as milligrams of gallic acid equivalents (mg GAE) per gram of dry matter.

2.7 Consumer acceptance of cracker samples

Consumer acceptance of the cracker samples was evaluated by a panel of 15 untrained panellists (employees and students of the Albert Kázmér Faculty of Agricultural and Food Sciences at Széchenyi István University, Mosonmagyaróvár). The panellists rated the samples on a 5-point hedonic scale (5 = like very much, 1 = dislike very much, 3 = neither like nor dislike). The evaluated sensory attributes were appearance, odour, taste, texture, and overall acceptability.

All three cracker samples (control, nettle seed-enriched, and nettle leaf-enriched) were presented simultaneously to the panellists to allow direct comparison. Evaluations were carried out using a structured questionnaire. The results are presented as mean scores ± standard deviation.

The study was conducted in accordance with ethical guidelines. Informed consent was obtained from all panellists prior to their participation, and appropriate measures were taken to protect their rights and privacy.

2.8 Data analysis

All experimental results for stinging nettle seeds, leaves, and cracker samples were processed using Microsoft Office Excel. The results are expressed as mean values ± standard deviation ($n = 3$). Calibration curves for the spectrophotometric methods were prepared using second-order polynomial regression (nonlinear least-squares method). The absorbance values of the sample extracts were interpolated from these curves to calculate the concentrations.

One-way analysis of variance (ANOVA) followed by Tukey’s post hoc test was used to determine significant differences between means. Differences were considered statistically significant at $p < 0.05$.

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3. RESULTS AND DISCUSSION

3.1 Total antioxidant (TAC) and polyphenol (TPC) content of stinging nettle seed and leaf samples

The dry matter content of nettle leaves was 21.2 ± 1.4 % (m/m), while that of nettle seeds was 72.6 ± 2.1 % (m/m). The TAC and TPC values of the nettle leaf and nettle seed samples are presented in *Table 2*.

Table 2: Total antioxidant (TAC) and polyphenol (TPC) content of stinging nettle leaf and seed samples (n = 3), different letters (a and b) denote significant differences (p ≤ 0.05) between different nettle parts

Sample	TAC mg AAE/g	TPC mg GAE/g
Nettle leaf	108.1 ± 7.7^{a}	46.6 ± 5.2^{a}
Nettle seed	45.7 ± 0.5^{b}	23.4 ± 1.2^{b}

Based on the results, the total antioxidant capacity of nettle leaves was approximately 2.4 times higher than that of nettle seeds. Albayrak et al. (2011) reported a total antioxidant content of 132.7 ± 2.1 mg AAE/g for nettle using methanol extraction, which is close to the value obtained for nettle leaves in the present study.

In terms of total polyphenol content, nettle leaves also showed markedly higher values, approximately twice that of nettle seeds. Consequently, nettle leaves contain substantially higher amounts of bioactive compounds and may exert more favourable physiological effects than nettle seeds.

Joshi et al. (2015) found that the total phenolic content of various *Urtica dioica* L. extracts was highest in the ethyl acetate fraction (13.06 ± 0.15 mg GAE/g). This value is considerably lower than the results obtained in the present study for both nettle leaves and seeds. Elez Garofulić et al. (2021) reported that the total polyphenol content of nettle leaves ranged from 3.56 ± 0.15 to 23.69 ± 0.30 mg GAE/g depending on the extraction conditions applied. These literature values are in agreement with the phenolic content determined for nettle leaves in this work.

Overall, the results and supporting literature data confirm that Urtica *dioica* L. is a rich source of phenolic compounds and possesses strong antioxidant properties (Kataki et al., 2012).

3.2 Total antioxidant (TAC), and polyphenol(TPC) content of stinging nettle enriched cracker samples

Based on the results presented in *Table 3*, both nettle leaf- and nettle seed-enriched crackers showed higher antioxidant content compared to the control cracker. These findings confirm that *Urtica dioica* L. is suitable for increasing the antioxidant capacity of bakery products.

The baked crackers exhibited significantly higher TAC and TPC values than the corresponding raw doughs. This increase is most likely due to concentration effects caused by moisture loss during baking. The short baking time (15 min at 180 °C) did not appear to cause substantial degradation of the heat-sensitive bioactive compounds.

Interestingly, in both the raw dough and baked cracker samples, the nettle seed-enriched variants consistently showed higher antioxidant and polyphenol contents than the nettle leaf-enriched samples, despite the lower values observed in the pure dried nettle seeds. The highest values were recorded in the baked seed-enriched crackers (TAC: 17.4 ± 1.9 mg AAE/g; TPC: 7.7 ± 0.4 mg GAE/g).

These results are consistent with those of Mitrović et al. (2022), who observed that adding nettle seed flour or nettle seed phenolic extracts to cookies increased the DPPH radical-scavenging capacity and

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reducing power of both free and bound phenolic compounds after heat treatment. Similarly, previous studies have demonstrated that incorporating nettle leaves or extracts into baked goods improves their technological, nutritional, and functional properties (Đurović et al., 2020; Rutakhli et al., 2019). Heat treatment has also been reported to increase the levels of phenolic compounds, such as phenolic acids, tannins, and flavonoids, in various food matrices (Alide et al., 2020; Călinoiu & Vodnar, 2019).

Table 3: The total antioxidant (TAC) and total polyphenol (TPC) content of the nettle-enriched cracker samples, as well as the raw cracker doughs and baked cracker samples (n = 3), different letters (a, b,c, d, e and f) denote significant differences (p ≤ 0.05)

Cracker sample	TAC mg AAE/g	TPC mg GAE/g
Control raw dough	0.3 ± 0.02^{a}	1.7 ± 0.3^{a}
Raw dough enriched with nettle leaves	2.3 ± 0.2^{b}	3.1 ± 0.4^{b}
Raw dough enriched with nettle seeds	8.2 ± 0.5^{c}	4.6 ± 0.4^{c}
Control cracker	5.4 ± 0.3^{d}	2.5 ± 0.2^{d}
Cracker enriched with nettle leaves	9.4 ± 0.2^{e}	5.0 ± 0.4^{c}
Cracker enriched with nettle seeds	17.4 ± 1.9^{f}	7.7 ± 0.4^{e}

In the polyphenol content analysis, the nettle seed-enriched samples also exhibited higher values compared to the nettle leaf-enriched crackers. The highest polyphenol content was found in the baked crackers enriched with nettle seeds (7.7 ± 0.4 mg GAE/g). Among the nettle-enriched samples, the raw dough containing nettle leaves showed the lowest polyphenol content (3.1 ± 0.4 mg GAE/g). These findings align with previous research demonstrating that increasing the proportion of plant-based ingredients can enhance the polyphenol content of baked products. For example, Drabińska et al. (2018) reported that the addition of broccoli leaves to gluten-free mini sponge cakes resulted in a proportional increase in polyphenol content as the amount of broccoli leaves increased.

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3.3 Consumer acceptance test results

Figure 1 shows the mean ratings of 15 panellists for the five sensory attributes (appearance, odour, taste, texture, and overall acceptability) of the three cracker samples (control, nettle seed-enriched, and nettle leaf-enriched).

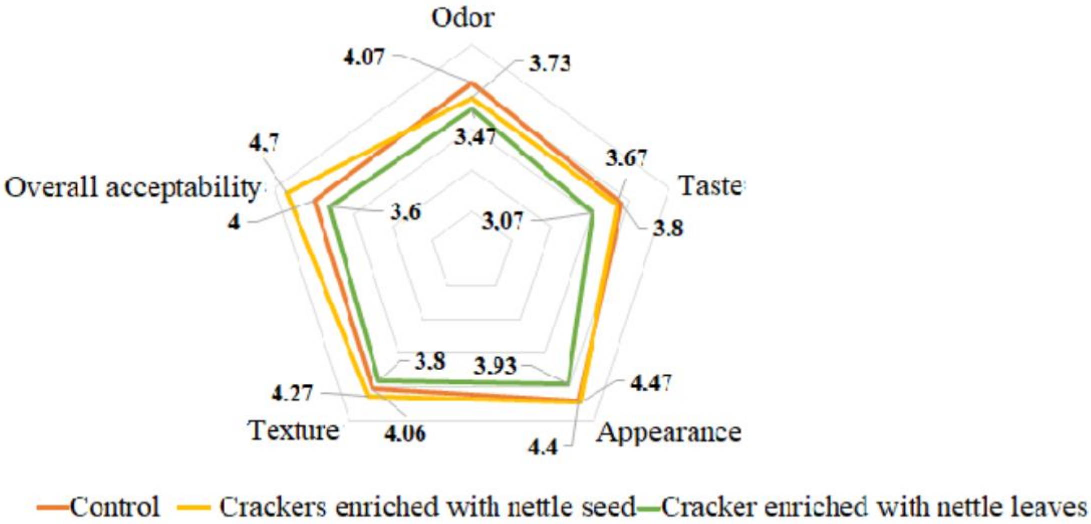

Figure 1. Consumer perception of nettle-enriched crackers

Based on the sensory evaluation, the nettle leaf-enriched cracker received the lowest scores for all attributes. The nettle seed-enriched cracker achieved the highest overall acceptability (4.7). None of the nettle-enriched samples matched the control cracker in odour (control: 4.1). For taste, the control sample was rated highest (3.8), followed closely by the nettle seed-enriched cracker (3.7).
In terms of appearance, the nettle leaf-enriched cracker received the lowest rating, while the difference between the control and nettle seed-enriched crackers was minimal; the latter scored highest (4.5). For texture, the nettle seed-enriched cracker received the highest score (4.3), followed by the control (4.1) and the nettle leaf-enriched cracker (3.8).
Overall, the nettle seed-enriched cracker was the most liked among the two enriched samples. These findings are consistent with those of Chochkov et al. (2025), who reported that control bread samples received higher taste scores than nettle-enriched bread samples. Similarly, Rădulescu et al. (2024) noted that adding nettle powder to bread dough imparts a distinctive taste and texture.

4. CONCLUSION

Higher levels of bioactive components were observed in the nettle-enriched crackers after baking, despite the typically expected baking losses, due to the heat sensitivity of these compounds. The results clearly demonstrate that nettle-enriched crackers have a more beneficial nutritional profile, owing to their higher antioxidant and polyphenol levels.
Nettle seeds proved to be a superior choice compared to nettle leaves for the supplementation of bakery products in terms of both antioxidant and polyphenol content. Overall, the spectrophotometric analyses confirm that both stinging nettle seeds and leaves are suitable ingredients for increasing the antioxidant and polyphenol values of bakery products, thereby potentially enhancing their health-promoting effects. Furthermore, sensory evaluation showed that the nettle seed-enriched sample also received the highest consumer acceptance.

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Nagy csalán (*Urtica dioica* L.) alkalmazhatóságának vizsgálata funkcionális sütőipari termék előállítására

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ÖSSZEFOGLALÁS

Manapság egyre nagyobb az igény az egészség megőrzését elősegítő, kivételes tápértékű és biológiai tulajdonságokkal rendelkező élelmiszerek iránt. A gyógynövények antioxidánsokban és polifenolokban gazdagok, valamint kedvező érzékszervi tulajdonságokkal rendelkeznek. Ezért a tanulmány célja egy csalánnal (*Urtica dioica* L.) dúsított, új funkcionális sütőipari termék kifejlesztése volt. A funkcionális élelmiszer alapja kréker volt, amelyet csalánlevéllel és csalánmaggal egészítettek ki. A célkitűzések között szerepelt annak bizonyítása, hogy a csalánlevél és a csalánmag kiváló bioaktív összetevők forrása, valamint hogy ezek az összetevők az élelmiszer-előállítás során is megmaradnak a termékekben. Emellett a csalánnal dúsított krékerek fogyasztói elfogadottságát érzékszervi bírálattal is vizsgálták.
Az eredmények szerint a szárított csalánlevél mindkét vizsgált paraméterben jelentősen magasabb értékeket mutatott, mint a csalánmag (TAC: 108,1 ± 7,7 mg AAE/g; TPC: 46,6 ± 5,2 mg GAE/g). A krékerminták összehasonlításakor a csalánmaggal dúsított sült krékerek rendelkeztek a legmagasabb polifenol-tartalommal (7,7 ± 0,4 mg GAE/g) és antioxidáns-tartalommal (17,4 ± 1,9 mg AAE/g), valamint ezek bizonyultak a fogyasztók körében a legkedveltebbeknek. Érzékszervi és táplálkozási szempontból a csalánmag a legjobb választás a krékerek dúsítására.
Kulcsszavak: nagy csalán, funkcionális élelmiszer, antioxidánsok, spektrofotometria, fogyasztói elfogadottság

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Színképelemzésen alapuló módszertan a búzafajták raktári elkülönítésére és keveredésének meghatározására

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ÖSSZEFOGLALÁS

Az élelmiszeriparban, különösen a gabonafeldolgozás területén, az élelmiszerek nyomonkövethetősége kiemelkedő jelentőséggel bír a minőségbiztosítás és az élelmiszerbiztonság szempontjából. A gabonatételek tárolása során az egyik legnagyobb kihívást a tételek hatékony elkülönítése és pontos lokalizálása jelenti. Az optikai módszerek, mint például a színképelemzés és a közeli infravörös (NIR) spektroszkópia, ígéretes megoldásokat nyújtanak e problémák kezelésére. Ebben a tanulmányban a CIELAB színrendszer alkalmazásával vizsgáltuk a gabonatételek tárolás közbeni keveredésének mértékét és a színbeli eltérések változását. A kutatás célja annak meghatározása volt, hogy a színjellemzők kombinált mutatójaként a HUE × C* mutató alapján milyen pontossággal lehet számszerűsíteni az egyes keveredési arányokat. Az általunk alkalmazott módszer lehetővé tette a színbeli változások objektív értékelését és a keveredések arányának meghatározását. Kísérleteink során beraktározott búzamintáknál azt vizsgáltuk, hogy hol helyezkedik el az a pont, ahol már nincs keveredés az egyes tételek között. A színméréseket D65 fényforrással felszerelt reflexiós kolориméter segítségével végeztük és minden mintát tíz ismétlésben vizsgáltunk. Az eredmények alátámasztották, hogy adott távolságra a gabonatételek keveredése már nem kimutatható. Az eredmények értékes információkat nyújtanak a gabonatételek lokalizációjához és a keveredési arány pontos szabályozásához síkraktárakban történő tárolás esetén.

Kulcsszavak: gabonaminőség, gabonatárolás, CIELAB színrendszer, optikai módszerek, nyomonkövethetőség

1. BEVEZETÉS

Az ellenőrzött élelmiszer előállítás, ezen belül gabonák feldolgozása az utóbbi évtizedekben egyre jelentősebb szerepet kap a minőségi élelmiszertermelésben. Azonban az élelmiszer alapanyagok (a termőföldtől az élelmiszer előállító üzemig) nyomon követése korlátozott mértékben megoldott. A kritikus elem a teljes „szántóföldtől az asztalig” („from-field-to-fork”) történő nyomonkövethetőség. Az élelmiszerbiztonság és azon belül az élelmiszerek nyomonkövethetősége sarkalatos pontját képezi az egyre szigorúbbá váló Európai Uniós élelmiszerszabályozásnak is. Az ellátási lánc minden szereplője számára napjainkban már több rendelet (178/2002/EK, 852/2004/EK) és számos független agrár- és élelmiszeripari szabvány/rendszer (EUREPGAP, HACCP, ISO 22000, ISO 22005 stb.) határozza meg az élelmiszer-biztonságra, higiéniára és nyomon követhetőségre vonatkozó minimális előírásokat.

2. IRODALMI ÁTTEKINTÉS

Az élelmiszer alapanyagok teljes körű nyomonkövetése jelenleg sok esetben nem kielégítő, amely kihívást jelent az ágazat szereplői számára. A gabonák minőségének értékelésére számos módszer áll rendelkezésre, beleértve a mikrobiológiai, kémiai és optikai eljárásokat (Riba et al., 2008). Az optikai technológiák három fő csoportba sorolhatók: a spektrofotometriás módszerek, a gépi látás és a színmérés. A spektrofotometriás eljárások a látható és az infravörös spektrumok elemzésére épülnek, és kiemelkedően hatékony eszközök a gabonák összetételének és állapotának vizsgálatában. A hiperspektrális képalkotás és a kemometria kombinációja lehetővé teszi a gabonaszemek pontos osztályozását és a szennyeződések detektálását. Berman és munkatársai (2007) az infravörös spektroszkópia alkalmazásával 95 %-os pontosságot ért el ausztrál búzafajták minősítésében. Philippe és munkatársai (2018) a durum búza spektrális és morfológiai tulajdonságainak kombinált vizsgálatával 96,5 %-os és 88,3 %-os osztályozási pontosságot ért el.
A VIS-NIR spektroszkópia (látható és közeli infravörös tartomány) és a gépi látás együttes alkalmazása lehetővé tette a DON (deoxinivalenol) szennyezett búzaszemek azonosítását, amely során a szennyeződések elkülönítésére 91,36 %-os pontossággal dolgoztak ki modellt (He et al., 2021). A gépi látás és a képfeldolgozási technikák alkalmazása is egyre elterjedtebb a gabonaminőség értékelésében. Zayas és munkatársai (1989), valamint Majumdar és Jayas (2000) morfológiai paraméterek alapján különböző gabonafajtákat azonosítottak, akár 98-100 %-os pontossággal. Vithu és Moses (2016) kimutatták, hogy a gépi látás hatékonyan kiválthatja a hagyományos, emberi megfigyelésen alapuló módszereket. Kar és munkatársai (2020) egy automatizált rendszert fejlesztett ki, amely képfeldolgozással azonosítja és kategorizálja a gabonaféléket, ezzel csökkentve a manuális vizsgálatok szükségességét. A mesterséges intelligencia alapú megközelítések szintén egyre nagyobb szerepet kapnak. Ebrahim (2014) gépi látással és mesterséges neurális hálózatokkal dolgozott ki modellt a búza tisztaságának ellenőrzésére, amely 96,25 %-os pontosságot ért el. A megközelítés a helyi fáziskvantálási leírók, valamint a szín- és formajellemzők integrációján alapul, mely meghaladja a hagyományos lokális leírók teljesítményét. Az SVM-RBF osztályozó gyors, pontos osztályozást tesz lehetővé, míg a kontrollált megvilágítás és precíz felvételi módszerek hozzájárulnak a megbízható minőségértékeléshez. A tárolási folyamatok során kiemelten fontos a penészesedés és a mikotoxin-szennyeződés kockázatának csökkentése.
A *Fusarium* fertőzés és az általa termelt mikotoxinok nemcsak a gabona minőségét rontják, hanem komoly élelmiszerbiztonsági kockázatot is jelentenek (Yi et al., 2022; Manandhar et al., 2018). Ennek ellenőrzésére egy költséghatékony megoldást jelenthet a CIELAB színmérő rendszer

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használata, amely lehetővé teszi a különböző minőségi paraméterekkel rendelkező gabonatételek lokalizálását és a szennyezett tételek azonosítását. A tárolási időszak során a gabona minőség- és mennyiségveszteség nélküli megőrzése kulcsfontosságú (Shepherd, 1993). A tárolás leggyakrabban azért történik, mert a termék fogyasztási helye más, mint az előállítás helye, a termék szezonális, de a fogyasztás egész évben zajlik, és a további feldolgozást többek között más helyen végzik (Jayas, 2012). A tárolási rendszerek nem megfelelő kialakítása jelentős betakarítás utáni veszteségeket eredményezhet, rontva az ágazat általános termelékenységét (Nadimi et al., 2023). A gabonák eltarthatóságát befolyásoló legfontosabb tényezők közé tartozik a hőmérséklet, a páratartalom és a tárolási idő, amelyek fizikai és kémiai változásokat idézhetnek elő, mint például elszíneződést, lipidoxidációt és fehérjedenaturációt (Hu et al., 2022; Qiang et al., 2024). A gabona tárolása olyan körülményeket igényel, amelyek megőrzik vagy javítják annak minőségét az aratást követően. Ennek érdekében elengedhetetlen a rovarok jelenlétének és a nedvességtartalom folyamatos ellenőrzése, amely rovarölőszerek, füstölőszerek és módosított atmoszféra alkalmazásával biztosítható. A megfelelő nedvességtartalom fenntartása és a szárítási technológiák optimalizálása szintén kulcsfontosságú. Az eltérő gabonafajták, például árpa, rizs és búza, specifikus tárolási feltételeket igényelnek a minőség megőrzése érdekében. A szállítás során a nyomonkövethetőség biztosítása elengedhetetlen, hogy az eltérő minőségű tételek elkülöníthetők legyenek (Brennan, 2017). Kísérleti eredmények igazolják, hogy bizonyos búzafajták eltérő mértékben reagálnak a tárolási körülményekre. Navnath és munkatársai (2023) megállapították, hogy az AAC Stronghold fajta ellenállóbb a károsodással szemben, míg az AAC Spitfire és CDC Defy fajták jelentősebb romlást mutattak. Nithya és munkatársai (2011) kutatásai alapján a magasabb nedvességtartalmú és magas hőmérsékleten tárolt durum búza hajlamosabb a penészesedésre és toxintermelésre. A gabonák szezonális betakarítása és folyamatos feldolgozása közötti konfliktus megoldása érdekében szükség van hatékony tárolási stratégiákra (Tong et al., 2019). Az optimális tárolási feltételek biztosítása nemcsak a termékminőség fenntartását, hanem a feldolgozási tulajdonságok megőrzését is szolgálja. Az egyes minőségi paraméterek nyomonkövetése és az automatizált vizsgálati rendszerek alkalmazása hozzájárulhat a tárolási stabilitás növeléséhez, csökkentve ezzel a gazdasági veszteségeket és az élelmiszerbiztonsági kockázatokat (Hui et al., 2025).

3. ANYAG ÉS MÓDSZER

3.1 Kísérleti helyszín

Kísérleteinket Közép-Európa középső részén található Szlovákia területén (16°–23° keleti hosszúság, 47°–50° északi szélesség) végeztük, melynek területe 49035 km^2 (Fendeková et al., 2018). A délnyugati régióban, az alföld területén, amely a Kis-Kárpátok hátulsó oldalától délre helyezkedik el, az éves csapadékmennyiség 500-650 mm között mozog (Pokorná et al., 2013; Skalský et al., 2024). A kísérletbe bevont parcellákon az éves csapadékmennyiség 2021-ben 535 mm, 2022-ben 472 mm és a 2023-as évben 744 mm volt. Az alföldek a Pannon-medence részét képezik (Kozak et al., 2013). A dél-szlovákiai Duna menti szikes mocsarak és sztyeppék a közép-európai szikes talajok legészakibb határán helyezkednek el (František, 1976). A mezőgazdasági földterületek több mint kétharmadát nagy ráfordítást igénylő őszi búza, kukorica, repce, árpa, napraforgó, cukorrépa és egyéb növények termesztésére használják (Skalský et al., 2024). A délnyugati síkvidékein hatalmas intenzíven művelt termőföldek találhatók (Hološková et al., 2023). A 2021, 2022, 2023-as években búzafajták is ilyen egyforma szikes talajadottságú területen lettek elvetve. A különböző színű búzafajtákat négy elkülönített mezőgazdasági parcellán termesztettük. A nagy pontosságú kalibrációs vizsgálatok

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elvégzéséhez jól elkülönülő színű búzafajtákat használtunk. Ezek között volt „hagyományos" köztermesztésben lévő, világosbarna szemszínű búzafajta, egy sárga színű, illetve két antociánban gazdag búzafajta. A hagyományos búzafajtákban csak nagyon kevés antocianinvegyület található (Abdel et al., 1999; Abdel et al., 2003). Az antocianinok a búza aleuron vagy maghéj részében halmozódnak fel és ezek biztosítják a szem kék, lila és vörös színét (Ficco et al., 2014). Az antociánban gazdag búzában delfinidin-3-glükozid is található meg (El-Sayed et al., 2006).

3.2 Kísérleti anyag (búzafajták)

A vizsgálatok során négy eltérő szemszínű őszi búzafajtát vontunk be: az IS-18W1161 és a Karkulka antociánban gazdag, lila szemszínű fajták; a Bonavita sárga szemszínű fajta; valamint a Genius világosbarna szemű, hagyományos fajta, amely kontrollként szolgált.
A kísérleti búzafajták rövidítései és vizsgálati évei a következők:
- GENIUS (K): világosbarna szemszínű; 2021, 2022 és 2023.
- KARKULKA (MK): antociánban gazdag lila szemszínű; 2021 és 2023.
- BONAVITA I (MB): sárga szemszínű; 2022.
- IS-18W1161 (AG): antociánban gazdag lila szemszínű; 2021, 2022 és 2023.
- BONAVITA II (CS): sárga szemszínű; 2021, 2022 és 2023.

Megjegyzés: a BONAVITA fajta két különböző termőhelyen termesztve került vizsgálatba a 2022-es évben, ezért két eltérő rövidítést (MB és CS) kapott.

3.3 Mintavétel és minta előkészítése

- A négy eltérő színű búzatételből ellenőrzött keverékmintákat készítettünk a színmérési kísérletekhez. Minden lehetséges fajtakombináció (két különböző fajta párosítása) esetében állítottunk elő kétkomponensű keverékeket.
- 2021-ben és 2022-ben a 4 fajta összes lehetséges párkombinációját (6-6 párt), míg 2023-ban 5 fajtakombinációt vizsgáltunk.
- Az egyes fajtakombinációkhoz tartozó keverési arányokat 0 % és 100 % között, 10 %-os lépésenként állítottuk be. Ezek alapján 11-féle keverési arányt mértünk egy fajtapárra. Évente mintegy 60 különböző összetételű mintát vizsgáltunk meg.
- A keverékek összeállítása előtt a kiinduló tételekből vett mintákat laboratóriumi körülmények között megtisztítottuk. Fajtánként 100 gramm szemtermést mértünk ki analitikai mérlegen, majd osztályozó szitarázóval megtisztítottuk a magokat a törmelékektől és idegen anyagoktól.
- A tisztításhoz kalibrált gabonaszitákat (1,0 mm nyílású körrosta és 3,5 mm hosszúkás nyílású rosta), valamint egy laboratóriumi szitarázógépet (SWING 160) alkalmaztunk. A szitálás 5 percig tartott 140 rázás/perc frekvenciával. A folyamat során az 1,0 mm alatti frakciót (finom por és törmelék), valamint a 3,5 mm-es rosta felett fennmaradó idegen magvakat és törtszemeket eltávolítottuk.
- A szitálás után csak az ép és tiszta búzaszemeket használtuk fel a keverési mintákhoz (a 2,0 mm-nél nagyobb szemű frakcióból) biztosítva a homogén mintaminőséget. A megtisztított mintákból pontos tömegméréssel kevertük ki a kívánt arányú kétkomponensű keverékeket.

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3.4 Színmérés

- Minden előkészített keverékmintából 200 darab búzaszemet vettünk ki a színméréshez és egy rétegben helyeztük a búzaszemeket a műszer mintakamrájába. Ez a mintaméret biztosította, hogy a minta kellően reprezentálja a keverék színjellemzőit.
- A méréseket egy HunterLab ColorFlex (45° megvilágítási és 0° megfigyelési geometria) reflexiós koloriméterrel végeztük laboratóriumi körülmények között. Minden mérési sorozat előtt a készüléket fehér és fekete etalonfelületekkel kalibráltuk.
- A színjellemzők rögzítéséhez a szabványos CIELAB színrendszert alkalmaztuk. A műszer minden mintánál mérte az L* (világosság), a* (vörös-zöld) és b* (kék-sárga) színtengely értékeket. Ezekből kiszámítottuk az összes színkülönbség értékét (ΔE*), valamint a színárnyalatot (HUE) és a színtelítettséget (C*), amely paramétereket az elemzéshez használtunk fel.
- A keverékminták színmérését tíz ismétlésben végeztük. A tíz ismétlésből számított átlag értékét vettük alapul, ami csökkentette a véletlenszerű mérési hibák hatását és növelte a színadatok megbízhatóságát.

3.5 Statisztikai elemzés

- Kétszakaszos elemzést végeztünk annak érdekében, hogy egyrészt kiválasszuk a legmegfelelőbb színváltozót a kilenc jelölt színváltozó közül, másrészt megvizsgáljuk, hogy az első lépésben kiválasztott színváltozó alapján megkülönböztethetők-e a különböző búzafajta homogén és heterogén keverékrészei.
- Az első lépésben korrelációanalízist hajtottunk végre. Meghatároztuk a Pearson-féle korrelációs együtthatók abszolút értékét (Pearson, 1895) a kilenc jelölt színváltozó és a két búzafajta aránya között az összes 17 gabonakeverékben. Az egyes színváltozók esetében kiszámítottuk a 17 korrelációs együttható átlagát, maximumát és szórását. Az eredmények alapján (részletes kifejtés a következő szakaszban) a HUE × C* színváltozó egyértelműen kiemelkedett a vizsgált változók közül, mivel a legmagasabb átlagos és maximális korrelációs együtthatót, valamint a legkisebb szórást mutatta. Ennek alapján a második lépésben a HUE × C* színváltozót használtuk.
- A 17 gabonakeverék mindegyikére lineáris modellt kalibráltunk, ahol a HUE × C* független változóként, míg a két búzafajta aránya válaszváltozóként szerepelt. A kalibrációs adathalmazt a modell betanítására használtuk, majd a kalibrált modell segítségével előrejeleztük a kétfajta búza arányát az értékelési adathalmazon mért HUE × C* színváltozó alapján. A modell teljesítményét mérőszámokkal (determinációs együttható – R^2, gyökátlagos négyzetes hiba – RMSE) értékeltük mind a kalibrációs, mind az értékelési adathalmazon. Ezen túlmenően a megfigyelt és a becsült fajtaarányokat binarizáltuk (azaz homogén vagy heterogén keverékként osztályoztuk), majd a modell által generált zavaró mátrix alapján további teljesítménymutatókat számítottunk ki: a valódi pozitív arányt (TPR) és a precizitást.
- A statisztikai elemzéseket és az ábrázolást az R statisztikai szoftver (R Core Team, 2024) és annak ‘caret’ (Kuhn, 2008), valamint ‘ggplot2’ (Wickham, 2016) csomagjai segítségével végeztük el.

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4. EREDMÉNYEK

4.1 A raktári keveredési zónák vizsgálata spektrofotometriás módszerrel a 2021–2023 közötti kísérleti évek alapján

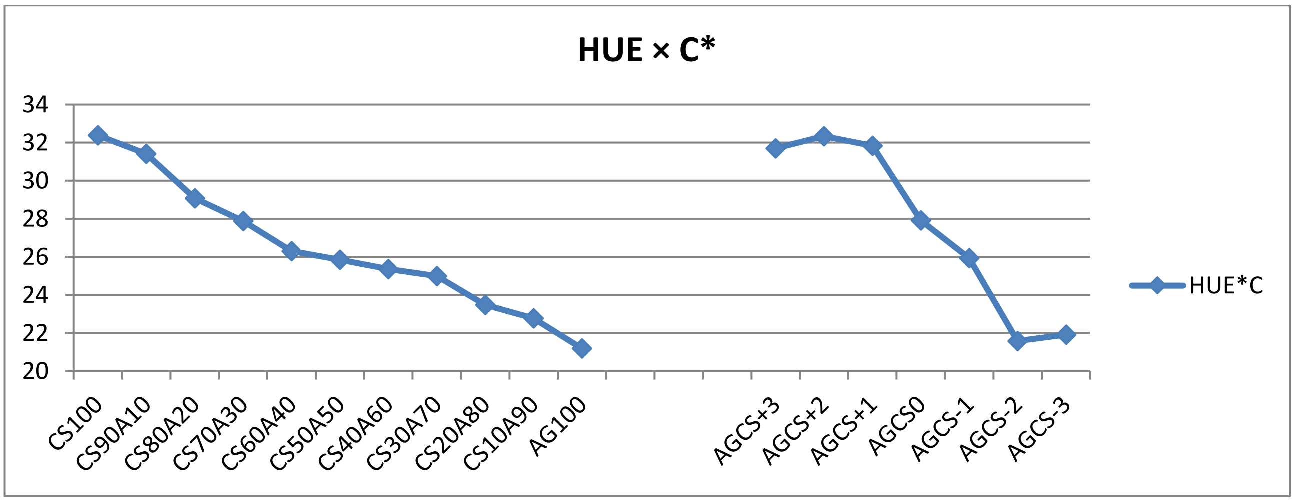
A kutatás célja annak vizsgálata volt, hogy a spektrofotometriás úton meghatározott HUE × C* mutató segítségével mennyire pontosan lehet számszerűsíteni a különböző búzafajták keveredési arányát raktári körülmények között. A vizsgálatok alapját a korábban meghatározott kalibrációs regressziós egyenesek képezték, amelyeket standard keverési minták alapján hoztunk létre. A lineáris regressziós modellek értékeit a vizsgált években az *1. táblázat* mutatja be.

1. táblázat: A HUE × C alapú lineáris regressziós modellek statisztikai jellemzői (2021–2023)*

Év	R^2 tartomány	R^2 átlag	RMSE (%)
2021	0,808–0,980	0,93	2,4
2022	0,885–0,987	0,94	2,0
2023	0,940–0,980	0,96	1,6

4.2 2021 – A keveredési modell kísérleti vizsgálata

A 2021-es kísérleti évben négy eltérő színárnyalatú búzafajtát (K, MK, AG, CS) öntöttünk le egymás mellé úgy, hogy azok fizikai kontaktusba kerültek, ezáltal természetes keveredési zónák jöttek létre. A mintavételezést gabona mintavevő szondával (stekkerrel) végeztük az érintkezési zónák középpontjától (0 pont) kiindulva 30 cm-es lépésekben, mindkét irányban és több rétegben. A spektrális adatok alapján pontonkénti keveredési arányok a kalibrációs egyenesek segítségével pontosan meghatározhatóak voltak. A HUE × C* mutató egyértelmű és jól követhető kapcsolatot mutatott a búzafajták keveredési arányával. A módszer megbízhatóságát az is alátámasztotta, hogy nemcsak a keveredés mértéke, hanem annak térbeli kiterjedése is pontosan meghatározhatóvá vált.



1. ábra: A CS és az AG búzaminták keverékei

Az *1. ábra* szerint az első szakasz CS100 és AG100 különböző arányú keverékeinek spektrális jellemzőit mutatja. A keverési arány 10 %-os lépésekben változik (pl. CS90AG10, CS80AG20 stb.), és a HUE × C* értékek csökkenő trendet mutatnak a CS100-tól az AG100 felé haladva.

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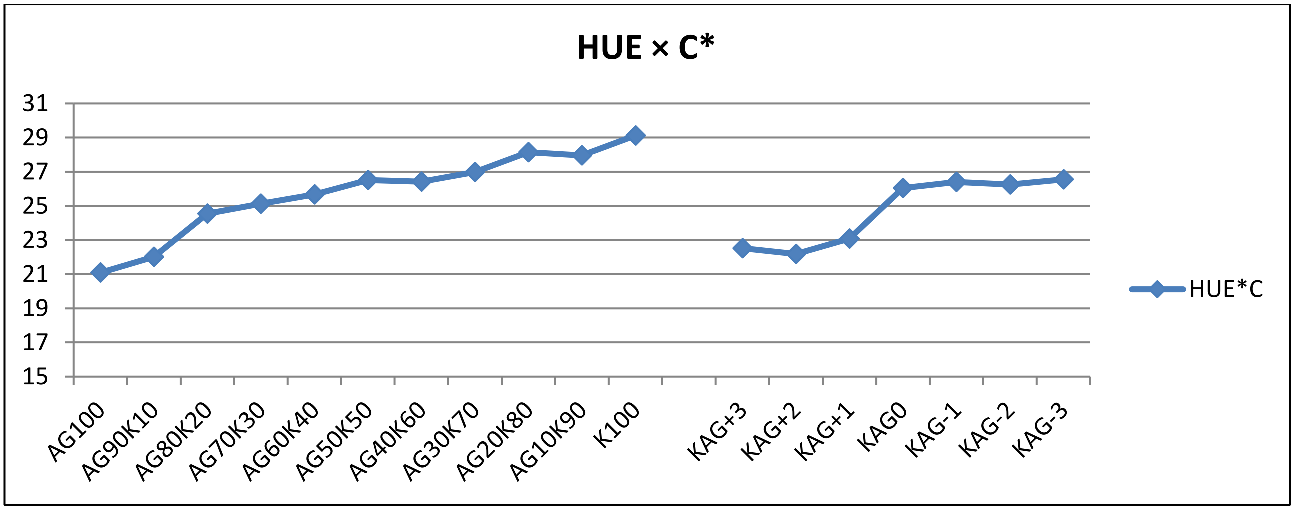
Ez a tendencia azt jelzi, hogy a két búzafajta spektrális jellemzői eltérnek, és a változás egyértelműen nyomonkövethető a keveredési arány függvényében. Az *1. ábránál* a jobb oldali szakasz (Raktári keveredés vizsgálata – AGCS-jelölés). A jobb oldali adatok a raktárban lévő búzahalmazok keveredésének spektrális változásait szemléltetik. Az AGCS0 a keveredési zónát jelöli, míg AGCS-1, AGCS-2, AGCS-3 az egyik gabonahalmaz felé, AGCS+1, AGCS+2, AGCS+3 pedig a másik irányba történő távolodást mutatják. Az ábra ezen szakasza azt bizonyítja, hogy a HUE × C* értékek a keveredési zóna közepén jelentősen változnak, majd a halmazok szélein stabilizálódnak. Az adatokból megállapítható, hogy a keveredés hatása egy bizonyos távolságon (kb. 120 cm) belül még kimutatható, azon túl pedig a gabonahalmazok spektrálisan elkülöníthetők. A trendvonal éles csökkenést mutat a keveredési zónán belül, majd az egyes búzahalmazoknál stabilizálódik, ami azt igazolja, hogy a két búzafajta között egy jól körülhatárolható átmeneti zóna található a raktárban.



2. ábra: Az AG és a K búzaminták keverékei

Az AG és K búzafajták keveredését bemutató *2. ábra* szintén két részből áll. A bal oldali szakaszban a kalibrációs keverékek eredményei láthatók, ahol a HUE × C* értékek egyenletes növekedést mutattak az AG100-tól a K100 felé haladva. Ez a trend jól érzékelteti a két fajta közötti spektrális eltérést és megerősíti, hogy a kalibrációs görbe segítségével a keverési arányok pontosan meghatározhatók. A jobb oldali szakasz a raktári minták vizsgálatát ábrázolja: a keveredési zónában a görbe érezhető változásokat mutatott, majd a zóna szélein stabilizálódott. Ez arra utal, hogy a keveredés hatása a raktárban jól körülhatárolható, és kb. 120 cm távolság után a gabonahalmazok már homogénnek tekinthetők.

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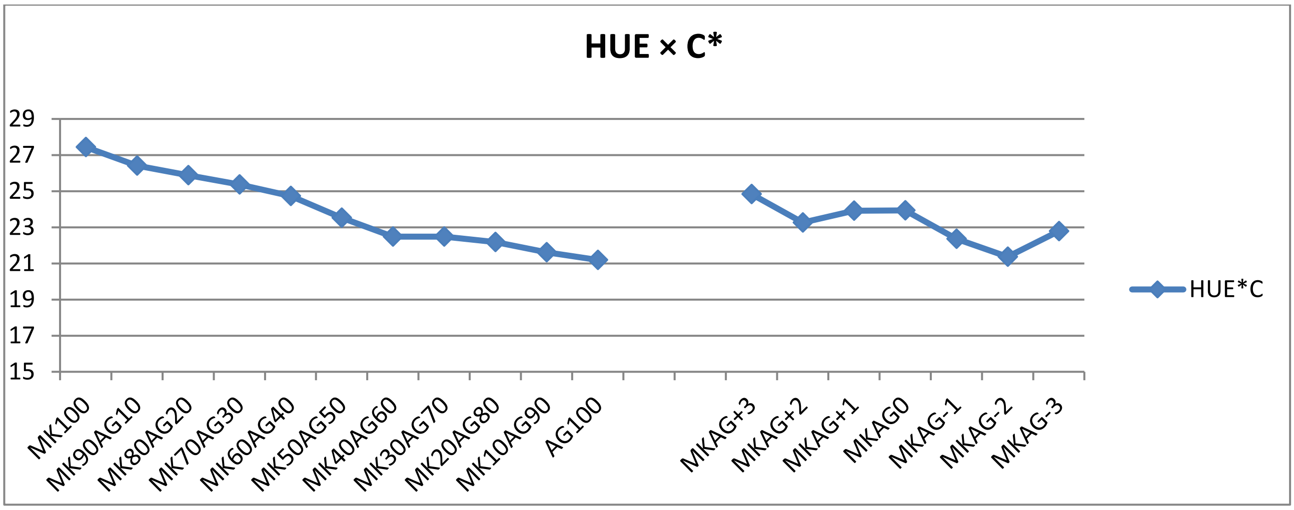
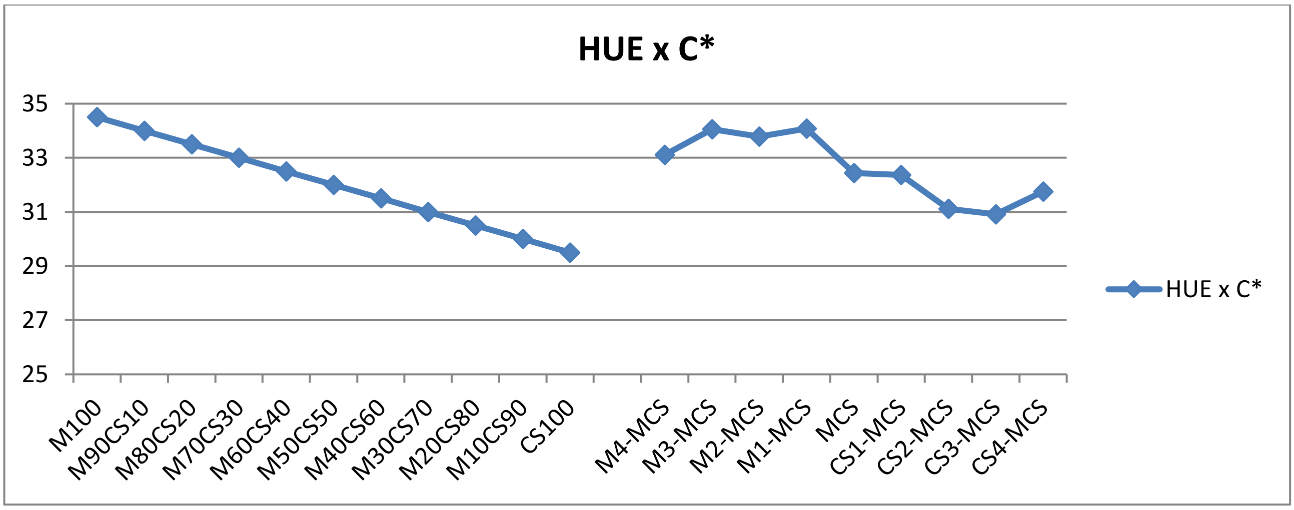


3. ábra: Az MK és az AG búzaminták keverékei

A *3. ábra* az MK és AG antociános búzafajták keveredését mutatja. A kalibrációs sorban a HUE × C* értékek enyhe, de következetes csökkenést jeleztek, ami arra utal, hogy a két fajta között csak kismértékű színbeli eltérés áll fenn. Ennek ellenére a keverési arányok laboratóriumi körülmények között még modellezhetők. A raktári adatokban a görbe már sokkal laposabb lefutást mutatott, a változások kevésbé voltak markánsak, így a keveredési zóna határai nehezebben voltak azonosíthatók. Ez arra világít rá, hogy a hasonló színprofilú fajták esetében a színképelemzés korlátozottabb érzékenységgel rendelkezik és a gyakorlati elkülönítés bonyolultabb.

4.3 2022 – A keveredési modell kísérleti vizsgálata

A 2022-es kísérletek során az AG, MB, CS és K fajták ismételten érintkeztek egymással, így a gabonák keveredése újra megfigyelhető volt. A kapott eredményeket a korábbi standard keverési minták grafikonjaival vetettük össze, és az összehasonlítás megerősítette, hogy a raktárban tárolt minták fajtánkénti összetétele spektrálisan pontosan meghatározható. A mérések alapján megállapítható volt, hogy a keveredés hatása nagyjából 120 cm-es távolságig mutatható ki, ezen túl a gabonahalmazok színképi szempontból homogénnek tekinthetők.



4. ábra: M és a CS búzaminták keverékei

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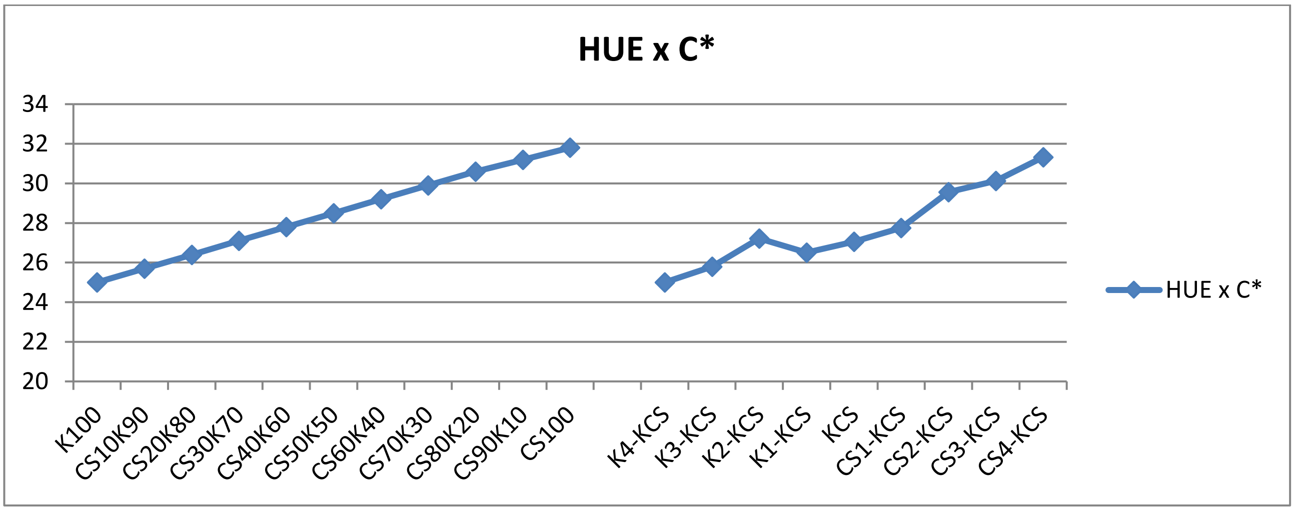
A *4. ábra* a két sárga színű búzafajta (M és CS) keveredésének vizsgálatát szemlélteti. A kalibrációs sor eredményei alapján a HUE × C* értékek mérsékelt, de folyamatos csökkenő tendenciát mutattak az M100-tól a CS100 felé haladva. Az eltérések nagyságrendje viszonylag csekély, ami a két fajta közeli spektrális tulajdonságaira utal. Ez azt jelzi, hogy bár a keveredési arányok színképelemzéssel elviekben meghatározhatók, az elkülönítés pontossága korlátozottabb, mint markánsabb színbeli különbségekkel rendelkező fajták esetében. A raktári mérések során kapott görbe lapos lefutása és a keveredési zóna határainak kevésbé éles jellege szintén a spektrális különbségek alacsony mértékét támasztják alá. Mindez arra utal, hogy a két búzahalmaz elkülönítése gyakorlati környezetben nehezített és a keveredés térbeli kiterjedése csak jelentősebb bizonytalanság mellett határozható meg.



5. ábra: A K és a CS búzaminták keverékei

Az *5. ábra* a hagyományos színű őszi búza (K) és a sárga színű búza (CS) keveredését szemlélteti. A kalibrációs sorban a HUE × C* értékek egyértelműen növekvő tendenciát mutattak a K100-tól a CS100 felé haladva, ami a két fajta markáns spektrális különbségét igazolja. Ez a folyamatos és jól követhető változás lehetővé teszi a keveredési arányok pontos meghatározását, illetve az ismeretlen minták összetételének visszakövetkeztetését, ami raktározási és minőségellenőrzési szempontból kiemelt jelentőséggel bír. A raktári vizsgálatok során kapott adatok szintén jól körülhatárolható átmeneti zónát jeleztek. A HUE × C* értékek gyors változása a keveredési határ térbeli lokalizálhatóságát támasztja alá. A görbe stabilizálódása azt mutatja, hogy kb. 120 cm távolság után a gabonahalmazok spektrálisan homogének és egyértelműen elkülöníthetők.

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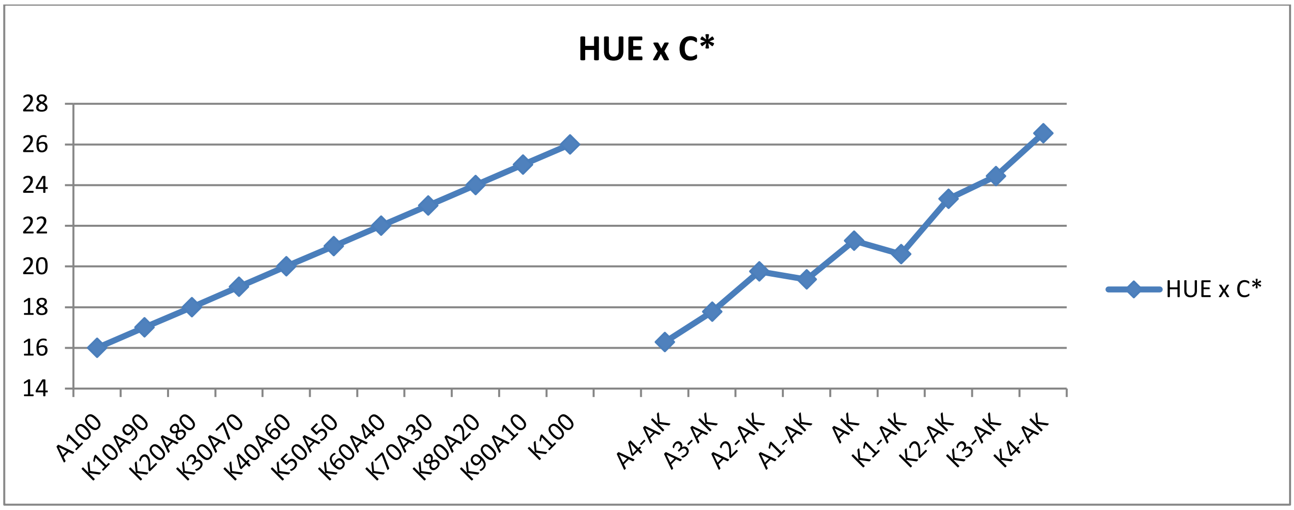
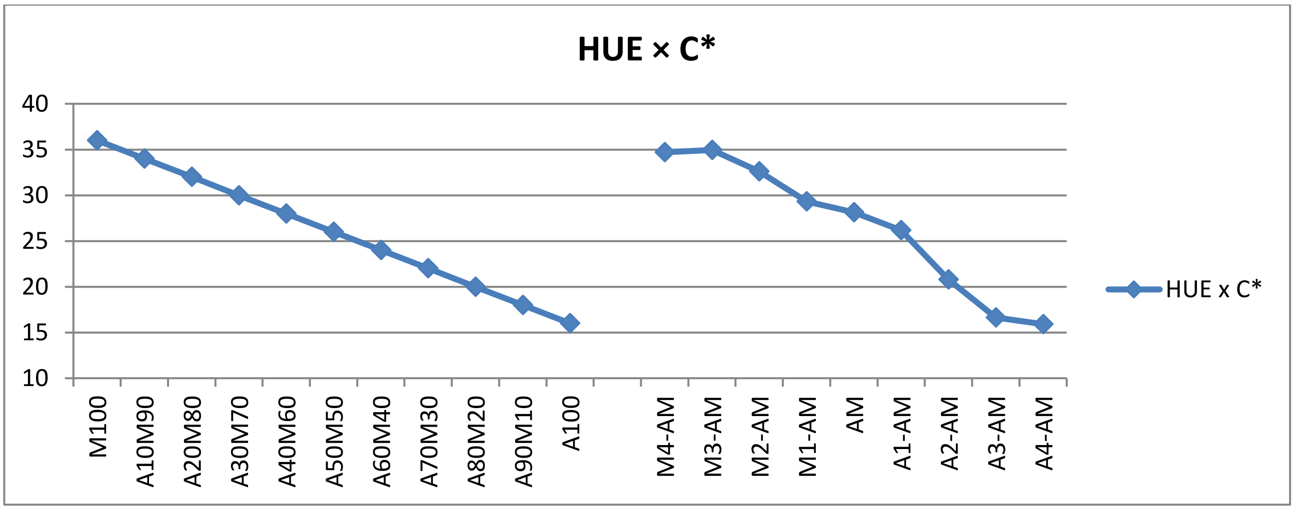


6. ábra: Az A és a K búzaminták keverékei

A *6. ábra* a hagyományos színű őszi búza (K) és az antociános búza (A) keveredésének vizsgálatát szemlélteti. A kalibrációs sorban a HUE × C* értékek egyértelmű, lineárisan emelkedő tendenciát mutattak az A100-tól a K100 felé haladva, amely a két búzafajta markáns spektrális különbségét támasztja alá. Ez a tendencia megerősíti, hogy a színképelemzés pontosan alkalmazható a keveredési arányok meghatározására, így az ismeretlen minták összetétele megbízhatóan visszakövethető. A raktári adatok szintén jól kirajzolódó átmeneti zónát jeleztek: az A dominanciájától (A4–A1) a K dominanciája felé (K1–K4) fokozatos változás figyelhető meg. A HUE × C* értékek gyors változása a keveredési zónában egy élesen meghatározható határ meglétére utal, amely a gyakorlatban kb. 120 cm-en belül érzékelhető. A görbe végső stabilizálódása igazolja, hogy ezen a távolságon túl a gabonahalmazok spektrálisan homogének és egyértelműen elkülöníthetők.



7. ábra: Az M és az A búzaminták keverékei

A *7. ábra* a sárga búza (M) és az antociános búza (A) keveredésének vizsgálatát mutatja. A kalibrációs sorban a HUE × C* értékek folyamatos, jól követhető csökkenést jeleztek az M100-tól az A100 felé, ami a kétfajta markáns spektrális eltérését igazolja. A raktári adatokban egyértelműen kirajzolódó

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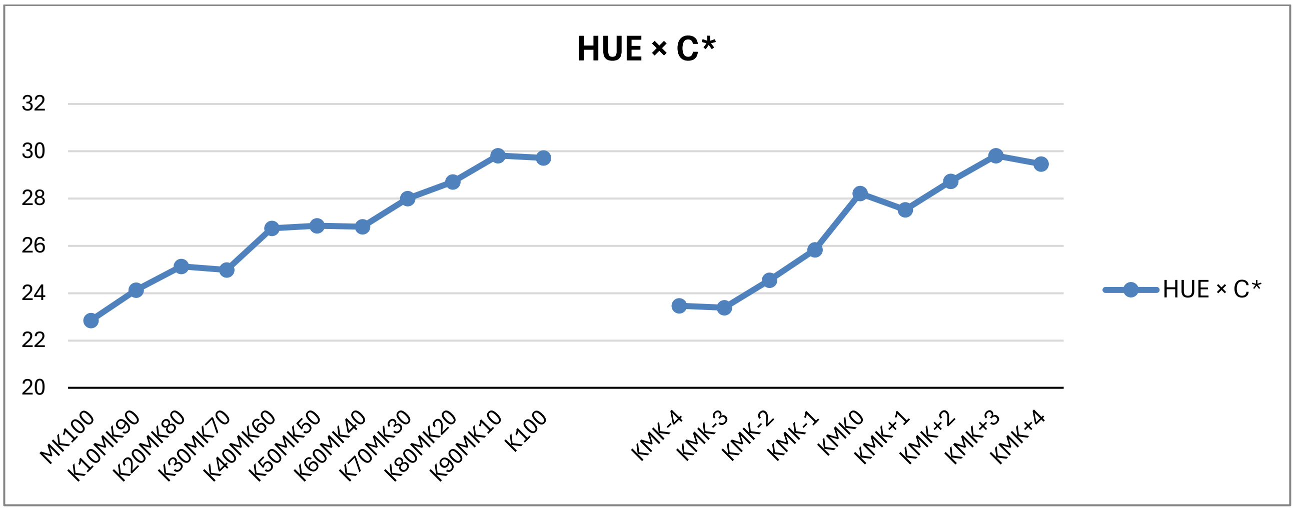
átmeneti zóna volt azonosítható: az M dominanciájától (M4–M1) az A dominanciája felé (A1–A4) a HUE × C* értékek éles változást mutattak. A keveredési határ így jól elkülöníthető, míg a görbe stabilizálódása jelzi, hogy kb. 90-120 cm távolságon túl a két gabonahalmaz spektrálisan homogénnek tekinthető.

4.4 2023 – A keveredési modell kísérlete

A 2023-as évben négy eltérő színárnyalatú búzafajta (K, MK, AG, CS) került vizsgálatra, azonos elrendezésben. A mintavételi és mérési eljárás nem változott. A keverékek (AGCS, MKCS, KCS, MKM, KAG) spektrumai mentén a 0-ás tengelytől való eltérés jól dokumentálható volt: a spektrális görbék bal és jobb oldali szakaszai jól tükrözték a fajtaösszetételben bekövetkezett változásokat. A mérések itt is igazolták, hogy 120 cm távolságon túli keveredés már nem érzékelhető, vagyis a különböző búzahalmazok spektrálisan élesen elkülönülnek.



8. ábra: Az MK és a K búzaminták keverékei

A *8. ábránál* a kalibrációs sor egyértelműen növekvő trendet mutatott a HUE × C* értékekben az MK100-tól a K100 irányába, ami azt jelzi, hogy a két búzafajta spektrális jellemzői jól elkülönülnek. A raktári adatok vizsgálata során szintén jól kirajzolódott a keveredési zóna: a HUE × C* értékek a központi tartományban alacsonyabbak voltak, majd fokozatosan közelítettek a tiszta fajták spektrális értékeihez. Ez arra utal, hogy a keveredés térben jól követhető, és kb. 120 cm távolságon túl a két gabonahalmaz spektrálisan homogénként, élesen elkülönülve jelent meg. A 2023-as kísérleti év eredményei azt mutatják, hogy a keveredési zóna térbeli kiterjedése korlátozott. A legtöbb esetben az átmeneti zóna körülbelül 100-120 cm távolságig volt kimutatható a két gabonahalmaz érintkezési pontjától. Ezen a távolságon túl a minták színparaméterei már stabilak maradtak, ami azt jelzi, hogy a gabonahalmazok homogénnek tekinthetők.

5. KÖVETKEZTETÉSEK, JAVASLATOK

Az elmúlt három év vizsgálatai megerősítették, hogy az őszi búza tételek közötti keveredés nem véletlenszerű, hanem jól körülhatárolható tendenciákkal írható le. A kalibrációs sorok (pl. *3.* és *4. ábra*) alapján a HUE × C* értékek egyértelmű tendenciát mutattak, amelyek lehetővé tették a keveredési arányok pontos meghatározását. Ez különösen igaz volt a markánsan eltérő

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spektrális tulajdonságokkal rendelkező fajtákra, például az antociános és a sárga búzákra, ahol a keveredési határ élesen kirajzolódott. Ezzel szemben a spektrálisan hasonló fajták, például két sárga típus keveredése, laposabb görbéket eredményezett, ami a módszer érzékenységi korlátaira világít rá. A raktári mérések (pl. *5.* és *6. ábra*) következetesen kimutatták, hogy a keveredési határzóna térben lokalizálható, és kb. 100-120 cm távolságig terjed. Ezen túl a gabonahalmazok spektrálisan homogénnek tekinthetők és jól elkülöníthetők. A keveredési mintázatok pontos feltérképezése nemcsak a tudományos megértést segíti, hanem közvetlen ipari jelentőséggel is bír: lehetővé teszi a kitárolási veszteségek csökkentését, a szeparációs folyamatok hatékonyabb tervezését, valamint az élelmiszerlánc nyomonkövethetőségének biztosítását. A spektrofotometriás módszer alkalmas mind a kalibrációs modellek kidolgozására, mind a gabonák raktári keveredések térbeli lokalizálására. Ugyanakkor a homogén spektrális profilú tételek elkülönítéséhez további analitikai fejlesztések – például célzott hullámhossztartományok, NIR-spektroszkópia vagy kémiai markerek – integrálása szükséges. Az eredmények egyértelműen igazolják, hogy a színképelemzés hozzájárulhat a fenntartható tárolási stratégiákhoz és a gazdasági veszteségek mérsékléséhez. A spektrometriás vizsgálatok hatékonysága eltérő spektrális tulajdonságú gabonafajták esetében igazolt, ugyanakkor homogén spektrális profilú tételek esetén a különbségek detektálása korlátozott. Célszerű lenne a módszert kiegészíteni további analitikai technikákkal (pl. NIR-spektroszkópia, fajtaspecifikus komponensek, digitális képfeldolgozás), amelyek növelhetik a fajtaszeparáció érzékenységét. Az eredmények alapján a gabonák esetében kb. 100-120 cm-es keveredési határzóna figyelembevétele javasolt. Ez lehetővé teszi a veszteségek csökkentését, valamint a minőségi homogenitás biztosítását a további feldolgozás előtt. Célszerű lenne a módszert integrálni az ipari minőségbiztosítási rendszerekbe, ahol objektív és gyors eszközként szolgálhat a gabonatételek ellenőrzésében. További vizsgálatok indokoltak a spektrofotometriás és más optikai vagy molekuláris módszerek kombinálására, amelyek még pontosabb eredményeket nyújthatnak a spektrálisan hasonló gabonafajták elkülönítésében.

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Methodology Based on Colorimetry for the Separation of Wheat Varieties in Storage and the Determination of Mixing

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ABSTRACT

Traceability of food products, particularly cereals, is crucial to ensure food safety and quality control throughout the food supply chain. One of the major challenges in grain storage is the accurate localisation and separation of different grain batches during storage and handling. Optical analytical techniques, including colour analysis and near-infrared spectroscopy, offer promising tools for addressing these challenges. This study aimed to investigate the applicability of the CIELAB colour measurement system for quantifying the mixing ratios of wheat varieties during storage. Special attention was given to the combined colour parameter HUE × C*, which was used as an indicator to estimate the proportion of different wheat varieties in mixed samples. Controlled mixtures of wheat varieties with distinct kernel colours were prepared and analysed using a HunterLab ColorFlex reflectance colorimeter equipped with a D65 light source. Each sample was measured in ten repetitions to ensure measurement reliability. Based on calibration curves established from standard mixtures, the HUE × C* index showed a strong relationship with the mixing ratio of wheat varieties. The method allowed for the objective evaluation of colour differences and enabled the estimation of mixing proportions in stored grain batches. Storage experiments conducted between 2021 and 2023 demonstrated that grain mixing occurs within a limited spatial zone, and beyond approximately 100-120 cm, the grain batches become spectrally distinguishable and can be considered homogeneous. The results indicate that colorimetric analysis can serve as an effective and reliable tool for monitoring grain batch separation and identifying mixing zones in flat storage systems. The proposed method provides valuable support for improving traceability, optimising storage management, and enhancing quality control in cereal storage systems.

Keywords: grain quality, grain storage, CIELAB colour system, colorimetry, traceability, wheat mixing

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Digital Technologies in Agricultural Supply Chains in Central Africa: A Scoping Review of Equity, Resilience, and Adoption Barriers

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ABSTRACT

Digital technologies are increasingly reshaping agricultural supply chains by improving access to information, financial services, and markets. However, their role in fostering equity and resilience among smallholder farmers in Central Africa remains unclear. This scoping review examines the application of digital technologies in agricultural supply chains in the region and assesses their implications for these outcomes. Following the PRISMA extension for scoping reviews, a systematic search was conducted across Scopus, Web of Science, and Google Scholar for publications from 2015 to 2025 using keywords related to digital agriculture, agricultural supply chains, equity, resilience, and Central Africa. After removing duplicates, 139 unique records were screened. Of these, the 100 most relevant studies were assessed for full-text eligibility based on predefined inclusion criteria. Seven studies published between 2016 and 2024 were ultimately included in the analysis. The findings show that mobile-based technologies and communication platforms dominate digital agriculture initiatives in Central Africa. Key tools identified include SMS-based services, the e-Soko market pricing system, digital extension platforms such as CamAgro and the Twigire Muhinzi model, mobile financial services (mobile money), climate information services, and traditional communication channels such as radio, television, and mobile phones. These technologies improve farmers' access to market information, extension support, and climate-related knowledge. Yet adoption remains limited by weak digital infrastructure, low digital literacy, high costs, and persistent urban-rural digital divides. The review indicates that these accessible digital tools may contribute to greater equity and resilience in agricultural supply chains by enhancing information access, financial inclusion, and climate adaptation. Realising this potential will require substantial investments in rural digital infrastructure, targeted capacity-building programmes, and policies that address structural digital inequalities in Central African agricultural systems.

Keywords: digital agriculture, agricultural supply chains, equity, resilience, digital barriers

1. INTRODUCTION

Digital transformation has become an important driver of agricultural development in the global economy, particularly in regions characterised by structural vulnerabilities such as Central Africa. Agriculture remains a key sector across African economies, employing a large share of the workforce and contributing significantly to national GDP (Abbasi et al., 2022). Despite its importance, the sector continues to face persistent structural challenges, including fragmented supply chains, limited market access, weak infrastructure, and increasing climate-related disruptions. These factors constrain productivity and threaten the long-term resilience and equitable development of agricultural systems in the region.

In recent years, digital innovations have been increasingly promoted as tools to address these challenges and improve the efficiency of agricultural supply chains. Technologies such as mobile platforms, artificial intelligence (AI), blockchain, the Internet of Things (IoT), and digital financial services have been identified as mechanisms to enhance transparency, offer reliable data management capabilities, improve information flows, and facilitate market access for farmers (Krishnan & Banga, 2020; Bahn et al., 2021; Bertalan et al., 2023). Studies also highlight the potential of digital technologies to strengthen adaptive capacity and support more resilient agri-food systems, particularly in contexts affected by climate variability, market volatility, and geopolitical disruptions (Anbumozhi et al., 2021; Belhadi et al., 2024; Gao & Gao, 2024).

Beyond productivity improvements, digitalisation is increasingly linked to broader development objectives, including fairness, equity, and inclusion within agricultural supply chains. Fairness refers to the just distribution of resources, opportunities, and benefits among supply chain actors. At the same time, equity emphasises the need to address structural disadvantages faced by specific groups such as smallholder farmers, women, and rural communities (Samoggia & Beyhan, 2022). Emerging technologies can support these goals by improving traceability, transparency, and access to information, thereby strengthening farmers' bargaining position and reducing information asymmetries in agricultural supply chains (Charlebois et al., 2024; Gikunda, 2024; Bertalan et al., 2024). In addition, evidence from short food supply chain initiatives, particularly community-supported agriculture, suggests that closer producer-consumer linkages can reduce information asymmetry and enhance transparency and fairness in agricultural supply chains (Kacz et al., 2019).

However, the benefits of digital transformation are not evenly distributed. A major challenge across many African countries is the persistent digital divide, reflected in unequal access to digital infrastructure, connectivity, devices, and digital skills (Abdulai, 2022; Mhlanga & Ndhlovu, 2023; Uyeh et al., 2023). In contexts where digital adoption remains uneven, technological innovation may unintentionally reinforce existing inequalities rather than reduce them. This issue is particularly relevant in Central Africa, where smallholder farmers and marginalised communities often face limited access to digital resources and institutional support (Nchofoung et al., 2022). Moreover, the increasing role of private-sector actors in digital agriculture raises concerns about governance, data ownership, and power asymmetries within agri-food systems (Arthur et al., 2024).

Resilience has therefore become a central concept in discussions of digital agricultural transformation. In agricultural supply chains, resilience refers to the capacity of systems and actors to anticipate, absorb, adapt to, and recover from shocks such as climate events, market disruptions, or pandemics. The COVID-19 pandemic highlighted the vulnerability of conventional agricultural supply chains and demonstrated the potential of digital technologies to maintain market connections, support farmer livelihoods, and facilitate information exchange during crises

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(Kumari et al., 2023; Njuguna et al., 2025; Tossou et al., 2024; Quayson & Osei, 2020). Nevertheless, resilience outcomes depend not only on technological availability but also on social, institutional, and governance factors that shape how digital tools are accessed and used (Vidanagamachchi et al., 2025; Xue et al., 2025).
Although a growing body of literature examines digital agriculture globally, relatively little research has explored how digital transformation interacts with equity and resilience in agricultural supply chains in Central Africa. Existing findings are often fragmented, focusing on specific technologies or individual countries rather than offering a comprehensive regional perspective. This gap limits policymakers' and researchers' ability to understand the broader implications of digitalisation for inclusive and resilient agricultural development in the region.
To address this gap, this study conducts a scoping review of digitalisation in agricultural supply chains in Central Africa. The review focuses on peer-reviewed studies published between 2015 and 2025, identified through systematic database searches. By synthesising the available literature, the study aims to examine how digital technologies are being applied within agricultural supply chains in the region and to assess their implications for equity and resilience among smallholder farmers. Specifically, it seeks to identify the digital tools applied, analyse the geographic distribution of existing studies, and assess how these technologies influence fair access to information, markets, and financial services. The review addresses the following research questions:

- What digital technologies are currently used in agricultural supply chains in Central Africa?
- How do these technologies contribute to equity and resilience among farmers?
- What barriers limit the adoption of digital agricultural technologies in the region?

2. METHODOLOGY

This study employed a scoping review methodology guided by the PRISMA extension for scoping reviews to systematically analyse the literature on digital transformation, equity, and resilience in Central African agriculture (Page et al., 2021; Tricco et al., 2018). A multidatabase search strategy was conducted across Scopus, Web of Science, and Google Scholar using a structured Boolean search that combined five thematic clusters: "digital agriculture", "agricultural supply chains", "equity" or "fairness", "resilience", and "Central Africa".
The search terms used in databases were: ("digital agriculture" OR "smart farming" OR "precision agriculture" OR ICT OR digitalisation) AND ("agricultural supply chain" OR "food supply chain" OR agribusiness) AND (equity OR fairness OR inclusion OR "social justice") AND (resilience OR "supply chain resilience") AND ("Central Africa" OR Cameroon OR Chad OR "Central African Republic" OR Congo OR Gabon OR Rawand).
The initial search identified 600 records. After removing 461 duplicate records, 139 unique studies were screened based on titles and abstracts (*Figure 1*). The 100 most relevant articles (as determined by the authors) were assessed for full-text eligibility using predefined inclusion criteria. Studies were included if they were published in English between 2015 and 2025, addressed digital technologies in agriculture, and examined equity, resilience, or adoption barriers within Central African contexts.
Following the screening process, seven studies met the final inclusion criteria and were retained for thematic analysis. Data extraction was conducted using Zotero and Microsoft Excel, enabling systematic coding of bibliographic information, technology categories, geographic focus, and adoption barriers, including equity and resilience dimensions (Brennan, 2016).

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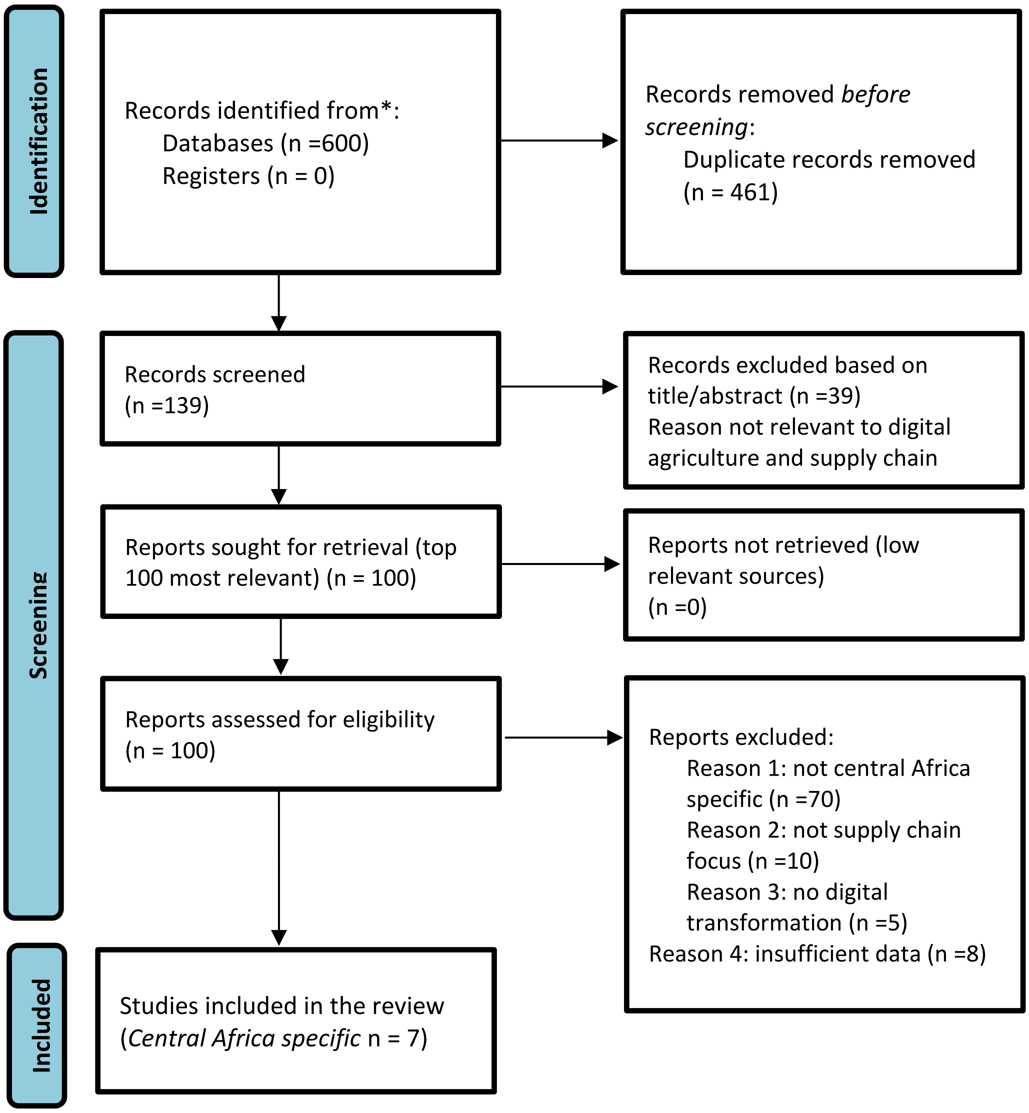

Figure 1: PRISMA flow diagram of the study selection process

Source: Adapted from Page et al. (2021).

3. RESULTS

3.1 Digital technologies and their contributions to equity and resilience in Central Africa

Table 1 presents the digital tools identified in the seven reviewed studies and their contributions to equity and resilience outcomes in agricultural supply chains in Central Africa. The results indicate that the technologies used in the region are primarily low-cost communication-based tools. These include digital platforms, mobile financial services, digital extension systems, radio and mobile phone communication technologies, climate information services, and SMS-based mobile platforms. These technologies play an important role in improving farmers' access to agricultural information, markets, and financial services, thereby supporting more equitable participation in agricultural systems. At the same time, several of these tools, particularly climate information

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services, digital extension services, and mobile market platforms, enhance farmers' capacity to respond to climate variability, market fluctuations, and production risks. The table suggests that the currently adopted technologies support information access, financial inclusion, and climate adaptation – key dimensions that may strengthen both equity and resilience in agricultural supply chains in Central Africa.

Table 1 also shows the publication years of the reviewed studies, indicating a gradual increase in research on digital technologies in agricultural systems over the past decade. The earliest study included in the review was published in 2016, followed by studies in 2017, 2019, 2021, 2022, and 2024. Although the search spanned 2015 to 2025, this pattern suggests growing academic and policy interest in the role of digital technologies for information dissemination, financial inclusion, and climate services.

In terms of geographic distribution, the studies are concentrated in a limited number of countries within Central Africa. Rwanda accounted for most of the identified studies, while only one study each was found for Cameroon and the Democratic Republic of Congo. Other countries in the Central African region, including Chad, the Central African Republic, Gabon, and Equatorial Guinea, were not represented in the reviewed literature (Manzoor & Wei, 2025). This uneven distribution, with five of the seven studies originating from Rwanda (often classified as East Africa), highlights a significant geographic research gap and indicates that empirical evidence on digitalisation in agricultural supply chains remains limited across much of Central Africa (see *Table 1*).

Table 1. Digital technologies and their contributions to equity and resilience in Central Africa

Author(s)	Year	Country	Technology category	Equity contributions	Resilience contributions
Mbairanodji et al.	(2024)	Cameroon	Digital platforms (CamAgro portal), decision support systems	Improves farmers' access to agricultural information, advisory services, and market linkages, supporting more inclusive participation in value chains.	Helps farmers make better production and management decisions through data and advisory tools, improving farm productivity and adaptive capacity.
Solo Zerbo & Pohl	(2022)	Democratic Republic of the Congo	Mobile financial services (mobile money)	Expands financial inclusion by enabling farmers to receive payments, transfer money, and access financial services without formal banking systems	Strengthens farmers' financial capacity to cope with shocks and invest in inputs, improving economic resilience
Neza et al.	(2021)	Rwanda	Digital extension services (Twigire Muhinzi model)	Enhances equitable access to agricultural knowledge through national extension	Builds farmers' technical skills and knowledge, improving their ability to respond

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				systems and farmer-to-farmer learning approaches	to climate and production risks
Nahayo et al.	(2019)	Rwanda	Communication tools (radio, television, mobile phones)	Provides low-cost, widely accessible channels for disseminating agricultural information to rural, low-literacy farmers	Delivers timely farming advice and climate information that supports adaptive decision-making
Clarkson et al.	(2017)	Rwanda	Climate information services (digital and mobile training)	Improves farmers' access to climate knowledge and agricultural advisory services	Helps farmers adjust planting schedules and crop management in response to climate forecasts, reducing climate-related risks.
Coulibaly et al.	(2017)	Rwanda	Climate information services (participatory digital tools, radio)	Encourages inclusive participation by integrating farmer knowledge with digital climate information systems	Supports collective learning and climate risk management strategies among farming communities
Nyasimi et al.	(2016)	Rwanda	Mobile platforms (SMS, e-Soko pricing system), radio	Improves market transparency by providing farmers with real-time price information and market access	Enables farmers to respond to market fluctuations and make informed selling decisions, strengthening livelihood stability

Source: The author

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3.2 Digital barriers to technology adoption in Central Africa

The reviewed studies highlighted several barriers to the adoption of digital technologies in agricultural supply chains across Central Africa, including limited digital and communication infrastructure in rural areas (Choruma et al., 2024). Many farming communities still face unreliable internet connectivity, weak mobile network coverage, limited access to electricity, and low digital literacy, all of which restrict the use of digital platforms and mobile-based services. These infrastructural challenges particularly affect remote rural farmers who rely heavily on basic communication tools such as radio and mobile phones to access agricultural extension services (Mbairanodji, 2024), as shown in *Figure 2*.

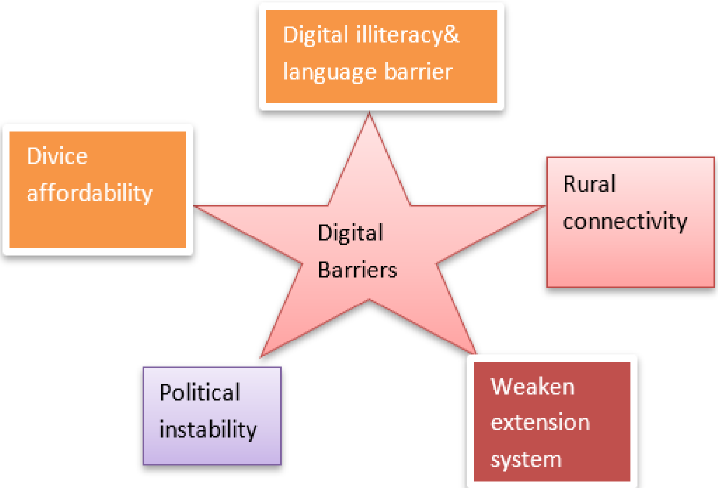

Figure 2. Barriers to the adoption of digital technologies in agricultural supply chains in Central Africa

Source: The author

4. DISCUSSION

4.1. Implications for equity and resilience in the agricultural supply chain in Central Africa

This review found that digital technologies may improve equity and resilience in agricultural supply chains in Central Africa. Mobile financial services and digital payment platforms appear to play a particularly important role in expanding financial inclusion for farmers with limited access to formal banking systems and in providing climate information. This finding is consistent with previous studies (Mwangakala et al., 2023; Nahayo et al., 2019; Ndhlovu, 2026; Nurudeen Michael & Eunice Ogunsola, 2023; Smidt & Jokonya, 2022). By facilitating access to extension services, savings mechanisms, and digital transactions, these tools allow farmers to optimise the use of agricultural inputs, manage financial risks, and stabilise their livelihoods more equitably.

Digital information platforms also contribute to resilience by improving farmers' access to timely information on weather conditions, market prices, and agricultural practices. This information can support better decision-making, improve climate adaptation strategies, and reduce the vulnerability of smallholder farmers to environmental and economic shocks (Apicella, 2025; Sun et al., 2026). In this way, digital technologies can strengthen the adaptive capacity of agricultural systems and improve the resilience of agricultural supply chains.

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These findings suggest that social and institutional factors strongly influence the relationship between digital agriculture and resilience. Trust networks, collective farmer organisations, and local governance structures can significantly affect the adoption and effective use of digital technologies (Razak et al., 2024; Zindi, 2026).

4.2 Technological patterns in digital agricultural supply chains in Central Africa

The results of this review indicate that the widespread use of mobile-based technologies and digital platforms primarily characterises digital agriculture in Central Africa. In contrast, more advanced technologies remain limited in their application. This pattern is also common in many other African contexts. The dominance of mobile solutions reflects the region's structural realities, where mobile phones are often the most accessible digital tools for farmers. Applications such as SMS-based advisory services, mobile money systems, and digital marketplaces play an important role in facilitating market access, improving price transparency, and enabling financial transactions within agricultural supply chains (Choruma et al., 2024).

The results further show that advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain are increasingly discussed in the literature; however, their practical implementation remains limited within the region. In many countries, these technologies are primarily applied in experimental projects, pilot programmes, or research initiatives rather than being widely integrated into everyday farming practices (Apicella, 2025; Fernando et al., 2024; Yuan et al., 2025). As mentioned in the previous section, this pattern of digital technology use in Central Africa reflects the infrastructural and institutional barriers identified in the results, including limited digital infrastructure, technical capacity, and financial resources. Bridging this technological gap may require targeted investments in digital infrastructure, training, and institutional support systems that enable smallholder farmers to access and effectively utilise advanced technologies.

4.3 Structural barriers to digital adoption in Central Africa

The synthesis of the reviewed studies identifies several interconnected barriers that continue to limit the expansion of digital agriculture in Central Africa. These barriers operate across infrastructural, economic, institutional, and human capacity dimensions (Mazwane et al., 2022; Mhlanga & Ndhlovu, 2023; Smidt & Jokonya, 2022). Infrastructure limitations remain one of the most significant challenges. Many rural areas in Central Africa continue to experience unreliable internet connectivity, limited electricity supply, and inadequate telecommunications infrastructure. These structural constraints significantly restrict farmers' ability to access and utilise digital agricultural services.

Human capacity constraints represent another major barrier. The results emphasised that farmers lack the digital skills required to navigate digital platforms effectively. Low levels of digital literacy, limited access to training opportunities, and language barriers further reduce farmers' ability to engage with digital technologies; this finding aligns with that of Mazwane et al. (2024).

Economic factors also play a critical role. The cost of smartphones, internet data packages, and subscription-based digital services can be a huge burden for smallholder farmers with limited financial resources (Choruma et al., 2024). As a result, even where digital tools are technically available, affordability remains a key determinant of adoption. Consequently, these findings suggest the need to develop and integrate strategies that combine technological innovation with investments in infrastructure, capacity building, and inclusive policy frameworks.

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5. LIMITATIONS, RESEARCH GAPS, AND DIRECTIONS FOR FUTURE RESEARCH

The review is limited by the lack of information on the digital regulatory framework and issues of digital scalability in Central African countries (Aranguří et al., 2025; Das & Kamal, 2025; McFadden et al., 2022). The use of more standardised evaluation frameworks in future studies would improve the comparability and reliability of research in this area. A significant research gap exists in the geographic coverage of the literature. Empirical studies focusing specifically on Central Africa remain scarce. Although the present review included studies from the region, most are from Rwanda. Most research on digital agriculture in Africa has focused on other regions, particularly East Africa (Hackfort, 2021; Manzoor & Wei, 2025; Porciello et al., 2022). As a result, there is limited evidence on how digital technologies function within the specific institutional, infrastructural, and socio-economic conditions of Central African countries. Further research is needed to determine whether early adoption leads to sustainable digital use and long-term improvements in farmers' livelihoods and supply chain performance.

6. CONCLUSION

The main goal of the current review was to explore the role of digital technologies in agricultural supply chains in Central Africa, with a particular focus on their contributions to equity and resilience. The study followed the PRISMA extension for scoping reviews to identify relevant peer-reviewed articles. The findings showed that accessible, low-cost technologies largely shape the digital landscape in Central Africa, particularly Rwanda. Tools such as digital platforms (e.g., the CamAgro portal), mobile financial services, digital extension systems, communication technologies (including radio and mobile phones), climate information services, and SMS-based market platforms (e.g., e-Soko) were the most used technologies identified in the reviewed studies. These technologies support information dissemination, market access, financial transactions, and farmer training.

The evidence suggests that these technologies have the potential to enhance equity and fairness within agricultural supply chains by improving farmers' access to markets, financial services, and agricultural knowledge (Nchofoung et al., 2022). Mobile financial services and digital extension platforms contribute to more inclusive participation by enabling smallholder farmers, women, and rural communities to access resources that were previously difficult to obtain. In addition, climate information services and communication technologies strengthen farmers' adaptive capacity, thereby supporting resilience to climate variability and market shocks (Nahayo et al., 2019).

However, the findings also reveal that the benefits of digitalisation are unevenly distributed. Persistent digital divides—driven by limited infrastructure, low digital literacy, and economic constraints—continue to act as barriers to access to digital technology for many smallholder farmers in Central Africa (Yousif et al., 2025). Addressing these structural barriers through targeted investments in infrastructure, capacity-building, and inclusive digital policy frameworks is an important component of ensuring that digital transformation contributes to more sustainable, equitable, and resilient agricultural practices in Central Africa (Vuvor et al., 2025).

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Digitális technológiák a közép-afrikai mezőgazdasági ellátási láncokban: átfogó szakirodalom-áttekintés a méltányosságról, a rezilienciáról és a bevezetést gátló tényezőkről

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ÖSSZEFOGLALÁS

A digitális technológiák egyre inkább átalakítják a mezőgazdasági ellátási láncokat az információhoz, a pénzügyi szolgáltatásokhoz és a piacokhoz való hozzáférés javításával. Ugyanakkor az egyenlőség és a reziliencia előmozdításában játszott szerepük a kisbirtokos gazdálkodók körében Közép-Afrikában továbbra is tisztázatlan. Az átfogó szakirodalmi áttekintés vizsgálja a digitális technológiák alkalmazását a mezőgazdasági ellátási láncokban a régióban, és értékeli ezeknek az eredményeknek a következményeit. Az átfogó szakirodalmi áttekintés PRISMA kiterjesztését követve szisztematikus keresés zajlott a Scopus, a Web of Science és a Google Scholar adatbázisokban 2015 és 2025 közötti publikációkra, a digitális mezőgazdaság, mezőgazdasági ellátási láncok, egyenlőség, reziliencia és Közép-Afrika kulcsszavak használatával. A duplikátumok eltávolítása után 139 egyedi rekord került leszűrésre. Ezek közül a 100 legrelevánsabb tanulmányt teljes szöveges értékelésre jelöltük ki, előre meghatározott befogadási kritériumok alapján. Végül hét, 2016 és 2024 között megjelent tanulmány került bevonásra az elemzésbe. Az eredmények azt mutatják, hogy a mobilalapú technológiák és kommunikációs platformok dominálják a digitális mezőgazdasági kezdeményezéseket Közép-Afrikában. A legfontosabb azonosított eszközök közé tartoznak az SMS-alapú szolgáltatások, az e-Soko piaci árképző rendszer, a CamAgro és a Twigire Muhinzi modellhez hasonló digitális kiterjesztési platformok, a mobil pénzügyi szolgáltatások (mobilpénz), az éghajlati információs szolgáltatások, valamint a hagyományos kommunikációs csatornák, mint a rádió, a televízió és a mobiltelefonok. Ezek a technológiák javítják a gazdálkodók hozzáférését a piaci információkhoz, a kiterjesztési támogatáshoz és az éghajlattal kapcsolatos ismeretekhez. Az adoptációt azonban továbbra is korlátozza a gyenge digitális infrastruktúra, az alacsony digitális írástudás, a magas költségek és a városi-vidéki digitális szakadékok. Az elemzés szerint ezek az elérhető digitális eszközök hozzájárulhatnak az egyenlőség és a reziliencia növekedéséhez a mezőgazdasági ellátási láncokban az információhoz való hozzáférés, a pénzügyi befogadás és az éghajlati alkalmazkodás javításával. E potenciál kihasználásához jelentős beruházások szükségesek a vidéki digitális infrastruktúrába, célzott kapacitásépítő programokba, valamint olyan politikákba, amelyek kezelik a digitális egyenlőtlenségeket a közép-afrikai mezőgazdasági rendszerekben.

Kulcsszavak: digitális mezőgazdaság, mezőgazdasági ellátási láncok, egyenlőség, reziliencia, adaptációs akadályok

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Barriers to Integrating the Circular Economic Model Into the Municipal Solid Waste Management System: Systematic Review

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ABSTRACT

The circular economy is considered a key tool for sustainable development, capable of transforming the traditional economic model, operating it as a closed-loop system, and utilizing "waste" as a resource for the production of new products. The research results systematically discuss the theory, including the problems and obstacles to the integration of the circular economy model into the municipal solid waste management system. It structures the problems and obstacles found in the literature from a dual perspective that complicate, hinder, or even delay the integration. The study did so by reviewing 116 scientific articles from five perspectives–economic, social, environmental, technological, and policy–considering the stages of effective municipal solid waste management: waste generation; collection, sorting; reuse, recycling, recovery from waste; final waste disposal. The systematic review showed that, in addition to numerous economic, social, and environmental obstacles to the integration of the circular economy, technological and political obstacles must also be taken into account. However, to overcome all of these, an effective waste management system must first be operated in each country. To do this, for each stage of municipal solid waste management, the problems and obstacles identified in the study for the given country should first be overcome and resolved.
Keywords: circular economy, municipal solid waste management, barriers, global, systematic review

1. INTRODUCTION AND LITERATURE REVIEW

In 2020, 2.24 billion tonnes of solid waste were generated in the world, i.e., an average of 0.79 kg of waste was produced per day by an inhabitant of the Earth (Chen et al., 2023; Jayasinghe et al., 2023), which has decreased to 2.1 billion tons according to the latest data (United Nations, 2024b). This figure is predicted to increase by 70 % by 2050 (World Bank, 2018) and reach 3.8 billion tonnes, which represents an exponential increase in waste production (Etim, 2024) unless we act urgently.

Inadequate waste management (WM) is a growing global problem with serious economic, environmental, and social consequences (environmental damage, public health hazards) that we have to face. Municipal solid waste management (MSWM) is a critical activity worldwide in terms of sustainability, but it faces challenges in waste generation, collection, treatment, and disposal.
Recognizing the significant challenges posed by inadequate WM, international organizations are increasingly advocating for immediate, comprehensive waste management measures (Abe & Didham, 2013). However, this requires coordinated efforts by communities at all levels (United Nations, 2024a; Lama, 2024).
The European Commission (2023) also emphasized that national authorities must step up their political efforts and accelerate national action, as even the member states of the European Union (EU) are still far from their 2025 goals. The basis of the EU's WM and policy, as well as its legislation, is the waste hierarchy, as documented in the EU framework directive on waste (Directive 2008/98/EC). One of the main goals of this is to minimize the harmful effects of waste generation and treatment, while the other is to improve the efficiency of resources.
In the literature, the concept of the circular economy (CE) is widely debated. The model now carries its ecological principles, as it was closely linked to reuse and recycling (Kirchherr et al, 2023). The concept of the CE changes the traditional "take-make-waste" management model. This approach envisages a restorative and regenerative approach to economic activities and industrial processes. The aim of the model is to try to keep resources, materials and products in circulation for as long as possible using a system-oriented approach; therefore, durability, repairability and longevity are prioritized during the design of products and systems (Bakker et al., 2021; Tukker, 2015). If the given product reaches the end of its life cycle, the component materials are returned to the production cycle, reducing the amount of waste and minimizing the need for new raw materials, i.e., reuse prevents them from becoming waste (Den Hollander et al., 2017; Morseletto, 2020; Zink & Geyer, 2017). The aim of the concept is therefore to recover waste as a resource for the production of new products and values at the end of their life cycle, thereby closing the loop in the cycle (Di Maio & Rem, 2015; Popović & Radivojević, 2022). CE emphasizes resource efficiency at every stage of the product's life cycle, whether through effective design, minimizing resource waste in production, or responsible consumption (Geisendorf & Pietrulla, 2018; Hapuwatte & Jawahir, 2021; Mestre & Cooper, 2017). CE, when designed thoughtfully and inclusively, can sustainably protect the environment, strengthen the economy, and advance social justice (EPA, 2024).
The CE system diagram, also known as the butterfly diagram, illustrates the continuous flow of materials in CE, which has two main cycles. In the technical cycle, products and materials are kept in flow and circulation through processes, such as repair and remanufacturing, reuse, and recycling. During the biological cycle, nutrients from biodegradable materials are returned to nature to regenerate it (Ellen MacArthur Foundation, 2021).
Knowing all this, it can be said that the application of the CE approach has many economic (increasing employment, job creation, economic growth, promoting innovation) (Horbach et al., 2015; Mhatre et al., 2021; Schroeder et al., 2019; Suchek et al., 2021), social (minimizing inequalities, promoting well-being, encouraging cooperation) (Mies and Gold, 2021; Schröder et al., 2020; Velenturf & Purnell, 2021) and environmental (reducing pollution levels, resource load) (Quina et al., 2018; Xavier et al., 2021) advantages.
However, many cultural, social, and environmental barriers of CE have also been identified. One such cultural barrier is the hesitant corporate culture (Kirchherr et al., 2017). Challenges related to quality and availability appear as social constraints for secondary materials (Hsu et al., 2022).

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Regarding the environmental aspect, there is a lack of information on the benefits of circular systems for the natural environment (Harris et al., 2021).

Based on the above ideas, the following research question was formulated: What are the problems and barriers of integrating the CE model into MSWM? A systematic literature review method will be used to answer this question. Nowadays, specialized literature databases have grown significantly across most scientific fields, making it hard to keep up with the latest research results. Systematic literature analysis has become an increasingly widespread method and a key tool for scientific research (Kartali, 2023).

The result of this research systematically discusses the theory, including the problems and barriers to integrating the CE model into the MSWM system. From a dual point of view, it structures the problems and barriers found in the literature that make it difficult, hinder, or even delay the integration of the circular economic model into MSWM. By summarizing the results, findings, and possible recommendations, the aim of the study is to help integrate the concept and practice of CE into MSWM. The study can also function as a forward-looking analysis that identifies past and present shortcomings and tries to make recommendations that can lay the foundation for future research and development of sustainable concrete practices on the subject.

2. MATERIALS AND METHODS

A systematic literature review (SLR) is defined by Fink (2014) as a method that uses a structured and documented procedure to review, evaluate, and synthesize the available scientific literature for a specific research question or topic. According to Denyer and Tranfield (2009), a systematic review is a specific methodology that, in itself, is an independent research project and explores a clearly defined question, usually arising from a practical problem, with the help of existing studies. The SLR uses a scientific methodology that collects and analyzes all existing research results related to a specific question, and then seeks to answer professional questions by evaluating them through well-defined steps (Kamarási & Mogyorósy, 2015). The method, therefore, identifies, selects, and critically evaluates research in order to answer a clearly formulated question (Dewey & Drahota, 2016).

SLR can moderate the influence of heuristics (Spector & Thompson, 1991; Tranfield et al., 2003), thereby more specifically revealing and explaining the current position of science regarding the examined issue and problem (Rousseau et al., 2008). Traditional literature methods are often criticized for being highly subjective (Petticrew & Roberts, 2006); however, the search, selection, and processing frameworks set by this method ensure a certain level of objectivity and reproducibility (Gough & Thomas, 2012). SLR also plays an important role in the development of Supply Chain Management (SCM) knowledge (Moraes et al., 2020).

During the literature review, the author of the study searched five academic research databases–Science Direct, SpringerLink, Wiley Online Library, Web of Science, and JSTOR Journals–for scientific journal articles in English. A special search was conducted for the period between January 2010 and October 2024 using the keywords "municipal solid waste management" OR "MSWM" AND "circular economy" that were found in the abstract or title.

Applying the special filters, the keywords were found in a total of 1100 articles in the listed databases. These scientific works provided the basic set for narrowing down the publications to be processed in the study. After that, the author of the study filtered out the duplicates, leaving only documents with open and free access in the set of scientific journal articles, resulting in 516 articles. A further narrowing down was done based on the scientific classification of the articles

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(environmental, social, business and management, and sustainable science), title, and content of the abstract. Based on these, the author of the study selected 202 studies for full reading. After fully familiarizing with the studies, the author selected articles relevant to answering the research question, based on which the author could obtain an answer to the research question. Finally, the study reduced the set to a total of 116 relevant articles from which the problems and barriers to the integration of the CE model into MSWM could be identified and used for further analysis and grouping of the identified factors. The results of the four-round search process are shown in *Table 1*.

Table 1: Results of a four-round search process and narrowing down

Databases	**Number of filter results**			
	Round 1: Based on a search with keywords in the title, keywords, abstract	**Round 2: Duplication with filtering, based on open access/free**	**Round 3: Academic field classification based on abstract content**	**Round 4: Based on reading the full announcement**
JSTOR Journals	117	10	3	1
Science Direct	119	31	21	15
SpingerLink	39	8	6	4
Web of Science	817	464	169	96
Wiley Online Library	8	3	3	0
TOTAL	1100	516	202	116

The PRISMA flow diagram *(Figure 1)* depicts the flow of information through the different phases of a systematic review. It maps out the number of records identified, included and excluded, and the reasons for exclusions.

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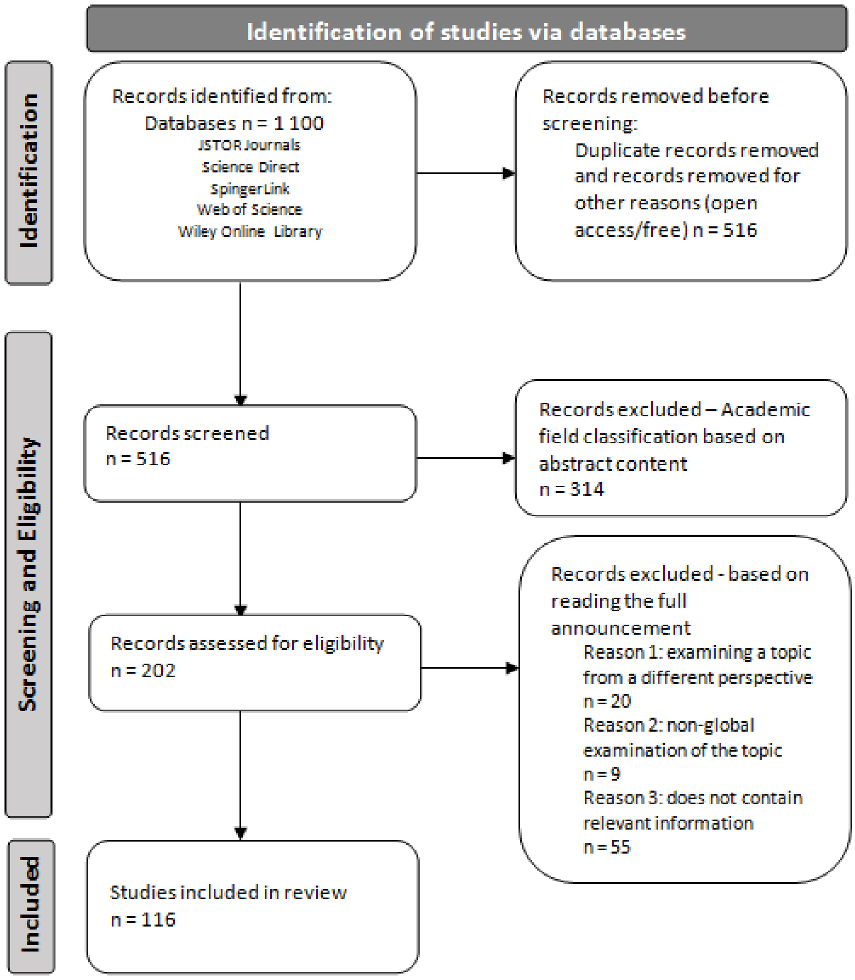

Figure 1: PRISMA flow diagram

As shown in *Figure 2*, most studies in the mentioned topics were published in 2020. It is worth highlighting that journals in other subjects (e.g., earth, law, geography, engineering, energy, economics, ecology, materials science, etc.) also deal with the research topic. This can be beneficial in terms of a holistic and broad presentation of research results. Due to the multidisciplinarity of the chosen research topic, it is advisable to process the results of several scientific fields when preparing the systematic literature review, when grouping and presenting the results.

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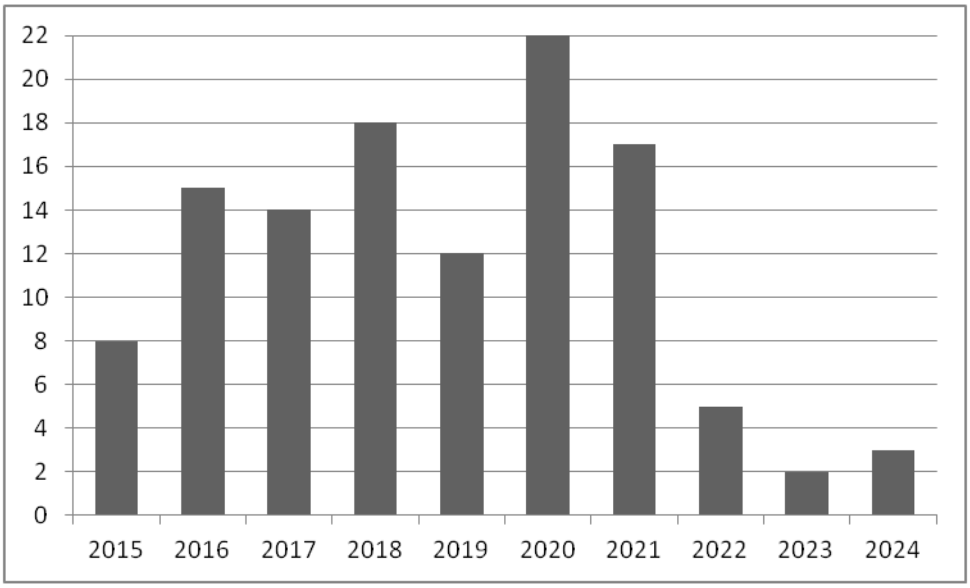

Figure 2: Distribution of the publication years of selected studies

3. RESULTS

After processing the articles, based on the qualitative content analysis of the selected 116 studies, the study organized the results based on three main aspects, in line with the basic framework of the CE that addresses three central pillars: economic development (economic aspects), social upliftment (social aspects), and a healthy environment (environmental aspects). However, based on the systematic review, the author of the study believed that it was appropriate to examine the topic from two additional perspectives – political and technological – (*Table 2*); therefore, these aspects were also added to the systematization.

Effective solid waste management (SWM) includes several stages: *(1)* collection and sorting of waste, (2) reuse and recycling of waste, (3) recovery from waste, (4) final disposal of waste. Each stage has its own significance in the efficiency of the MSWM system (Sondh et al., 2024), so the author of the study investigated the research question according to the stages. However, as a starting point, the author of the study thought that the generation of municipal solid waste (MSW) should also be dealt with, since the amount, quality, and nature of the generated waste determine the entire process of waste management. Of the identified stages of effective solid waste management, the stages of waste reuse and recycling, and the stage of recovery from waste were combined to categorize the results because these stages result in the usability of secondary products derived from waste.

Table 2 summarizes the problems and obstacles to integrating the CE model into the municipal solid waste management system from economic, social, environmental, technological, and political perspectives. The results show that the problems and obstacles related to municipal solid waste generation are presented in the literature primarily from an economic and political perspective. Technological and social obstacles are typical during waste collection and sorting. Problems related to the reuse, recycling, and utilization of waste are largely social, technological, and political in nature. In the case of final waste disposal, environmental and technological problems and obstacles come to the fore.

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Table 2: Problems and barriers of the integration of CE model into MSWM system from an economic, social, environmental, technical political point of view

Framework of CE	
0. Generation	
Economic aspects	different economic situations of countries; complexity of waste management system; increase in production; other priorities competing for resources; lack of understanding of factors affecting waste management system; increasing burden on local government budgets
Social aspects	different social structures; resource waste; food waste; lack of awareness
Environmental aspects	resource constraints; resource waste; exponential growth of waste; waste varies in quantity, nature, quality, and composition by country, region, and space
Technological aspects	no information
Political aspects	increasing burden on local governments
1. Collection – sorting	
Economic aspects	complex task; lack of financial resources; disorganization; lack of responsible production; high operating and maintenance costs; lack of multilateral partnerships with other sectors
Social aspects	lack of knowledge about waste; lack of awareness to segregate waste; lack of public participation; insufficient and remoteness of recycling containers; length of collection time; lack of responsible consumption; lack of stakeholder cooperation, social inequalities; lack of integration of informal sector into MSWM system
Environmental aspects	lack of knowledge; low environmental awareness; waste heterogeneity; MSW is complex, complicated; dependence on primary raw materials; waste does not enter the recycling stream
Technological aspects	different SWCs; different logistics and operational activities; insufficient infrastructure; time constraints; poor collection route planning; lack of information on collection schedules; insufficient number and capacity of collection vehicles; lack of waste separation systems; insufficient number and spacing of separate waste collection containers; incorrect collection practices and transportation of waste fractions and bins; lack of segregation according to the source of waste generation
Political aspects	disorganization; limited ability of government to meet demand for MSWM services; lack of multilateral partnerships with other sectors; ineffective implementation of waste management policies; lack of state capacity to manage waste to the required extent
2. Treatment: reuse, recycling, recovery	
Economic aspects	complex, complicated capital-intensive task; lack of financial resources; high waste management costs, inefficient waste management protocol; lack of market demand for secondary raw materials; lack of financial strategies ensuring the financial viability of waste service providers; emerging supply chains;
Social aspects	scepticism about WtE or W2E; social inequalities; low awareness; NIMBY; lack of social recognition; social discrimination; lack of public awareness, stakeholder involvement; lack of communication of risk factors; poor public awareness; local community resistance to waste management; incomplete data collection and evaluation; ZWE position; value and potential of MSW not recognized; excessive consumption of primary materials
Environmental aspects	significant global footprint of SW production; different environmental conditions; other, non-environmental priorities; incomplete data collection and assessment; incomplete environmental knowledge; strict environmental regulations, legislation;
Technological aspects	WtE/W2E is not just about incineration; lack of technological knowledge; application of traditional waste management practices; lack of waste recovery systems; lack of understanding of factors affecting the waste management system; lack of adequate waste pre-treatment; maturity of technologies; implementation of waste management practices in an inadequate time and coverage; lack of waste management infrastructure; poor quality of waste management products

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Political aspects	lack of systematic national policies and legislation; implementation barriers, limited procedures for WtE/W2E technologies; limited recycling practices and policies; MSWM policy exists but is not implemented effectively; regulatory barriers to commercialization of new technologies; weak bureaucratic structures of MSWM institutions; shortcomings in MSWM governance; gap between MSWM policy and practices; limited control; ineffective policy regulatory framework
3. Disposal	
Economic aspects	lack of financial resources
Social aspects	lack of awareness; lack of skilled labor; lack of public acceptance of the establishment of landfills
Environmental aspects	“infinite” decomposition time; air pollution; water pollution; soil pollution; selection of landfill sites
Technological aspects	indiscriminate dumping, open dumping; mass, open burning; use of incorrect disposal procedures; lack of well-designed, equipped landfills; lack of technology; no recycling, utilization
Political aspects	lack of legislation

Countries face many MSWM challenges. This review emphasizes the effectiveness of the phases of the MSWM system based on the 4 Rs of CE framework–reduce, reuse, recycle, and recover–by highlighting and systematizing waste collection and sorting, reuse and recycling, extracting value from waste, and the importance of its utilization.
The analysis and evaluation of CE practices based on economic, social, and environmental aspects help monitor the development of sustainable WM. The three pillars must develop in harmony with each other for a stable and efficient WM model.
In the following, I will describe in detail the problems and barriers categorized from a dual point of view, as well as their effects and possible ways to remedy them.

4. DISCUSSION AND CONCLUSION

The circular economy is considered a key tool for sustainable development, which is capable of transforming the traditional economic model when it operates as a closed-loop system and utilizes “waste” as a resource for the production of new products.
This systematic review identified numerous problems and barriers to integrating the CE model into MSWM. The study did so by reviewing 116 scientific articles from five perspectives–economic, social, environmental, technological and policy–considering the stages of effective municipal solid waste management: waste generation; collection, sorting; reuse, recycling, recovery from waste; final waste disposal. The systematic review showed that, in addition to the numerous economic, social, and environmental barriers to the integration of the circular economy, technological and political barriers must also be considered. The literature presents the problems and obstacles related to the generation of municipal solid waste from an economic perspective. The most typical problems are: differences in countries' economic situations, increased production, and competing priorities for resources. Technological obstacles are common in waste collection and sorting; the most common are: insufficient infrastructure, time constraints, lack of waste separation systems, and lack of segregation according to the source of waste generation. Problems related to the reuse, recycling, and utilization of waste are also largely technological in nature, such as: lack of technological knowledge, lack of waste recovery systems, inadequate waste pretreatment, and inadequate timing and coverage for implementing waste management practices.

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Technological problems and obstacles also come to the fore in the case of final waste disposal, including: indiscriminate dumping and open dumping; lack of technology; and no recycling or utilization. However, to overcome all of these, an effective waste management system must first be in place in each country. To do this, for each stage of municipal solid waste management, the problems and obstacles identified in the study for the given country should first be overcome and resolved.
CE-controlled WM emphasizes environmental justice and thus provides an opportunity to effectively alleviate these problems and eliminate barriers. A CE-led waste management system has the potential to provide a structure that stabilizes and strengthens the economy, improves natural resource management, and protects individuals' human rights (Sondh et al., 2024).
Although many studies have investigated sustainable MSW approaches, there is a lack of holistic approaches to MSW monitoring and management at the global level (Das et al., 2019). However, achieving circularity requires a holistic system approach, which includes production, consumption, and WM (Bianchi & Cordella, 2023).
A sustainable production and consumption model requires businesses to change their production patterns, while at the same time focusing on involving consumers, who need economic opportunities to access affordable, sustainable products. Technological progress can facilitate the exploitation of economies of scale and experience, making sustainable development competitive. Transboundary flows of waste should be minimized and all countries should be enabled to adopt technologies that maximize reuse and recycling while minimizing unsustainable waste management practices (e.g., use of landfills) (D'Adamo et al., 2024).
However, the challenges to achieving the optimum are not only technical, but also economic, political, and cultural. Sustainability goals require finding a balance between economic profitability and sustainable consumption to meet citizens' needs (D'Adamo et al., 2024).
However, no consensus has yet been reached on the best MSW management approach, as evaluation criteria in existing studies are inconsistent. For converting MSW to energy, economic metrics, such as capital, compliance, and operating cost, are important aspects of implementation (Hoang et al., 2022). Developed countries are using WtE technologies more widely (Chen et al., 2020), as they have recognized the real potential of WtE to simultaneously solve waste and energy problems globally (Skaggs et al., 2018). The transformation of waste into useful energy can not only reduce pollutants entering the environment but also diversify the energy sources available, depending on the technological capabilities of individual nations, regions, and settlements.
However, expanding the circular economy in municipal solid waste management not only means technological development, but also a change in perspective, institutional reform, transformation of economic incentives, and social participation. The emphasis should be on a waste-to-resource approach, prevention, and the development of local cycles. From a systems perspective, municipal waste management is not "waste management", but a local resource management system that strives to close the material cycle and minimize environmental impact.
Several analyses have shown the significant ecological benefits of reusing water, energy, and materials, which reinforce the value of circular strategies for sustainability (Nikolou & Tsagarakis, 2021). However, strict policies to combat illegal waste flows can undermine CE practices (D'Amato et al., 2018).

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A körforgásos gazdaság integrációs akadályai a települési szilárdhulladék-gazdálkodásban: szisztematikus áttekintés

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ÖSSZEFOGLALÁS

A körforgásos gazdaságot a fenntartható fejlődés kulcsfontosságú eszközének tekintik, amely képes átalakítani a hagyományos gazdasági modellt, zártláncú rendszerként működtetni azt, és a „hulladékot” új termékek előállításához szükséges erőforrásként hasznosítani. A kutatási eredmények szisztematikusan tárgyalják az elméletet, beleértve a körforgásos gazdasági modell települési szilárdhulladék-gazdálkodási rendszerbe való integrációjának problémáit és akadályait is. Kettős perspektívából strukturálja a szakirodalomban található problémákat és akadályokat, amelyek bonyolítják, akadályozzák vagy akár késleltetik az integrációt. A tanulmány ezt 116 tudományos cikk öt – gazdasági, társadalmi, környezeti, technológiai és politikai – szempontból történő áttekintésével tette, figyelembe véve a hatékony települési szilárdhulladék-gazdálkodás szakaszait: hulladékkeletkezés; gyűjtés, válogatás; újrafelhasználás, újrahasznosítás, hulladékból való visszanyerés; végső hulladékártalmatlanítás. A szisztematikus áttekintés kimutatta, hogy a körforgásos gazdaság integrációjának számos gazdasági, társadalmi és környezeti akadálya mellett a technológiai és politikai akadályokat is figyelembe kell venni. Mindezek leküzdéséhez azonban először minden országban hatékony hulladékgazdálkodási rendszert kell működtetni. Ehhez a települési szilárdhulladék-gazdálkodás minden szakaszában először le kell küzdeni és megoldani az adott országra vonatkozóan a tanulmányban azonosított problémákat és akadályokat.

Kulcsszavak: körforgásos gazdaság, települési szilárdhulladék-gazdálkodás, akadályok, globális, szisztematikus áttekintés

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A Review on Chitosan Nanoparticles as a Biostimulant and Their Applications in Agriculture

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ABSTRACT

The increasing worldwide demand for food production exerts a significant strain on agriculture, which faces ongoing challenges from biotic and abiotic stressors that restrict crop growth. Chitosan nanoparticles (ChNPs) have emerged as a sustainable biostimulant alternative to chemical agro-inputs owing to their biodegradability, biocompatibility, and multifunctional biological properties. Chitosan, obtained from the deacetylation of chitin, which is largely derived from crustacean waste, can be converted into nanoparticles via ionic gelation. This process results in increased surface area, better penetration, and superior biological efficacy. ChNPs act as an effective biostimulant by activating plant defence systems, enhancing photosynthesis, improving nutrient absorption, promoting root growth, and increasing resilience to abiotic stresses such as drought, salinity, and heat. They also improve yield characteristics and postharvest quality in various crops. Moreover, ChNPs exhibit antibacterial, antiviral, antifungal, and insecticidal properties, providing robust protection against a wide range of diseases and pests. In addition to regulating plant growth, ChNPs serve as non-viral gene delivery vehicles and contribute to soil health by enhancing microbial activity and enabling controlled-release fertiliser formulations. Hybrid ChNPs-based nanocomposites that incorporate metals, polymers, microalgae, and bacteria further enhance their agricultural efficacy by improving nutrient delivery, stress tolerance, and biocontrol effectiveness. Despite considerable progress, future research should prioritise field-scale validation and optimisation of hybrid nanostructures for broader agricultural applications. ChNPs represent a versatile, environmentally sustainable nanotechnology platform with broad potential for sustainable agriculture and soil management.

Keywords: biostimulant, chitosan nanoparticles, controlled-release fertiliser, nutrient uptake

1. INTRODUCTION

The modern world faces a strong demand for food crops, putting enormous pressure on agriculture to increase output. Agriculture, on the other hand, faces significant hurdles due to biotic and abiotic factors that affect yield (Shcherban, 2023). To address these issues, agrochemicals have been utilised; however, this has led to deterioration of soil health, agroecosystem problems, environmental pollution, and the development of chemical resistance in insects and pathogens. As a result, a transition from chemical to biological sources is required to address these negative effects (Kashyap et al., 2015). Biostimulants are appropriate choices in such an environment.

Biostimulants are substances or microbes that, when applied to plants or the rhizosphere, stimulate natural processes to improve nutrient uptake efficiency, boost stress tolerance, and augment crop quality features, regardless of their nutrient content (du Jardin, 2015). They work by modulating physiological processes in plants, making them more efficient in utilising available resources and more resilient to environmental stresses (Yakhin et al., 2017). Many biostimulants are available today that benefit crops. Among them, chitosan nanoparticles are a distinctive option because they are biocompatible, biodegradable, and eco-friendly (Nandini et al., 2025). Research has demonstrated that chitosan application can enhance photosynthetic efficiency, improve water relations, increase nutrient uptake, stimulate root growth, and boost the production of beneficial secondary metabolites. All these effects make chitosan a suitable biostimulant in agriculture (Emami Bistgani et al., 2017).

Chitosan is a linear polysaccharide obtained by deacetylation of chitin and can be extracted from fungal cell walls and crustacean shells (Orzali et al., 2017). The properties of chitosan, such as biocompatibility, non-toxicity, biodegradability, plant growth regulation, antimicrobial activity, and stress inhibition, make it suitable for agricultural applications (Ingle et al., 2022; Sangwan et al., 2023). When formulated into nanoparticles, chitosan exhibits enhanced surface area, improved penetration capabilities, and superior biological activity compared to its bulk form (Kumaraswamy et al., 2018). That is why the nanoparticle form is preferred over the bulk form.

This review highlights the characteristics and extraction methods of chitosan nanoparticles (ChNPs), emphasising their applications in crop production and soil conditioning. It also explores their potential for gene delivery and the exciting possibilities of creating hybrid ChNPs by combining organic and inorganic agents.

2. CHITOSAN: AN OVERVIEW OF THE EXTRACTION, STRUCTURE AND PROPERTIES

Chitosan is obtained from chitin, a structural polysaccharide that is the primary component of arthropod exoskeletons, especially in crustaceans such as prawns, crabs and lobsters, as well as in the cell walls of fungi and certain algae (Elieh-Ali-Komi & Hamblin, 2016). The chitosan used in industrial applications is predominantly sourced from crustacean shells, particularly those of crabs, shrimps, and prawns, which are abundant byproducts of the food processing sector (Pellis et al., 2022). The global seafood processing sector produces millions of tonnes of crustacean shell waste each year, providing an abundant, renewable source for chitin extraction (Xu et al., 2013). The commercial manufacture of chitosan from this waste stream is an outstanding example of circular economy principles, transforming what would otherwise be discarded material into valuable products (Kandra et al., 2012).

In crustacean shells, chitin is complexed with protein and calcium carbonate, and several stages are involved in the extraction of chitin and its conversion into chitosan (Younes & Rinaudo, 2015).

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The synthesis of chitosan from crustacean shells includes multiple consecutive procedures (No & Meyers, 1995). *Figure 1* demonstrates the process. First, shells are demineralised using mild hydrochloric acid to remove calcium carbonate and other minerals. The proteins are then deproteinised with sodium hydroxide, and the chitin is obtained (Abdou et al., 2008). The resultant chitin is subsequently deacetylated, often using concentrated sodium hydroxide at high temperatures, converting N-acetyl-glucosamine units to glucosamine units (Sini et al., 2007). The degree of deacetylation, which represents the proportion of deacetylated units, is a crucial characteristic that determines chitosan's properties and biological activities.

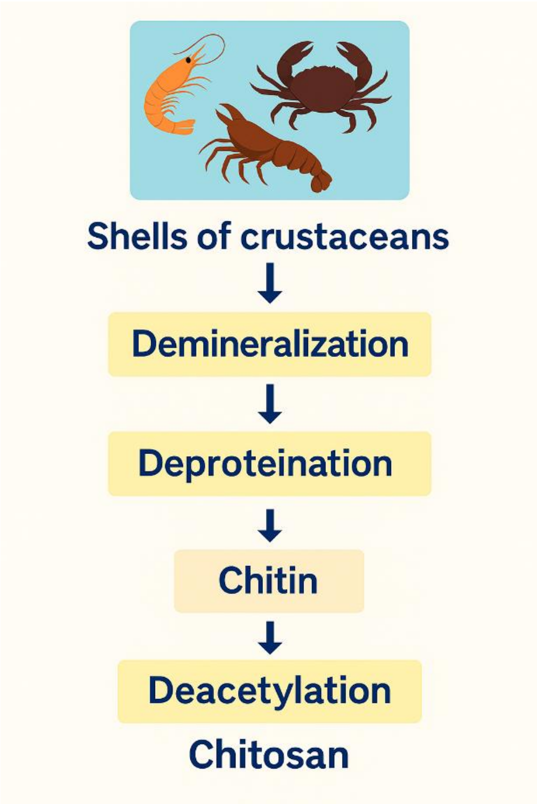

Figure 1: Extraction procedures of chitosan from crustacean shells

Chitosan is a linear polysaccharide consisting of randomly arranged β-(1→4)-linked D-glucosamine and N-acetyl-D-glucosamine units. The chemical structure comprises three functional groups: a primary hydroxyl group at C-6, a secondary hydroxyl group at C-3, and an amino group at C-2 (Aranaz et al., 2021). These functional groups, particularly the amino group, are responsible for chitosan's distinctive properties and its capacity to undergo various chemical modifications (Mourya & Inamdar, 2008). The presence of free amino groups endows chitosan with polycationic properties in acidic conditions, distinguishing it from its parent molecule, chitin, which is electrically neutral (*Figure 2*).

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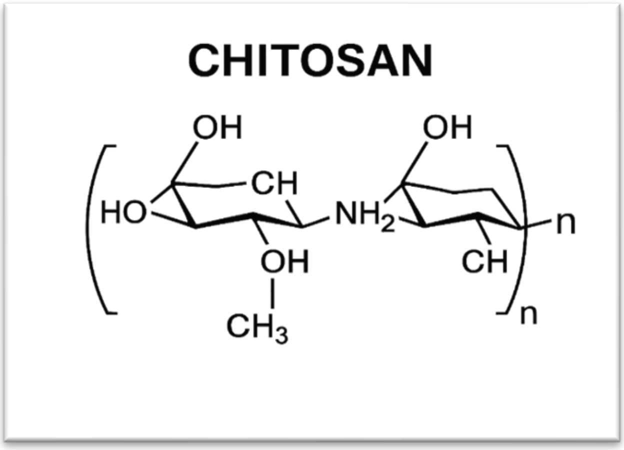

Figure 2: Structure of chitosan

Chitosan's molecular weight varies widely depending on source and manufacturing method, typically ranging from 10 to 1000 kDa. The physicochemical properties of chitosan, such as viscosity, solubility, and biological activity, are greatly influenced by its molecular weight. Lower molecular weight chitosan has greater water solubility and cellular permeability than high molecular weight chitosan (Zhang & Neau, 2001).

3. CONVERSION OF CHITOSAN INTO NANOPARTICLE FORM

The transformation of chitosan from bulk polymer to nanoparticle form is a pivotal innovation that markedly enhances its functional capabilities and broadens its applicability across several domains (Sreekumar et al., 2018). Nanoparticles ranging from 1-100 nanometres display superior characteristics attributable to their elevated surface area-to-volume ratio, enhanced bioavailability and cellular absorption, improved penetration of biological barriers, regulated and sustained release capabilities, and increased stability and protection of encapsulated substances (Hoang et al., 2022; Sreekumar et al., 2018). The ionic gelation method is the most widely used procedure for this conversion.

The ionic gelation process involves dissolving chitosan in an aqueous acidic solution to yield chitosan cations, which are subsequently added to a polyanionic tripolyphosphate (TPP) solution while continuously stirring. Chitosan undergoes ionic gelation and precipitates into spherical particles due to the complexation of opposing charges (positive and negative). Cross-linking chitosan with an agent such as TPP results in inter- and intra-molecular cross-linkages due to their opposing charges, yielding chitosan nanoparticles (Gutiérrez-Ruíz et al., 2024; Hoang et al., 2022).

4. BIOSTIMULANT ACTION OF CHITOSAN NANOPARTICLES IN AGRICULTURAL CROPS

ChNPs have emerged as promising biostimulants in modern agriculture, offering sustainable alternatives to conventional chemical inputs for enhancing crop productivity and resilience. The utilisation of ChNPs in agriculture has garnered considerable interest owing to their diverse modes of action, which encompass eliciting plant defence responses, stimulating growth and development, augmenting nutrient uptake, and enhancing stress tolerance (Kashyap et al., 2015). ChNPs can be administered by several means, including seed treatment, foliar application, soil soaking, and root immersion. These application techniques provide accurate and

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effective delivery of ChNPs, optimising their protective advantages while reducing environmental impact (Nandhini et al., 2025).

4.1 Elicitation of plants' defence by ChNPs

ChNPs are recognised by plant cell receptors as pathogen-associated molecular patterns (PAMPs), triggering a series of defence signalling pathways (Pichyangkura & Chadchawan, 2015). Chitosan, upon detection by pattern recognition receptors (PRRs) on the plant cell surface, triggers the generation of reactive oxygen species, which act as secondary messengers in defence signalling and activate mitogen-activated protein kinase cascades (Iriti & Faoro, 2009). These signalling events lead to the upregulation of defence-related genes and the production of pathogenesis-related proteins, such as chitinases, β-1,3-glucanases, and peroxidases, which collectively bolster the plant's resistance to pathogen infection (Hadwiger, 2013).

Research has shown that ChNPs treatment elicits systemic acquired resistance (SAR) in multiple crops, conferring enduring immunity against future pathogen assaults (Benhamou & Thériault, 1992). The induction of defence responses by ChNPs has been demonstrated to augment cell wall thickness via increased lignification and callose deposition, thereby forming physical barriers against pathogen invasion (El Hadrami et al., 2010).

4.2 ChNPs in plant growth and development

ChNPs play a key role in the growth and development of several plants. Chitosan foliar spray enhances okra growth, yield, and photosynthesis rate (Mondal et al., 2012). In strawberry plants, the treatment helps boost leaf growth, yield, and root biomass (El-Miniawy et al., 2013).

At the molecular level, chitosan nanoparticles enhance the expression of genes involved in photosynthesis, carbon metabolism, and nitrogen assimilation, thereby improving overall plant metabolic efficiency (Abuelsoud et al., 2023). Furthermore, chitosan enhances the activity of essential enzymes in nitrogen metabolism, including nitrate reductase and glutamine synthetase, hence promoting superior nitrogen utilisation and protein synthesis (Górnik et al., 2008).

4.3 Nutrient uptake stimulation

ChNPs have demonstrated the capacity to enhance the bioavailability of vital macro- and micronutrients by inhibiting their precipitation or fixation in soil and facilitating their absorption by plant roots (Abdel-Aziz et al., 2016). In coffee plants, treatment with ChNPs increased uptake rates and improved biophysical activity (Nguyen Van et al., 2013).

ChNPs treatment has been shown to enhance the expression of genes encoding high-affinity nitrate, phosphate, and metal ion transporters, resulting in improved nutrient uptake in both optimal and deficient environments (Li et al., 2020). Moreover, chitosan nanoparticles enhance root growth and proliferation, specifically the formation of lateral roots and root hairs, hence augmenting the root surface area for nutrient absorption (Dzung et al., 2011). The augmented nutrient profile from ChNPs application results in superior crop quality metrics, including elevated protein levels, improved oil quality, and higher concentrations of vitamins and minerals in harvested produce (Maluin & Hussein, 2020).

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4.4 Stimulation of yield

Yield is a primary concern in agriculture, and ChNPs significantly enhance production across various plants. In one study, foliar application of ChNPs on wheat grown in sandy soil increased yield compared with the control group treated with conventional fertiliser (Abdel-Aziz et al., 2016). In strawberry plants, spraying with ChNPs increases yield without affecting fruit quality (El-Miniawy et al., 2013). Another study on lupine plants under drought conditions indicates that the treatment enhances both yield quantity and quality (Bakhoum et al., 2022). From all this, it can be concluded that ChNPs are suitable for increasing yield in various plants.

4.5 ChNPs against abiotic and biotic stress

Under stress, ChNPs modulate plants' antioxidant defence system, increasing the activity of enzymatic antioxidants such as superoxide dismutase, catalase, ascorbate peroxidase, and glutathione reductase, which collectively scavenge excess reactive oxygen species and mitigate oxidative damage. Chitosan treatment also increases the accumulation of non-enzymatic antioxidants such as ascorbic acid, glutathione, and phenolic substances, which provide additional protection against oxidative stress (Hidangmayum et al., 2019; Zeng & Luo, 2012).

During drought stress, plants treated with chitosan close their stomata, reducing water loss. It has also been observed that chitosan treatment increases abscisic acid levels, which assist stomatal closure (Iriti et al., 2009). In heat-stress conditions, ChNPs promote the synthesis of heat shock proteins, which function as molecular chaperones to prevent protein aggregation, facilitate proper protein folding, and protect cellular structures from thermal damage (Malerba & Cerana, 2016). In response to salinity stress, antioxidant enzyme activities increase and malondialdehyde levels decrease, reducing the deleterious effect of salt stress in rice plants treated with ChNPs (González et al., 2015).

The protective activity of chitosan nanoparticles against biotic stress begins with their molecular identification by plant defence systems. Through PRRs on the plant plasma membrane, plants recognise ChNPs as PAMPs or microbe-associated molecular patterns (Pichyangkura & Chadchawan, 2015). ChNPs treatments trigger the generation and transmission of signals to distant tissues, preparing the entire plant for enhanced defence responses upon subsequent pathogen attack (Malerba & Cerana, 2016).

It was discovered that ChNPs inhibit the replication of plant viruses, halting growth and spread. This may be because when chitosan nanoparticles penetrate plant tissues, they bind strongly to nucleic acids, causing various types of damage and specific inhibition (El Hadrami et al., 2010; Kulikov et al., 2006). In potato and tomato, foliar treatment with ChNPs for bacterial wilt, caused by the bacterium Ralstonia solanacearum, decreased bacterial populations, disrupted bacterial cell structure, and reduced disease incidence (Khairy et al., 2022). Furthermore, ChNPs can penetrate fungal hyphae and interfere with DNA transcription and protein synthesis, disrupting critical cellular processes (Saharan et al., 2013). ChNPs have been shown to act as potential insecticides against soybean pests, namely *Aphis gossypii* and *Callosobruchus maculatus*, as they drastically reduce the number of eggs laid by females (Sahab et al., 2015). Thus, ChNPs are a suitable substitute for plants under both abiotic and biotic stress.

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4.6 Post-harvest application of ChNPs

ChNPs have valuable uses in postharvest management, with ChNPs-based coatings extending the shelf life of fruits and vegetables by creating a semi-permeable barrier that regulates gas exchange, reduces moisture loss, and inhibits microbial growth (Sharif et al., 2018). In bananas, they were applied to delay ripening. An increase in antioxidant and vitamin C content was also observed (Suseno et al., 2014). The application of ChNPs markedly improved the shelf life, aesthetic appeal, and many quality characteristics of refrigerated tomatoes (García et al., 2014).

5. GENE TRANSFER MECHANISM OF ChNPs

ChNPs are a popular tool for certain non-viral gene transfer techniques. Nanoparticles apply to both monocotyledonous and dicotyledonous plants, as well as all sorts of organs. Secondly, this gene-carrier form can efficiently bypass transgenic silencing by regulating the number of DNA copies associated with nanoparticles. In one experiment, they used ChNPs to transfer thionine genes into potato plants to protect them against fungal infection. As a result, the plants developed the ability to defend themselves against the fungal attack, becoming transgenic (Abdel-Razik et al., 2017).

6. SOIL HEALTH IMPROVEMENT BY ChNPs

Chitosan application can positively influence soil biological properties and overall soil health. Studies have shown that chitosan promotes beneficial soil microorganisms, including bacteria involved in nitrogen fixation and nutrient cycling, as well as fungi that form symbiotic associations with plant roots (Sharp, 2013). A study on the soil application of ChNPs showed increased microbial populations, thereby enhancing soil fertility (Divya et al., 2021). The augmentation of the microbial population was directly correlated with chitosan decomposition, indicating its impact on soil fertility (Sawaguchi et al., 2015).

Soil pollution, primarily caused by the application of chemical fertilisers, is a significant environmental concern. ChNPs can serve as a coating for this fertiliser to minimise environmental loss and regulate its release; this is known as a controlled-release fertiliser (Zahoor et al., 2025). Microencapsulation can also be achieved using ChNPs, which can protect active compounds and help control their release (García-Carrasco et al., 2023).

7. CHITOSAN NANOPARTICLE HYBRID NANOCOMPOSITES

Chitosan-based hybrid nanocomposites are formed by combining chitosan nanoparticles with various materials, including metal oxides, microalgae, bacteria, and other polymers, to enhance their functionality and broaden their agricultural applications (Kumaraswamy et al., 2018).

ChNPs-metal oxide nanocomposites are a promising category of hybrid nanomaterials for agricultural applications. Chitosan nanoparticles integrated with zinc oxide (ZnO) exhibit augmented antibacterial efficacy against plant diseases and facilitate enhanced nutrient delivery to crops (Xing et al., 2015). The integration of copper oxide nanoparticles into chitosan matrices has demonstrated efficacy in managing fungal infections while supplying vital micronutrients to plants (Saharan et al., 2015). Silver nanoparticles incorporated into chitosan matrices exhibit potent antibacterial activity and have been effectively utilised as seed coating agents to safeguard against seed-borne diseases (Shukla et al., 2013).

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The combination of copper and zinc with ChNPs increased defence enzyme activity in plants (Karamchandani et al., 2024).
They can also be combined with biocontrol agents such as bacteria and microalgae to enhance their properties. Encapsulated plant growth-promoting rhizobacteria in ChNPs exhibit enhanced survival and regulated release, thereby augmenting their efficacy in fostering plant growth and safeguarding against soil-borne diseases (Divya & Jisha, 2018). In one study, microalgae were incorporated into chitosan, resulting in improved yield parameters and enhanced drought tolerance in winter wheat plants (Molnár et al., 2023).
Chitosan-alginate nanoparticles have been extensively researched for the encapsulation and controlled release of insecticides, fertilisers, and biopesticides (Kumaraswamy et al., 2018). Chitosan-cellulose nanocomposites exhibit improved water retention and have been utilized to control drought stress (Malerba & Cerana, 2019).

8. FUTURE PERSPECTIVES

ChNPs can be utilised more extensively in agriculture as an alternative to chemical biostimulants. Future studies should focus on their applications in open fields rather than in closed environments. The majority of the experiments are conducted on a small scale or under greenhouse conditions. Furthermore, there is significant potential for ChNPs in conjunction with other particles, as their combination performs more efficiently than standard ChNPs. There is also considerable scope for combining ChNPs with precision agriculture technologies.

9. CONCLUSION

Chitosan nanoparticles (ChNPs) are a highly promising, environmentally benign innovation for sustainable agriculture, offering numerous advantages beyond traditional chemical inputs. Their conversion from chitosan to a nanoscale form markedly amplifies their biological efficacy, facilitating superior plant defence activation, augmented nutrient absorption, enhanced photosynthetic performance, and heightened resilience to abiotic and biotic stressors. ChNPs enhance crop yields, elevate postharvest quality, and promote soil health by stimulating beneficial microbes and facilitating controlled-release fertiliser treatments. Their adaptability is further augmented by hybrid nanocomposites that integrate metals, polymers, microalgae, and beneficial microbes, thereby improving antibacterial efficacy, nutrient transport, and stress resistance. Moreover, their function as non-viral gene delivery vehicles creates new opportunities for sophisticated plant biotechnology. Although most existing discoveries originate in controlled laboratory or greenhouse settings, it is essential to extend research to open-field contexts to confirm their large-scale relevance. ChNPs serve as a sustainable, innovative tool that supports contemporary agriculture in addressing global food security issues while reducing ecological damage.

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Kitozán nanorészecskék biostimuláns hatása és mezőgazdasági felhasználási lehetőségei: irodalmi áttekintés

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ÖSSZEFOGLALÁS

A világszerte növekvő élelmiszertermelési igény jelentős nyomást gyakorol a mezőgazdaságra, amely folyamatos kihívásokkal néz szembe a biotikus és abiotikus stresszorok miatt, amelyek korlátozzák a növények növekedését. A kitozán nanorészecskék (ChNPs) fenntartható biostimulánsként jelentek meg az agrokémiai inputok alternatívájaként, köszönhetően biológiai lebomlásuknak, biokompatibilitásuknak és multifunkcionális biológiai tulajdonságaiknak. A kitozán, amelyet elsősorban rákfélék hulladékából származó kitin deacetilezésével nyernek, ionos gélképzéssel nanorészecskékké alakítható. Ez a folyamat nagyobb felületet, jobb penetrációt és magasabb biológiai hatékonyságot eredményez. A ChNPs hatékony biostimulánsként működnek a növényi védelmi rendszerek aktiválásával, a fotoszintézis fokozásával, a tápanyag-felvétel javításával, a gyökérnövekedés elősegítésével, valamint a szárazság, sóstressz és hőstressz elleni ellenállóképesség növelésével. Emellett javítják a termésmennyiség jellemzőit és a betakarítás utáni minőséget különböző növényekben. Továbbá a ChNPs antibakteriális, antivirális, antifungális és rovarirtó tulajdonságokat mutatnak, így robusztus védelmet nyújtanak számos betegség és kártevő ellen. A növényi növekedés szabályozásán túl a ChNPs nem virális génszállító eszközként is szolgálnak, és hozzájárulnak a talaj egészségéhez a hasznos mikroorganizmusok tevékenységének fokozásával, valamint a kontrollált kiadású műtrágya-formulációk lehetővé tételével. A fémeket, polimereket, mikroalgákat és baktériumokat integráló hibrid ChNPs-alapú nanokompozitok tovább növelik mezőgazdasági hatékonyságukat a tápanyag-szállítás, a stressztűrés és a biológiai védekezés javításával. A jelentős előrelépések ellenére a jövőbeli kutatásoknak elsőbbséget kell adniuk a hibrid nanostruktúrák nyílt terepi hitelesítésének és optimalizálásának a szélesebb körű mezőgazdasági alkalmazás érdekében. A ChNPs sokoldalú és környezetbarát nanotechnológiai platformot képviselnek, széles potenciállal a fenntartható mezőgazdaságban és a talajkezelésben.

Kulcsszavak: biostimuláns, kitozán nanorészecskék, lassan felszabaduló műtrágya, tápanyag-felvétel

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Abbreviations

ChNPs: Chitosan nanoparticles
PAMPs: Pathogen-associated molecular patterns
PRRs: Pattern recognition receptors
TPP: Polyanionic tripolyphosphate

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Evaluation of an Autonomous Hole-Drilling Robot in Afforestation Operations

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ABSTRACT

Over the past several decades, agricultural mechanisation has advanced rapidly, and most Hungarian crop producers now have access to modern machinery. In contrast, the machinery fleets of forestry enterprises and contractors – with only a few exceptions – still consist largely of ageing equipment. The technological sophistication of forestry machinery continues to lag far behind that of other agricultural sectors. Yet the strengthening and competitiveness of forestry enterprises are inconceivable without the adoption of modern machines and technologies. A further serious challenge is the growing labour shortage affecting the sector. For these reasons, the integration of digital technologies, automated machinery, and robotics into forestry operations has become inevitable. In recent years, a family of horticultural robots has been developed in Hungary. Last autumn, our research team tested one member of this machine family in an oak afforestation project within the Nagykanizsa Forestry District of Zalaerdő Plc. This paper presents operational experience from field tests and provides an economic evaluation of the machine's performance.

Keywords: autonomous self-propelled robot, autonomous navigation software, precision forestry, GPS-based positioning, performance and cost analysis

1. INTRODUCTION

Technological development is indispensable for modern, efficient, profitable, and competitive agricultural production. Over the past few decades, agricultural mechanisation has advanced rapidly, and Hungarian crop producers generally have access to modern machinery fleets (Popp et al., 2018). In contrast, a significant proportion of the machinery fleets of domestic forestry enterprises and contractors consists of ageing equipment, and the forestry sector has fallen far behind agriculture in technological sophistication. This represents a significant obstacle to strengthening and modernising the forestry service sector. Given the current labour shortage, mechanisation is vital, as the implementation of planned forestry operations – silvicultural and timber-harvesting activities –

requires a stable base of reliable forestry enterprises (Major & Kovácsevics, 2023). These factors – particularly the observable labour shortage in the sector – clearly indicate that mechanisation levels in individual silvicultural and forest utilisation activities must increase, thereby improving operational efficiency. For these reasons, the integration of digital technologies, automated machines, and robots into forestry operations is inevitable.

Information technology (IT) has now reached the forestry sector, and robotisation has become an integral part of forestry machinery development. Numerous experiments and machine-development projects are underway worldwide, with manufacturers continuously introducing new autonomous machines applicable to various areas of forest management (Czupy, 2023; Horváth, 2016; Horváth & Czupy, 2022).

Moreover, promising domestic developments have emerged.

2. MATERIALS AND METHODS

2.1 Background

In Hungary, among other domestic developers, Hári Tech Kft. began designing and manufacturing specialised small-scale, custom-built self-propelled robots in 2019. The company continuously develops and refines its machines, which are tested and optimised on a 50-hectare family horticultural farm (Hári, 2021). Currently, four types are produced, all equipped with Kubota diesel engines offering rated outputs of 18 kW (24 hp) and 48 kW (65 hp). The robots feature rubber-track undercarriages with hydraulically adjustable track widths, enabling adaptation to various terrain types and operational conditions.

A wide range of implements can be attached, including – but not limited to – auger drills, sprayers, fertiliser spreaders, mulchers, cultivators, and mowers.

Robot operation is supported by the company’s proprietary “hariPilot” autonomous control software. The latest models include onboard cameras, allowing operators to monitor the work process in real time and intervene when necessary. Positioning relies primarily on GPS, with correction data supplied by commercial services (e.g., Lechner, Corrigo) or a local base station, achieving an operational accuracy of approximately ± 2 cm.

The robots are equipped with multiple safety features, including automatic shutdown in the event of a malfunction, tilt sensors, and collision-avoidance systems, ensuring safe operation even under demanding conditions.

2.2 Description of the Examined Machine

Among the machines manufactured by Hári Tech Kft., the haRiBOT V3 self-propelled robot – which has already proven its efficiency under horticultural conditions – was selected for testing in a forestry environment (*Figure 1*). The experiment aimed to assess the robot’s performance under the specific operational and environmental conditions typical of forest management.

The haRiBOT V3 is equipped with 180 mm-wide rubber tracks, and its track gauge can be continuously adjusted hydraulically between 70 cm and 110 cm. Implements can be attached to both the front and rear of the machine. The front hydraulic lift has a lifting height of 200 mm and a load capacity of 100 kg, while the rear hydraulic lift offers a lifting height of 600 mm and a load capacity of 150 kg. To counterbalance heavy rear-mounted implements, additional front ballast weights can be installed.

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The robot has a maximum travel speed of 4.5 km/h and a total weight of 800 kg, which allows convenient transport on a trailer (*Figure 2*).

Figure 1: The haRiBOT V3 self-propelled robot at work

Figure 2: The haRiBOT V3 self-propelled robot – transportation

The control interface is located on the left side of the machine and includes the start button, ignition switch, throttle control, display panel, and emergency stop button. (An emergency stop button is also located on both sides of the robot and on the remote control.) The display panel shows operational parameters such as travel speed, engine revolutions per minute (RPM), and fuel level, and allows adjustment of related settings (*Figure 3*).
A waterproof tablet interface mounted on top of the robot enables the operator to configure work parameters – including boundary coordinates, row spacing, and plant spacing – and to monitor the work process in real time (*Figure 4*). The machine's operation can be mastered quickly thanks to the control software's logical, user-friendly design.
The robot is equipped with several safety features. In the event of a malfunction, it automatically shuts down to prevent accidents. The collision detection sensor provides a 270° field of view;

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upon detecting an obstacle, the robot first slows down and then stops. A tilt sensor prevents overturning by continuously monitoring the machine's inclination.

Figure 3: Control panel of the haRiBOT V3 self-propelled robot

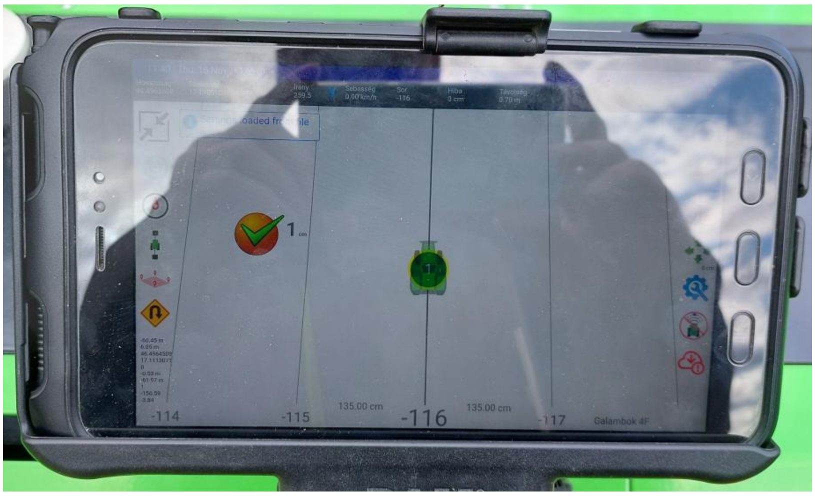

Figure 4: User interface of the hariPilot autonomous navigation software

2.3 Description of the Field Test

Since Hári Tech Kft. is located in Pötréte (Zala County), our research team conducted testing of the haRiBOT V3 robot under forestry conditions within the operational area of Zalaerdő Plc., Nagykanizsa Forestry District. The trials took place during the autumn afforestation season. The robot, equipped with an auger drill attachment, was used to dig planting holes for seedling establishment.

The forestry company proposed three forest subcompartments for the trials. Stump grinding had been carried out in two of them, while the third contained unground stumps, making it unsuitable for robot operation. The selected site was subcompartment Galambok 4F, where afforestation was planned using manual wedge-spade planting. Before planting, soil preparation was performed with a furrow-opening plough following stump grinding. The plot covered a total area of 3.02 hectares and was fenced to prevent wildlife damage.

Before commencing operation, the following input data were provided to the control software: EOV (Hungarian National Projection System) coordinates of the field boundaries, row spacing, plant spacing, and driving direction.

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The haRiBOT V3 self-propelled robot can be equipped with one, two, or three auger heads, depending on the desired row spacing. To improve operational efficiency, the work was performed with three auger heads operating simultaneously, with the robot moving perpendicular to the planting rows (*Figure 5*). The row spacing was 2.2 m, the plant spacing 45 cm, the auger diameter 13 cm, and the drilling depth 30 cm.

Once started from the defined initial point, the robot operated fully autonomously: it stopped at each predefined position, drilled the planting hole, retracted the auger head, and moved automatically to the next drilling position. Upon reaching the end of a row, it turned toward the next row and continued its operation. The turning radius at the field ends was approximately 3 m. The operator could take over manual control at any time using the remote controller. In this particular test, the robot was able to perform automatic turning at the end of the rows on only one side. Because the fence did not always follow the exact forest boundary, there was insufficient space for a full automatic turn in some sections. In such cases, control was temporarily switched to manual mode using the remote control to complete the turn. Afterwards, control was returned to the robot, which then automatically repositioned itself and resumed autonomous operation.

Figure 5: Application of three auger heads operating perpendicular to the rows

3. RESULTS

3.1 Evaluation of Work Quality

The self-propelled robot prepared the planting holes according to the specified row and within-row spacing, achieving high precision thanks to its ± 2 cm positioning accuracy.

Minor deviations of a few centimetres occurred occasionally when the robot tilted on uneven surfaces. This resulted from the drilling position (coordinate) being defined at the auger mounting point rather than at the drill bit tip. Consequently, depending on the auger length and the degree of tilt, small positional deviations of a few centimetres were observed.

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In certain spots, despite prior stump grinding, residual stump fragments in the soil prevented the robot from reaching the required drilling depth or from forming a planting hole at all (*Figure 6*). On one occasion, the auger became jammed in a thick root, requiring manual intervention to free the machine. The excavated soil was deposited next to the planting hole, providing enough material to cover the seedlings during planting. The ejection distance of the soil depends on soil cohesion and moisture content and can be adjusted by varying the auger's rotational speed.
In some cases, solar flares can noticeably affect the ionosphere, making precise (geodetic-level) positioning difficult or even impossible. Therefore, a local reference base station is recommended under such conditions.

Figure 6: Drilled planting holes

3.2 Performance Characteristics

Accurate knowledge of machine operating costs is indispensable for sound decision-making by forest managers and service providers. These costs represent a substantial share of total production expenditures and fundamentally influence operational profitability (Erdeiné Késmárki-Gally et al., 2022). As the technology improves, an increasing number of new machines are being introduced (Horváth, 2000; Horváth & Czupy, 2022), yet practical data on their operating costs under specific conditions are often unavailable. The haRiBOT V3 self-propelled hole-drilling robot is a case in point. For this reason, we analysed its performance and cost parameters.
The field performance of the haRiBOT V3 depends primarily on:

- row spacing (a),
- within-row spacing (b),
- the machine utilisation factor (K03).

Performance is also affected by:

- plot length (L) (since the machine moves perpendicular to the rows, this corresponds to plot width),
- inter-hole travel speed (v),
- turning time at plot ends (tf).

Row spacing can be chosen arbitrarily. However, when drilling two or three rows simultaneously, it is advisable to operate perpendicular to the intended planting rows (see *Figure 5*). The analysis considered typical values used by the Nagykanizsa Forestry District: 1.8 m, 2.0 m, 2.2 m, 2.4 m, and 2.5 m. Within-row spacing – that is, the distance between adjacent holes in a row – can be freely selected (starting from the minimum defined by the hole diameter) when drilling a single row. When drilling two or three rows simultaneously (moving perpendicular to the intended planting rows), the minimum and maximum within-row spacing depend on the beam length and

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the number of mounted auger heads, while still being limited by the minimum spacing defined by the hole diameter. The analysis used values typical for the Nagykanizsa Forestry District: 40 cm, 45 cm, 50 cm, 55 cm, and 60 cm.
The machine utilisation factor (also referred to as the time utilisation factor or the ratio of productive to total working time) depends on maintenance, repairs, and other downtime. In practice, its value ranges between K_{03} = 0.5 and 0.8.
Plot length affects area performance through the number of headland turns. In practice, plot lengths range between 100 and 400 m.
Due to the short inter-hole distances, field measurements indicated an average inter-hole travel speed of v = 1.1 km/h.
The turning time at plot ends, determined by the machine's design and operation, is constant and was measured as t_f = 30.15 s on average.
The time required to complete one pass of auger drilling (*Eq. 1*) is given by the sum of total travel time, drilling time, and turning time:

$$t_1 = \frac{L}{v} + x \cdot t_g + t_f \tag{1}$$

where:
x = L/a+1, number of drilling positions per pass;
t_g = 12.32 s, average drilling time per hole, based on field measurements.
The productive-time and shift-time area performance values of the hole-drilling robot, as functions of the influencing parameters, are summarised in *Table 1* and *Table 2* and can be calculated using the following equations (*Eq. 2* and *Eq. 3*):

$$W_{01} = \frac{n \cdot b \cdot L}{t_1} \tag{2}$$

where: n = 3, number of holes drilled simultaneously per operation;

$$W_{03} = W_{01} \cdot K_{03} \tag{3}$$

Table 1: Productive-time area performance: W01 [ha/h]

a [m] / ***b*** [m]	1.8	2.0	2.2	2.4	2.5
0.40	0.041	0.044	0.046	0.049	0.050
0.45	0.046	0.049	0.052	0.055	0.056
0.50	0.051	0.055	0.058	0.061	0.063
0.55	0.056	0.060	0.064	0.067	0.069
0.60	0.061	0.066	0.070	0.073	0.075

Table 2: Shift-time area performance: W_{03} [ha/h]

K_{03} / W_{01} [ha/ha]	0.5	0.6	0.7	0.8
0.041	0.020	0.025	0.029	0.033
0.050	0.025	0.030	0.035	0.040
0.060	0.030	0.036	0.042	0.048
0.070	0.035	0.042	0.049	0.056
0.075	0.038	0.045	0.053	0.060

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3.3 Cost Analysis

The purpose of the cost analysis was to determine, for the haRiBOT V3 self-propelled robot:

- the hourly operating cost (HUF/h), and
- the operational cost of auger drilling (HUF/ha).

The cost analysis was carried out using 2024 prices.

The initial input data for the machine are as follows:

- Machine price including the attachment: A = 2,470,000 HUF according to the manufacturer (excluding VAT, since it is refundable and does not affect the operating cost);
- Annual operating time (number of annual working hours): t_{year} = 150 h, based on our measurements and literature data;
- Depreciation rate: p = 17 %;
- Repair cost factor (percentage of the machine price allocated annually to repairs and maintenance): r = 15 %, based on the 2022 average for hole-drilling machines at the MATE-MI (Hungarian University of Agriculture and Life Sciences, Institute of Technology) reference farm (no long-term data are available for the tested machine);
- Other cost factor (percentage of the machine price allocated annually to other costs): e = 0.40 %, also based on the 2022 average for hole-drilling machines at the MATE-MI reference farms.

The hourly fixed operating cost (ownership costs only) of the hole-drilling robot (*Eq. 4*) is calculated as:

$$F_{03} = \frac{A(p+r+e)}{t_{year}} = \frac{2{,}470{,}000(0.115+0.004)}{150} = 5{,}335\ HUF/h \quad (4)$$

The operational cost of auger drilling (*Eq. 5*) depends on:

- the hourly operating cost (F_{03}), and
- the machine's area performance during working time (W_{03}),

and is given by:

$$M_{03} = \frac{F_{03}}{W_{03}} \quad (5)$$

The achievable area performance during working time ranges between W_{03} = 0.020 and 0.060 ha/h. Accordingly, the operational cost of auger drilling ranges between M_{03} = 88,920 and 266,760 HUF/ha. The numerical values of the operational cost (M_{03}) as a function of the shift-time area performance are presented in *Table 3*. The relationship between operational cost and area performance is illustrated in *Figure 7*.

Table 3: Operational cost of auger drilling

W₀₃ **[ha/h]**	**0.020**	**0.030**	**0.040**	**0.050**	**0.060**
M_{03} [HUF/ha]	266,760	177,840	133,380	106,704	88,920

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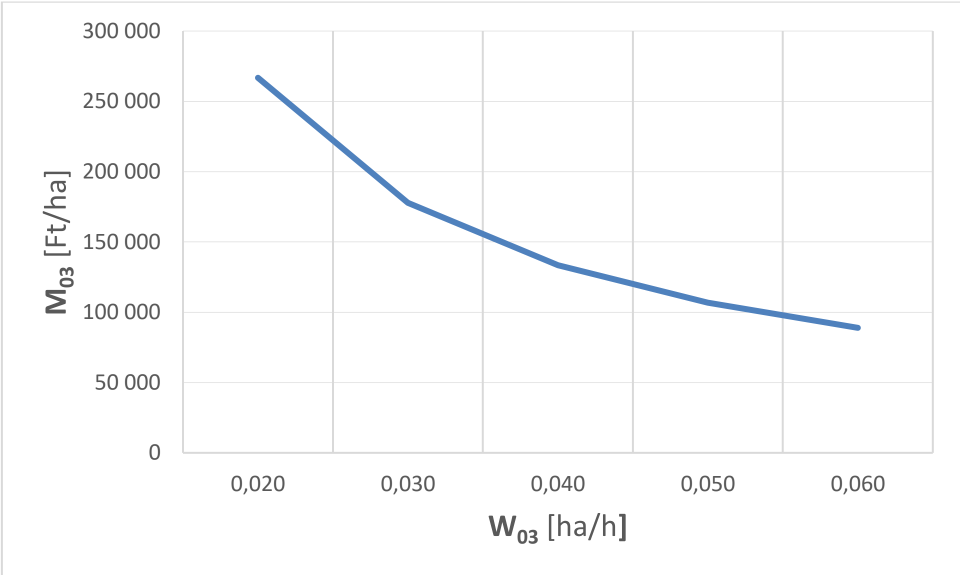

Figure 7: Operational cost of auger drilling as a function of area performance during working time

4. CONCLUSION

Our research suggests that self-propelled robots, when equipped with appropriate attachments, are already capable of performing forestry nursery tasks. With proper site preparation, they can also be applied in afforestation operations. However, further development is required to ensure reliable operation under diverse forest conditions.

The use of self-propelled robots is not yet legally regulated. In fenced areas where it is confirmed that no personnel are present, the machines can be left unattended. Otherwise, the operator must remain nearby. To this end, the remote control has an operational range of 200 m. At the same time, equipping self-propelled robots with additional safety devices – another method to reduce risk to anyone nearby – can increase the machine cost by 20-25 %.

The self-propelled robot can be fitted with multiple attachments, thereby increasing its utilisation and annual performance. Consequently, operating costs – including the hourly operating cost (F03) and the operational cost (M_{03}) - can be further reduced.

By employing additional attachments, the annual operating time can be increased to 500 hours. In this scenario, the operational cost of auger drilling is shown in *Table 4*, which presents significantly more favourable values.

Table 4: Operational cost of auger drilling at t_{year} = 500 h

W_{03} [ha/h]	0.020	0.030	0.040	0.050	0.060
M_{03} [HUF/ha]	80,028	53,352	40,014	32,011	26,676

The machine can be either purchased or rented. The manufacturer offers the robot for rent at a net rate of 18,000–22,000 HUF per operating hour, depending on the work volume. Using an average value of 20,000 HUF per operating hour and the shift-time area performance values (W_{03}) from *Table 1*, the operational cost of auger drilling (M_{03}) ranges between 333,333 HUF/ha and 1,000,000 HUF/ha. Based on these figures, it can be concluded that – even with a lower annual operating time (t_{year} = 150 h) – purchasing the machine is more cost-effective than renting.

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Önjáró gödörfúró robot vizsgálata erdősítési munkában

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ÖSSZEFOGLALÁS

Az elmúlt néhány évtizedben a mezőgazdasági gépesítés rohamosan fejlődött, a hazai növénytermesztésben többségében korszerű géppark áll a termelők rendelkezésére. Ugyanakkor az erdőgazdaságok és erdészeti vállalkozások gépparkjának jelentős részét néhány kivételtől eltekintve idős gépek alkotják. Az erdőgazdálkodásban használt gépek fejlettsége meg sem közelíti a mezőgazdaságban használtakét. Az erdészeti vállalkozások megerősödéséhez viszont elengedhetetlenek a korszerű gépek, technológiák. További problémát jelent az ágazatban is tapasztalható munkaerőhiány. Mindezek miatt elkerülhetetlen a digitális technológia, az automatizált gépek, robotok használatának bevezetése az erdészeti munkákban.

Az utóbbi években Magyarországon kifejlesztésre került egy kertészeti robot gépcsalád. A gépcsalád egyik tagját az őszi erdősítési időszakban a Zalaerdő Zrt. Nagykanizsai Erdészetének területén tölgy erdősítésben teszteltük. Jelen cikkünkben ennek üzemeltetési tapasztalatait mutattuk be, valamint ökonómiai értékelését végeztük el.

Kulcsszavak: autonóm magajáró robot, autonóm navigációs szoftver, precíziós erdészet, GPS-alapú pozicionálás, teljesítmény- és költségelemzés

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Work of our Predecessors/

Elődeink munkássága

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Linhart György (1844-1925) a magyar növénykórtan atyja, azaz az első, meghatározó személyisége, akit botanikusként és mikológusként is számon tartanak, éppen 100 esztendeje hunyt el. Abban a jeles időszakban volt Linhart a Magyaróvári Gazdasági Akadémia professzora, amikor a tudományos növénykórtan az egész világon óriási léptékkel indult fejlődésnek, a 19. század második felében a Strasburgi Egyetem professzora, Heinrich Anton de Bary vezetésével. Minden nemzet legjelesebb tudósát elküldte tanulmányútra az új növénykórtani és mikológiai ismeretek megszerzésére az iskolateremtő de Bary laboratóriumába. A fiatal, de már tapasztalt Linhartot 1874-ben kinevezték professzornak Magyaróvárra a Gazdasági Akadémiára, amely akkoriban kiváló tanárokkal és gyors fejlődéssel Európa egyik kiemelkedő felsőfokú mezőgazdasági iskolájává vált. Linhart 32 éven át volt ott tanár. 1897-ben megszervezte és 1910-ig vezette a Magyar Királyi Állami Vetőmagvizsgáló, Növényélet- és Kórtani Állomást, ugyancsak Magyaróváron. Itt alapozta meg a hazai növénykórtani és növényvédelmi kutatást. Kidolgozta a cukorrépa- és burgonyabetegségek, a gabonák üszög- és rozsdabetegségei elleni védekezést. Egész Európában átvették a Linhart-féle kosaras csávázást a búza kőüszög betegségek elleni küzdelemben, melyet a Tilletia spp. okoznak.
Kulcsszavak: Linhart György, A. de Bary, Magyaróvári Gazdasági Akadémia, cukorrépa betegségek, burgonya betegségek, gabona kőüszögök, Tilletia spp., Linhart-féle kosaras csávázás

Linhart György 1844. január 16-án Pesten született és Magyaróváron hunyt el 1925. január 27-én, éppen száz esztendeje. Vezetékneve „Linhardt” formában is szerepel még az egykorú forrásokban is, például a mai mosonmagyaróvári, róla elnevezett utca névtábláin és a város térképein ugyanúgy (Wikipédia 1 2009).

Linhart György, mint „a magyar növénykórtan atyja”-ként azaz az első, meghatározó személyiségeként tiszteljük, de botanikusként és mikológusként is számon tartják. Schilberszky Károlyra (1863–1935) a kertész kórtanosok tekintenek úgy, mint a „kertészeti növénykórtan atyjára”, a tudományterület megteremtőjére (Hornok 2025; Kövics 2025).

Amennyiben meghatározó, „atyai” személyiségekről ejtünk szót, akkor a szabad szemmel is látható „nagygombák” megfigyelőjét Carolus Clusius (1526-1609) flamand természettudóst nevezik a „mikológia atyjának” a 16. század közepén. A brit nemzetközösségben a „növénykórtan tudomány alapítójának” Miles Joseph Berkeley (1803–1889) brit botanikust, mikológust (főként a Phytophthora infestans kutatásai alapján) tartják (Massee 1913), jóllehet az európai kontinensen Heinrich Anton de Bary (1831–1888) német sebészt, mikrobiológust, botanikust tekintik leginkább a „növénykórtan (másik) atyjának”. Nála a Strasbourgi Egyetemen Európa nemzeti kórtanosai szinte kivétel nélkül megfordultak, az orosz Voronyintól (1838 – 1903) a brit Wardig (1854-1906), közöttük természetesen a magyar Linhart György is (Kövics 2025).

1. ábra. A fiatal Linhart György

Forrás: Az Óvári Gazdászok Szövetsége honlapja. Az 1864-ben beíratkozott évfolyam tagjainak fellelhető arcképei között

Hazánkban az agrároktatás központja a dualizmus időszakában (1867–1918) Magyaróváron volt, ahol olyan tanárok tanították a növénytannal kapcsolatos tárgyakat, mint az osztrák Haberlandt Frigyes (1851-1869), majd egy tanévre Kanitz Ágoston (1869-1870). Balás Árpád 1865-től Keszthelyen volt tanár, majd 1874-től akadémiai igazgató. 1884-ben pedig Magyaróvárra tanárnak és egyben igazgatónak nevezték ki. Ezzel kezdetét vette Óváron a nemzetközileg is jegyzett, kiemelkedő teljesítményt nyújtó tanári kar segítségével Európa egyik prosperáló intézménnyé alakulása, nagyban hozzájárulva ezzel a magyar mezőgazdaság fejlődéséhez. Balás Árpád vezetése alatt bontakozott ki az ún. Óvári Nagy Tanári Kar munkássága. Sokat tett az Akadémia körül kialakuló, országos hatáskörrel rendelkező, gombamódra szaporodó különböző kutatóintézetek létrehozása érdekében, amelyek alapítása és működése a magyar agrárkutatás igazi megindulását jelentették, Magyaróvár ezzel a hazai mezőgazdasági tudományos kutatás bölcsőjévé, illetve fellegvárává vált. Balás Árpád (1884-1897), Deininger Imre (1874-1878) és Linhart György (1874-1906) óvári tanárok mindhárman a Magyaróvári Császári és Királyi Gazdasági Felsőbb Tanintézetben végeztek, és kulcsszerepet játszottak a dualizmus-kori agrárintézmények fejlődésében (Pifkó 2018).
A fiatal Linhart Györgyöt gazdász tanulmányai (1864-1866) terelték a kutatómunka felé (1. ábra). Másfél évi gyakorlat után további tanulmányokra, három évre beiratkozott a Hallei Mezőgazdasági Főiskolára (História – Tudósnaptár KFKI). Ekkor kezdte meg szakirodalmi munkásságát is, itt Julius Kühn a növénykórtan egyik úttörő személyisége mellett tanult 1870-ig, s ekkor jelentek meg első szakdolgozatai is (Rapaics 1926).
Diplomájának megszerzését követően Oroszországban a karlovai uradalomban dolgozott Jelena Pavlovna nagyhercegnő birtokán, és tiszttartó volt Albrecht főherceg béllyei (magyar-német falu Baranya vármegyében, Fényes 1851) uradalmában (1870-1874) (Magyar írók élete és munkái 1891-1914).

Munkásságának elismeréseként 1874 október 1-én kinevezték az éppen akkor akadémiai rangra emelt Magyaróvári Magyar Királyi Gazdasági Akadémia rendes tanárává. Kinevezése megtörtént, ám a lelkiismeretes és a mikológiában máris jártas Linhart 1878-ban a Strasburgi Egyetemen dolgozott Anton de Bary növénykórtani laboratóriumában, s ott kapott iránymutatásokat élete munkásságához, amely abban az időben központja volt a mikológiának az egész világon.
Az Óvári akadémián német nyelven folytak az előadások a magyarral párhuzamosan (egészen 1884-ig még mindig voltak német- nyelvű előadások, csak 1884 óta lett kizárólagosan magyar az akadémia hivatalos nyelve), ahol a Növénytan tanszék vezetőjeként 32 esztendőn át, nyugdíjba vonulásáig működött (1874-1906) (Rapaics 1926). Gazdasági növénytant, növénybonctant, élettant, növénykórtant és ásványtant tanított. A gazdasági növénytan tanítását először emelte olyan színvonalra, amely a tudományos és a gyakorlati követelményeket egyaránt kielégítette. Ő vezette be a tanszékén a szemléltető oktatást. Az ifjú magyar gazdanemzedéket oktatva az egyike volt azoknak az igazi tanároknak, akik testük minden erejét és lelkük minden melegét hivatásuknak szentelték. Egész munkás életében a tudomány fejlesztése s annak a gazdatársadalom minél szélesebb rétegeiben való terjesztése érdekében dolgozott (2. ábra).

2. ábra. A középkorú Linhart, a tanárember portréja

Forrás: László L. 2000

Puritán egyéniségében egyesült a nagy tudás a szerénységgel, a szívjósága és a lélek finom érzékenysége a vasakarat erővel és fáradhatatlan munkássággal: előadásait az egyszerűség jellemezte, tudományos munkálkodását pedig az alaposság. Tanítványai nálánál jobb és igazabb tanárt nem igen ismertek, mert Linhart tanári működése alatt fáradhatatlan tevékenységgel dolgozott azon, hogy gazdag ismereteit közértékűvé tegye. Hallgatóinak nemcsak tanára, hanem valóságos atyja is volt, ezt bizonyítja az a nagy szeretet és tisztelet, amellyel hallgatói az akadémián, majd a gyakorlati életbe kikerülve, állandóan körülvették. A szeretet bizonyítéka az is, hogy a hallgatók évtizedek után is mint „jó Nagyságost" vagy pedig mint „Linhart papát" emlegették (Rothmeyer 1925). Joviális tanári személyiségéről humoros anekdoták is kerengtek: Kerpely (1925) nyomán egy felkészületlen hallgató „sikeres” vizsgájának történetét is elmeséli: „Buta szegény, jó Nagyságos úr”! -kiabálták a társai. És az áldott jó szívű professzor úr csak annyit mondott: „Na fusson! Fusson!” – és beírta a „kielégítő” osztályzatot (László 2006).

Linhartot állandóan foglalkoztatták a mezőgazdasági szakoktatás átszervezésének kérdései. Darányi Ignác földművelésügyi miniszter az 1890-es évek végén ismét felvevette az új budapesti mezőgazdasági főiskola felállításának tervét. Megbízást kapott tanulmányozni a külföldi példákat: ennek során felkereste a müncheni, zürichi, párizsi, bonni, hohenheimi, berlini, hallei és bécsi szakoktatási intézeteket, azonban ez a terv soha nem valósult meg (Magyar Agrártörténeti Életrajzok 1988). A külföldi példák nyomán nagy szerepet vállalt az immáron öt gazdasági akadémiára bővült agrár-felsőoktatásra egységesen vonatkozó, 3 éves képzésű, magasabb követelményű tanmenet összeállításában (Magyar Írók Élete és Munkái 1891-1914; Wikipédia 1 2009). A gazdasági vonatkozású növényfajoknak nemcsak felismerését, rendszertani ismeretét, hanem szövettani és élettani sajátságainak tudását is megkívánta.
Másik tevékenysége kísérletügyi téren nyilatkozott meg. Célja volt, hogy a gazdasági szaktudományokat fejlesztő kísérletügyi állomások alakuljanak. Korszerűsítette a vetőmagvizsgálat módszereit. A sokoldalú Deininger Imre a Debrecenből a magyaróvári akadémiára jutott a prehisztorikus magvak feldolgozása révén is hírnevet szerzett gazdatanár, aki 1878-ban megalapította az első hazai kísérletügyi intézményünket, a Vetőmagvizsgáló és Növényélettani Kísérleti Állomást (Rapaics 1926).
Linhart 1884-ben Deininger Imrétől átvette (a Gazdasági Akadémiához tartozó) vetőmagvizsgáló állomás vezetését, minthogy Deiningert kinevezték a keszthelyi tanintézet igazgatójává, majd 1897-ben megszervezte és 1910-ig vezette a Magyar Királyi Állami Vetőmagvizsgáló, Növényélet- és Kórtani Állomást, ugyancsak Magyaróváron. Itt alapozta meg a hazai növénykórtani és növényvédelmi kutatást. A 19. szd.végén a cukorrépa termesztés egyre jelentősebbé vált, de a a hazai vetőmag hiánya és a répát károsító betegségek fellépése miatt a szokásos magvizsgálatok mellett elvárta, hogy egészséges, jó minőségű vetőmagvakat hozzanak forgalomba. Kidolgozta a cukorrépa- és burgonyabetegségek, a gabonák üszög- és a rozsdabetegségei elleni védekezést (3. ábra).

3. ábra. A legismertebb Linhart György időskori portréja. Forrás: Moson Megyei Életrajzi Lexikon (2016)

Forrás: https://web.archive.org/web/20160806213258/http://mmel.nansoft.hu/?o=szc&c=364

A gabonák üszöggomba betegségei hosszú századokon át komoly kártételt jelentettek a gazdáknak. Isaac-Benedict Prévost svájci teológus és természetbúvár (1807) megállapítása, hogy az üszöggomba (később, 1873-ban J. Kühn nevezte el Tilletia laevis-nek) mikroszkópban megfigyelt csírázó spórái felelősek a betegség előidézéséért, sokáig feledésbe merültek (Prévost 1807). Prévost azt is megfigyelte, hogy a rézgálicnak üszögspóraölő tulajdonsága van (Kövics 1989).

Fél évszázaddal később, 1859-ben Julius Kühn kísérletei alapján látható volt, hogy a kőüszög magcsávázással leküzdhető, de a hazai gazdatársadalomba ezen ismeret nagyon nehezen tudott gyökeret verni azon ismeret, hogy mi okozza a gabona üszkösödését. Linhart fiatalabb munkatársával, Mezey Gyulával (1861 – 1922) egzakt kísérletekkel vizsgálták meg a rézgálicos csávázás használhatóságát a kőüszög elleni védelemre. Hosszú ideig még az is tisztázatlan volt, hogy a kőüszögök (Tilletia spp.) és a porüszögök (Ustilago spp.) biológiájukban alapvetően különböznek: az előbbiek csíranövény fertőzők és a spórák a mag felületén megtapadva elpusztíthatók, addig a porüszögök virágfertőzők, és a mag belsejében (endospermium) nem érhetők (pusztíthatók) el egyszerű kontakt csávázószerrel.
Az ún. Linhart-féle kosaras csávázás a búza kőüszög betegségei (Tilletia spp.) ellen a rézgálic oldatra alapozott csávázási módszert rajta keresztül ismerte meg a gazdaközösség, amelyet 1885-től az 1945–50-es évekig alkalmaztak (Kövics 2025). A kosaras csávázási módot – Linhart előírásait részletesen ismertetve – megtalálhatjuk Bognár Sándor (1994) kitűnő könyvében. A gazdálkodók körében az ismeretek terjesztését még képeslap formájában is, ismeretterjesztő módon elősegítették (4. ábra).

4. ábra. Búza vetőmag kőüszög (Tilletia sp.) elleni csávázási folyamatai rézgáliccal: az ún. Linhart-féle kosaras csávázás

Forrás: Ismeretterjesztő képeslap, Klösz György alkotása

A szőlőt nemcsak a behurcolt filoxéra (szőlő gyökértetű) megjelent Pancsován (1875, Torontál vármegye), majd a szőlő peronoszpóra 1880-as behurcolását követően a minisztérium Linhartot és Mezey Gyulát Franciaországba küldte tapasztalatok gyűjtésére, a termelők megsegítésére, amelyről több tanulmányban számoltak be (Magyar Agrártörténeti Életrajzok 1988).

A Köztelek folyóirat az Országos Magyar Gazdasági Egyesület (OMGE) közlönye, köz- és mezőgazdasági lap volt, amely 1891-1944 között jelent meg hetente kétszer. Linhart az OMGE tagja és szerzője is volt, mintahogy tagja a Magyaróvári Széchenyi Körnek is, amely hölgytagjai közül nősült (Moson Megyei Életrajzi Lexikon 2016).

LINHART GYÖRGY SZAKIRODALMI MUNKÁSSÁGA

A szakmai munkásság szakcikkekben, közleményekben megjelent írások összegyűjtése pontos bibliográfiai adatokkal – egy évszázad távlatában – csaknem lehetetlen. Éppen ezért az összeállításunkban részben általános, részben konkrét hivatkozásokkal néhány ezeket tárgyaló korábbi cikkek adataira támaszkodhattunk. Ezek kronológikusan követik Linhart munkásságának éppen időszerű tudományos érdeklődési területeit, ugyanakkor néhány kiemelkedő jelentőségű munkájára külön is utalunk. A szakirodalmi adatok – ismereteink szerntí eddigi legteljesebb – összeállítása a Magyar Írók Élete és Munkái (1891-1914), a Pallas Nagy Lexikona (1895), Balás (1897), a Magyar Könyvészet - Bibliographia Hungariae (Petrik 1906), a Magyar Mezőgazdasági Múzeum (MMgMK Digitális Könyvtár), Rothmeyer (1925), a Magyar Könyvészet (Kozocsa 1942) és Bognár (1994) összeállításai alapján készült, és melyek főként a fitopatológia témaköreit érintik (Linhart munkásságának össszegzése azonban korántsem teljeskörű, esetenként hiányosak vagy ellentmondásosak a bibliográfiai adatok).
Az egyes betegségek beazonosítását a hivatkozás végi zárójeles megjegyzések, illetve a ma érvényes tudományos nevek segítik „=", a bibliográfiai adatok hiányosságait „?" jelölik.
Linhart cikkei a hazai Természettudományi Közlönyben, a Gyümölcsészeti és Konyhakertészeti Füzetekben, a Köztelekben, a Magyar Nemzetben, a Kisérletügyi Közleményekben, továbbá külföldi lapokban jelentek meg.

Linhart Gy. és Cserháti Sándor (1876): A kártékony rovarok kérdéséhez. Apróbb közlemények.Természettudományi Közlöny 8(88): 474.
Linhart Gy. (1878): Magyarország szárított gombái. Természettudományi Közlöny, Budapest.
Linhart Gy. (1881): A gyümölcsfák állati és növényi ellenségei, ábrákkal. Gyümölcsészeti és Konyhakertészeti Füzetek
Linhart Gy. (1881): A szőlőpenész (Oidum Tuckeri). Budapest. /= A szőlő lisztharmata (Uncinula necator, = Erysiphe necator)/
Linhart Gy. és Mezey Gyula(1885): Vetőmag-csávázási kisérletek. Kőnyomat. Magyar-Óvár.
Linhart Gy. és Mezey Gy. (1885): (?) A rézgálicos csávázás (?) Mezőgazdasági Szemle 1885 (3) Magyar-Óvár.
Linhart Gy. és Mezey Gy. (1887): (?) A rézgálicos csávázás (?) Mezőgazdasági Szemle 5 Magyar-Óvár.
Linhart Gy. (1889): Vetőmag-csávázási kisérletek. Bolti csávák. A porüszög. Kőnyomat. Magyar-Óvár.
Linhart Gy. és Mezey Gy. (1889): (?) A rézgálicos csávázás (?) Mezőgazdasági Szemle 7 Magyar-Óvár.
Linhart Gy. és Mezey Gy. (1890): A dohány mozaikbetegsége. Kőnyomat. Magyar-Óvár.
Linhart Gy. (1890): A magyar-óvári állami vetőmagvizsgáló állomás 1878–1889. évig terjedő működésének összeállítása. Magyar-Óvár.
Linhart Gy. és Mezey Gy. (1889): Vetőmagcsávázási kisérletek. Magyar-Óvár.
Linhart Gy. (1891): A Jensen-féle (mint: „Jenson") porüszög elleni védekezés módja. Kőnyomat. Magyar-Óvár.
Linhart Gy. (1891): A Black-rot néven ismert szől(l)őbetegség tanulmányozása végett 1891-ben Francziaországba kiküldött megbizottak jelentései. Budapest. /A szőlő fekete rothadása (Guignardia bidwellii, = Phyllosticta ampelicida)/
Linhart Gy. (1892): A szől(l)ő Black-rot betegsége. Kőnyomat, Budapest.
Linhart Gy. és Mezey Gy. (1895): Szől(l)őbetegségek. 190 l. Nyolcz szines táblával és 85 szövegrajzzal. Magyar-Óvár.
Linhart Gy. és Mezey Gy. (1895): A szőlő peronos(z)póra betegsége(i). Magyar-Óvár.
Linhart Gy. (1896): A gabonafélék üszög- és rozsdabetegségei, különös tekintettel a védekezésre. Kőnyomat. Pátria, Budapest. 17 l.
Linhart Gy. (1898): A magyarországi felsőbb gazdasági tanügy újjászervezésének kérdése. Tanulmány. Magyar-Óvár.

Linhart Gy. (1898): Ujabb tapasztalatok a gabonarozsdáról. Különlenyomat a Természettudományi Közlöny 345. füzetéből 4 l.. Ny. n. Természettud. Közlöny, Budapest.
Linhart Gy. (1898): A magyarországi felsőbb gazdasági tanügy ujjászervezésének kérdése. Jelentés dr. Darányi Ignác val. belső t. tanácsos, földmivelésügyi m. kir. miniszter ur ő nagyméltóságához, Franciaország-, Németország-, Svájc- és Ausztriában az 1897. év nyarán tett tanulmányútról. Győrött, Nitsmann József könyvnyomdája. M.-Óvár. 129 l.
Linhart Gy. (1899): A magyarországi felsőbb gazdasági tanügy újjászervezésének kérdése. 2. kiadás. Tanulmány. Magyar-Óvár.
Linhart Gy. (1899): A búza torsgombája. Különlenyomat a Kisérletügyi Közlemények II. kötet, 3. füzetéből. 4 l.) Budapest, M. kir. növényélet és kórtani állomás. Pallas r.-t. könyvny. Magyar-Óvár. (Ophiobolus graminis, = Gaeumannomyces graminis)
Linhart Gy. (1899): A gabonarozsda tanulmányozása. 11. Pátria Könyvnyomda, Budapest. (= Puccinia spp.)
Linhart Gy. (1899): A magyar-óvári m. kir. vetőmag-vizsgáló, növényélet és kórtani állomás jelentése az 1898. jan. 1-től 1899. jun. 30-ig terjedő másfélévi működéséről. 8-r. 45 és 1 l. Czéh Sándor könyvny. M.-Óvár.
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Linhart Gy. (1903): Gyümölcsfáinknak élősdi gombák által okozott betegségei és az ellenük való védekezés. Földmívelésügyi Minisztérium Növényélet- és Kórtani Állomás. Magyar-Óvár.
Linhart Gy. (1904): A dinnye és ugorka lisztharmatbetegsége. Különleny. a kísérleti Közleményekéből. (8 r. 3 1.) Bpest. Pallas r.-t. ny. cit.: Magyar Könyvészet 1901-1910. 1917. Bp.11-12.f. 35. l. (Erysiphe cichoracearum, = Golovinomyces cichoracearum és/vagy = Podosphaera fuliginea) https://archive.org/stream/magyarkonyveszet52unse/magyarkonyveszet52unse_djvu.txt
Linhart Gy. (?): A burgonyavész. Földmívelésügyi Minisztérium Növényélet- és Kórtani Állomás, Magyaróvár, 13 1.
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Linhart Gy. (1913): Gazdasági kultúrnövényeink baktériumok által okozott betegségei. A m. kir. – fennhatósága alatt álló M. kir. Növényélet- és Kórtani Állomás Magyaróvárott. Bp. Magyaróvár, 1911–1913. Pátria. Mosonvármegye nyomda 10 l.

Linhart Gy. (1913): A szántóföldi gyomok. 2. kiad. A m. kir. – fennhatósága alatt álló M. kir. Növényélet- és Kórtani Állomás Magyaróvárott. Bp. Magyaróvár, 1911–1913. Pátria. 8 l.
Linhart Gy. (?): A szántóföldi gyomok irtása. Földmívelésügyi Minisztérium Növényélet- és Kórtani Állomás Magyaróvárott, Bp. Magyaróvár, 1911-1913. 130.
Linhart Gy. (1913): A burgonyavész. 2. kiad. A m. kir. – fennhatósága alatt álló M. kir. Növényélet- és Kórtani Állomás Magyaróvárott. Magyaróvár, 1911–1913. Pátria. 7 l.
Linhart Gy. (1913): Legfontosabb mezőgazdasági kultúrnövényeinken előforduló élősködő gombák, illetve baktériumok és az ellenök való védekezésmódok. 3. kiad. A m. kir. – fennhatósága alatt álló M. kir. Növényélet- és Kórtani Állomás Magyaróvárott. Magyaróvár, 1911–1913. Pátria. 26, 2 l.
Linhart Gy. (1914): Gyümölcsfáinknak élősdi gombák által okozott fontosabb betegségei és az ellenük való védekezés. 2. kiad. A m. kir. – fennhatósága alatt álló M. kir. Növényélet- és Kórtani Állomás Budapesten, 1914-1917. Budapest. Pátria. 29 l.
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Linhart Gy. (1914): Az árpa és a zab Helminthosporium betegsége. Földmívelésügyi Minisztérium Növényélet- és Kórtani Állomás Budapesten, 1914-1917. Budapest. 6 l. (= Pyrenophora teres ill. = P. avenae)
Linhart Gy. (1914): A bordói lé készítése és alkalmazása. 3. kiad. Földmívelésügyi Minisztérium Növényélet- és Kórtani Állomás Budapesten, 1914-1917. Budapest. Pátria. 5: 1 l.
Linhart Gy. (1914): A dinnye és ugorka állisztharmat betegsége. 2. kiad. Földmívelésügyi Minisztérium Növényélet- és Kórtani Állomás Budapesten, 1914-1917. Budapest. Pátria. 3: 1 l. (= Pseudoperonospora cubensis)
Linhart Gy. (?): A cukorrépa gyökérfekélye. Földmívelésügyi Minisztérium Növényélet- és Kórtani Állomás, Budapest.

MAGYARORSZÁG GOMBÁI (CENTÚRIÁK) – AZ ELSŐ MIKOLÓGIAI KÓRKÉP GYŰJTEMÉNY HAZÁNKBAN

Linhart Gy. (1882-1887): Schaedae Fungi Hungarici exsiccati. Cent. I – V. Magyar-Óvár.

/nyers fordítással németből: „Magyarország károsító (növénykórokozó) gombáinak herbáriumi szárítmányai”/

Használatos még a kórkép gyűjteményre a „Magyarország gombái”, a „Fungi Hungarici” megnevezés is (Pallas Nagy Lexikona 1895; Paál 1925).

A növénykórtani vonatkozású első mikológiai gyűjteményt Linhart tette közzé. A gyűjtemény felöleli a 19. század hazánkban károsító gombáinak legnagyobb részét (Jakucs és mtsai 2025). A megjelent kötetek (centúriák) (centurium, lat. a centum = száz; 100-as egységek), 5 kötet exsiccate (szárított növény, kórkép) gyűjtemény nemcsak magának vívott ki tudományos elismerést és nemzetközi hírnevet, hanem a magyar növénykórtan akkori mikológiai ismereteinek minden fontosabb területére betekintést nyújtott. Az öt kötet 200-200 példányban jelent meg és terjedt el Magyarországon, de eljutott számos külhoni növényvédelmi és botanikai intézetbe. Ez akkoriban a korszerű mikológiai törekvések elsöprő és egyetlen képviselője volt. Az egyes kötetekhez 15-20, mindösszesen 89 faj rajza részben eredeti, részben képek után készült ábra is tartozik. Bognár (1994) könyvében részletesen felsorolja az egyes centúriák gomba (illetve néhány esetben baktérium) genus-ainak fajszámait (amelyek felsorolásában kisebb

nyomdahibák előfordulnak). A kórképek meghatározásában Linhart mellett Schulzer István, Mágócsy-Dietz Sándor, Hazslinszky Frigyes, Hensch Árpád, Kalchbrenner Károly, Klein Gyula, Kosutány Tamás, Szépligeti Győző, Heinrich Rehm, Gustav Niessl, Pier Andrea Saccardo, Felix von Thümen és mások is részt vállaltak, velük gyakori levelezésben is állt.
(Linhart) „legjelentékenyebb munkája Magyarország gombái (Fungi Hungarici), mely több új fajt tartalmazva, 5 centuriában 3 nyelven (magyar, latin és német) irott magyarázó szöveggel és számos rajzzal M.-Óvárt 1882–87. jelent meg" (Pallas Nagy Lexikona 1895).
Érdekes tudomány-finanszírozási adalék, hogy Linhart munkájához a Magyar Tudományos Akadémia „Mathematikai és természettudományi bizottsága…a) Tudományos és különösen hazánkat érdeklő kutatások eszközlésére anyagi támogatást nyújtott:…9. Linhart György «Magyarország gombái» czímű munkája kiadására és magyarországi gombák további tanulmányozására 150 forintot" … (MTA Értesítő 1886).

LINHART ELISMERÉSEI

Tudásának tekintélye külföldön is elismerést szerzett. Gazdag hazai irodalmi munkássága mellett német, angol, francia és orosz szaklapokban sűrűn jelentek meg értékes közleményei.
Tudományos munkálkodása elismeréséül számos külföldi intézet rendes, vagy levelező tagjává választotta.
Világhírű gombagyűjteménye alapján (Schaedae Fungi Hungarici exsiccati. Cent. I – V.) a párizsi világkiállításon (1889) aranyéremmel jutalmazták.
Tulajdonosa volt a svéd „Északcsillag"-rend lovagkeresztjének, a francia „Officier deconstruction publique" tisztikeresztjének.
A magyar kormány is számos ízben jutalmazta kiváló érdemeit, királyi tanácsos, a Ferenc József-rend lovagkeresztese (1898) volt, 1922-ben a gazdasági főtanácsosi címmel ruházta fel a kormányzó (Rothmeyer 1925).

LINHART GYÖRGY EMLÉKEZETE

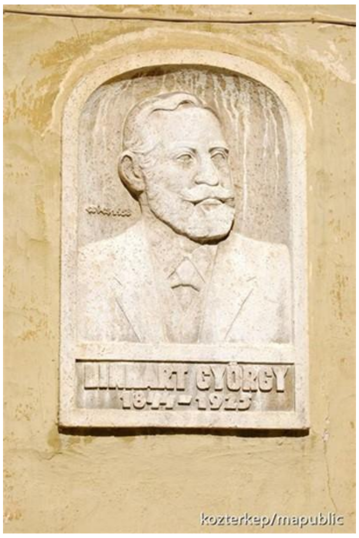
Linhart 1906-ban vonult nyugalomba, mint akadémiai tanár, de 1910-ig vezette a neki oly kedves Növényélet- és Kórtani Állomást. Ekkor végleg visszavonult az állami szolgálatból, de társadalmi tevékenységét majdnem haláláig folytatta (Rothmeyer 1925). Linhart nyugdíjazása után Mezey Gyula vette át Magyaróváron a növénykórtan oktatását.

Linhart György 80 éves korában, 1925. január 27-én halt meg, a mezőgazdaság nagy halottjának földi maradványait január hó 29-én helyezték örök nyugalomra a magyaróvári temetőben lévő márvány családi sírboltba.

- Linhart személyiségéről, munkásságáról különböző folyóiratok nekrológokban számoltak be magyar és német nyelven (Rothmeyer 1925; Paál 1925; Rapaics 1926).
- Megemlékező cikkek születésének évfordulóin: 125. év (Varga 1969), 130. év (Milinkó 1974; Szelei 1974), 155. év (László 1999; Kuroli 1999).
- Linhart halálozási évfordulóin: 75. év (Bognár 2000a,b,c; Geday 2001; László 2000), 100. év (Kövics 2025), vagy a jelen írás keretében (Kövics és Reisinger 2025).
- Az agrárium – oktatás – növényvédelem – növénykórtan különböző hosszúságú időszakokról szóló írásokban: 1030-1980 (Bognár 1994), a Magyaróvári Gazdasági Felsőbb Magántanintézet alapítása (1818), majd a jogutód Gazdasági Akadémia agrár-felsőoktatás bicentenáriuma alkalmából (Horváth 2019), a dualizmus (1867–1918) korának botanika oktatásáról (Pifkó 2018),

vagy a növénykórtan történetéről (Joel próféta könyve, Kr.e. 9-8. szd. ószövetségi hagyatékoktól Vánky Kálmánig, a 21. szd. elejéig) (Kövics 2019).

– Ide sorolandók azok az internetes források, amelyek szócikkeiből az új generációk gyors alapinformációkat szerezhetnek Linhart Györgyről, a jeles példaképről (Moson Megyei Életrajzi Lexikon 2016; Köztérkép; Agrároldal; Magyar Könyvészet 1712–1920; Wikipédia 1 2009).
– Óváron utcát neveztek el róla („Linhardt” írásmóddal).
– Portré domborműve a vár relief-panteon falán található, Csúcs Ferenc (1958) alkotása (5. ábra).



5. ábra. Linhart György portré-dombormű

Forrás: Köztérkép

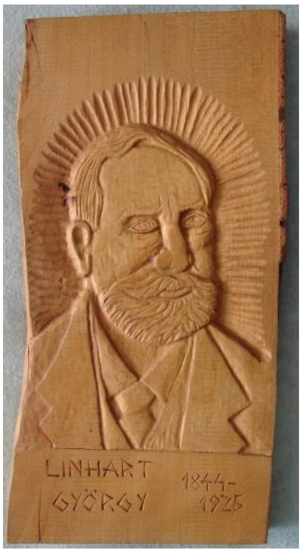
– A Linhart György-emlékérem szócikk (Wikipédia 2 2023). A Linhart György-emlékérmet tiszteletére alapította meg a Magyar Növényvédelmi Társaság a növénykórtan kiemelkedő személyiségeinek évenkénti elismerésére (Kövics 2025). Az elismeréseket a Növényvédelmi Tudományos Napokon, rendszerint a Magyar Tudományos Akadémia dísztermében adják át a rákövetkező év február hónapjában. Az emlékérem (6. ábra) és oklevél mellé a kitüntetett megkapja a tölgyből készített „vándor" fatáblát is (7. ábra), amely Fischl Géza növénykórtan-professzor faragványa Linhart György portréjával, a hátoldalán a kitüntetettek nevének bevésésével és az „átmeneti birtoklás” évszámával (Wikipédia 2 2023). A szócikk tartalmazza a kitüntettek neveit és laudációjuk bibliográfiai adatait 1992-2024 időszakban. (Megjegyzés: A Wikipédia nevezett szócikkéből csak a hátlap fotóját tartották meg, a többit eltávolították.)

6. ábra. A Linhart György-emlékérem elő- és hátlapja. Az érem tervezője Csiby Mihály

Fotó: Kövics György

7. ábra. Linhart György (1844-1925) tölgy „vándor” fatábla elő- és hátlapja (1992-től). Fischl Géza faragványa

Fotó: Kövics György



– A magyar nemzet számára maradandót alkotó, illetve hősi személyek temetkezési helyének védelmére született meg 1999-ben az úgynevezett Nemzeti Sírkert, amely több mint 6200 sírt számlál országszerte. A Nemzeti Örökség Intézete (NÖRI), a mosonmagyaróvári önkormányzat, a Széchenyi István Egyetem Albert Kázmér Mosonmagyaróvári Kara, az Óvári Gazdászok Szövetsége, valamint Nagy István agrárminiszter, a térség országgyűlési képviselője a magyaróvári temetőben közösen adták át a Nemzeti Sírkertbe sorolt sírhelyeket jelölő, ún. okos parcellakövet 2024. szeptember 26-án (Moson Vármegye Tematikus Magazin 2024). Országosan immár több mint negyven temetkezési helyen találhatók olyan parcellakövek, amelyek egy QR-kód segítségével nemzetünk nagyjainak személyiségét mutatják be röviden. A Magyaróvári temető okos parcellaköve 21 jeles személyiségről – közöttük Linhart Györgyről is – megemlékezik (Nemzeti Örökség Intézet 2025).

LINHART TEVÉKENYSÉGÉNEK SZÍNHELYEI SZÁZ ÉV MÚLTÁN

A Magyaróvári Magyar Királyi Gazdasági Akadémia, majd a nyomában létesült másik négy (Keszthely, Debrecen, Kassa, Kolozsvár) felsőfokú mezőgazdász-képző intézményekből a Trianon Békediktátummal (1920. június 4.) az utóbbi kettőt elszakították az anyaországtól. Az akadémiák főiskolákká, majd Agráregyetemekké alakultak 5 éves képzési idővel – a kor igényeit és a tudományos fejlődést követve. A permanens szervezeti átalakulások összevonásokat, 2006-tól a bolognai képzési struktúra (3 év BSc, 2 év MSc és PhD) kritika nélküli átvételét eredményezte.

A Magyar Királyi Állami Vetőmagvizsgáló, Növényélet- és Kórtani Állomás, továbbá az Országos Phylloxera Kísérleti Állomás (1880), amely 1890-ben Magyar Királyi Állami Rovartani Állomássá alakult, az 1932-ben Budapesten létrehozott Növényvédelmi Kutatóintézet jogelődjei voltak (Gáborjányi 2000; Kövics 2025). Éppen ezért kicsit csalókák azon „jubiláló” cikkek címei, amelyek a 200 éves Növényvédelmi Kutatóintézetről (különböző jelzőkkel – felügyeleti szervek előtagjaival, pl. MTA, jelenleg HUN-REN – láttak el) szólnak, mintahogy a Debreceni Egyetem fennállásának kezdeti idejét (2000) a de facto jogelőd egyetem létesítésének dátumát (az 1918-ban alapított Debreceni Magyar Királyi Tisza István Tudományegyetem) nemes egyszerűséggel az 1538-as alapítású (valóban ősi) Református Kollégiumra vezeti vissza, jelvényén az „alapítás” patinás évszámát felhasználva.

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Commemoration of György Linhart, the Father of Hungarian Plant Pathology, on the Hundredth Anniversary of His Death

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György Linhart (1844-1925), the father of Hungarian plant pathology, that is, the first, decisive personality, who is also considered a botanist and mycologist, died exactly 100 years ago. Linhart was a professor at the Academy of Agriculture in Magyaróvár at a significant period when the development of scientific plant pathology began to develop on a huge scale all over the world, in the second half of the 19th century, under the leadership of Heinrich Anton de Bary, a professor at the University of Strasbourg. The most distinguished scientists of each nation were sent on a study trip to the laboratory of the founder Anton de Bary to acquire new knowledge of plant pathology and mycology. In 1874, the young but already experienced Linhart was appointed professor at the Academy of Agriculture in Magyaróvár, which at that time became one of Europe's outstanding higher agricultural schools with excellent teachers and rapid development. Linhart was a teacher there for 32 years. In 1897 he organized and led the Hungarian Royal State Seed Examination, Plant Physiology and Pathology Station, also in Magyaróvár. Linhart laid the foundations for Hungarian plant pathology and plant protection research. He developed the control of sugar beet and potato diseases, smut and rust diseases of grains. Throughout Europe, Linhart's basket seed treatment by copper sulphate was adopted in the control of bunt diseases of wheat, which is caused by Tilletia spp. fungi.

Keywords: György Linhart, A. de Bary, Magyaróvár Academy of Agriculture, sugar beet diseases, potato diseases, wheat bunts, Tilletia spp., Linhart's basket seed-dressing by copper sulphate

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Ez a tanulmány az Óvári Gazdászok Szövetsége Egyesület engedélyével, másodközléssel jelenik meg; eredetileg az *Ujhelyi Imre és Szajkó László Emlékülés* emlékkiadványában került közlésre. Republished with the permission of the original publisher (Óvári Gazdászok Szövetsége Egyesület); originally published in the commemorative volume of the *Ujhelyi Imre and Szajkó László Memorial Session*.

160 éve született Ujhelyi Imre, a Tanár, a Vezető, a Tenyésztésszervező

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„Az oktatásnak nem lehet célja pusztán az ismeretek felhalmozása. A tanítás igazi feladata az, hogy a fiatal embert gondolkodó, önállóan ítélni tudó és a gyakorlatban cselekvő emberré formálja. A tudomány csak akkor ér valamit, ha a mindennapi életben és a gazdaság munkájában is hasznára válik a társadalomnak. Ezért az iskola feladata nem csupán a könyvből tanítás, hanem az életre nevelés, ahol a tudás, a tapasztalat és a munka egységet alkot.”

Ujhelyi Imre

Ujhelyi Imre (1866-1923) születésének 160. évfordulója, állattenyésztésünk jelenlegi helyzete, az előttünk álló feladatok kapcsán illő visszatekinteni a Magyaróvári Gazdasági Akadémia „nagy tanári karából” is kiemelkedő egyéniségének életútjára, oktatói, kutatói, szakmai szervezői tevékenységére. Kora legkiemelkedőbb állattenyésztője volt, akinek nagyon sokat köszönhet az ágazat. Példája azt sugallja, hogy az állattenyésztés fejlesztése elképzelhetetlen színvonalas oktatás, kutatás, tenyésztésszervezés nélkül.
Ujhelyi Imre 1866. január 12-én, Dunapatajon született. Az elemi iskola elvégzése után Kalocsán, Szekszárdon és Baján tanult. Majd a felvételi követelményként megszabott gazdasági gyakorlat letöltése után felvételt nyert a Magyaróvári Gazdasági Akadémiára (1. kép). Ott az állatbonc- és élettant, az általános állattenyésztést, a lótenyésztést, a szarvasmarhatenyésztést, a tejgazdaságtant és az állatgyógyászatot, az egykori keszthelyi gazdásztól, Cselkó Istvántól tanulta.

1. ábra: Magyaróvári Gazdasági Akadémia tablója (1886)

Oktatóinak jellemzésére tőle származik a „nagy tanári kar” megfogalmazás, amelynek később ő is a tagjává vált. Az akadémiát kiváló eredménnyel végezte el, majd 1886-ban a Károlyiak nagykárolyi birtokára került gazdasági írnoknak. 1887-ben beiratkozott a Budapesti Állatorvosi Tanintézetbe, ahol sokat tanult többek között *Tormay Bélától, Monostori Károlytól, Azary Ákostól, Hutyra Ferenctől*.
Az állatorvosi diplomát is megszerezve 1889-ben a Somogyszentimrei Földmívesiskolához került, majd ez év októberében áthelyezték a Magyaróvári Gazdasági Akadémiára, ahol oktatott, kutatott, fejlesztett, segítette a környékbeli gazdák tevékenységét, majd hosszú ideig az akadémiai igazgatója volt.

AKADÉMIAI OKTATÓI TEVÉKENYSÉGE

Óvárra kerülve bekapcsolódott az *„állatbonc és élettan”* és az *„állategészségtan”* tárgyak oktatásába. Később *Cselkó Istvántól* átvette és önállóan oktatta az *„állatbonc és élettan” tárgyat,* az első tanév I. félévében heti 4 órában, az *„állatgyógyászat, állategészségtan, állatkereskedés”* tárgyakat a második tanév II. félévében heti 3 órában. Emellett délutánonként az I. és II. félévben heti 2 óra gyakorlatot is tartott (*2. ábra*). Oktatói elfoglaltságát a hét elejére ütemezte, annak érdekében, hogy a hátralévő napokon látogathassa a környékbeli *gazdákat, segíthesse tevékenységüket.*

2. ábra: Állattenyésztési gyakorlat az Akadémián

Jelentős tananyagfejlesztő tevékenységet is végzett. Például az *„Állatgyógyászat”* 387 oldalas tankönyve nagyban segítette az akadémia hallgatóinak elméleti felkészülését. Nagy hangsúlyt fektetett a gyakorlati oktatásra. Ahogy írja „A most elérhető eredmény sehogy sem elégíthet ki; hallgatóink, amit fáradtsággal elsajátítanak, könnyűszerrel felejtik el, mert legnagyobbrészt nem látják a tanultakat. A bajon segíteni akarnék, s némileg talán segíthetek is. Szándékom ugyanis, hogy jövő félévben a hallgatókat csoportonként a helybéli vágóhídra vezetem ki, s itt képletesen és természetben mutathatom be az egyes egészséges állati szervezetet”. Emellett az akadémia gazdaságába és a környező állattartó gazdákhoz is vitte gyakorlatra az akadémiai hallgatóit. Nagy tanári tekintélyét tovább növelte, hogy az egyik gyakorlat alkalmával megmentett a felfúvódástól egy csorda marhát. Mivel szike nem volt nála, bicskát és trokárhengerként a szivarszipkát használta.

3. ábra: Az állattenyésztési Tanszék laboratóriuma (1910)

Az akadémia igazgatójaként is kiemelt feladatának tekintette az oktatás fejlesztését. A feladatokat az alábbi öt pontban foglalta össze:

„1. Az akadémia laboratóriumát ki kell bővíteni és úgy felszerelni, hogy a gyakorlati oktatásnak megfelelő alapja lehessenek (*3. ábra*).

2. A tanárok számát szaporítani kell.

3. A tanárok állását és tekintélyét emelni kell, hogy a legjobb erőket meg lehessen kapni.

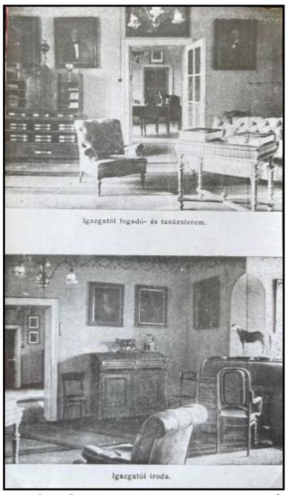
4. Szaporítani kell az asszisztensek számát.

5. A tantervet meg kell változtatni, és a tanulmányi időt három évre kell felemelni.”

4. ábra: A "Nagy Tanári Kar"

Azt a szellemiséget, amit a „nagy tanári kartól” kapott (*4. ábra*), 30 éves tanári működése alatt generációknak adta át. Számos külföldi útján szerzett tapasztalatait ugyancsak hasznosította mind az oktatásban, mint a kutatásban, fejlesztésben és tenyésztésszervezésben. Az állattenyésztés harcos egyénisége volt minden területen. A tenyésztők igen széles táborát nevelte, akik tanításainak eredményeit, korszerű módszereit a gyakorlatba közvetlen átültetve segítették az állattenyésztés magasra emelését. *Schandl József* akadémikus, volt tanítvány megfogalmazása szerint *„….az Óvári Akadémián végzett gazdaifjak az Ujhelyi-féle irányelvek apostolaként széledtek el a magyar földön.”* Tanítványai közül neves állatorvos, állattenyésztő és más tudósok, professzorok kerültek ki. Az „Ujhelyi Iskola” tanítványa volt többek között *Bánvárth Sándor* akadémiai tanár, a Magyaróvári Gazdasági Akadémia igazgatója, *Bittera Miklós* óvári akadémiai tanár, *Csiki László* keszthelyi akadémiai igazgató, tanár, *Keller Oszkár*, keszthelyi akadémiai tanár, *Konkoly Thege Sándor* egyetemi tanár, *Manninger Adolf* a Debreceni Mezőgazdasági Kísérlet Intézet igazgatója, *Náray Andor* debreceni gazdasági akadémiai igazgató, *Schandl József* akadémikus, *Surányi János* akadémikus, *Csukás Zoltán* akadémikus, *Stolp Ödön* debreceni akadémiai igazgató és még sokan mások. A felsorolt, és az itt név szerint nem említett nemzetközi hírű tudós tanítványok Óváron, és más hazai és külföldi intézményekben folytatták *Ujhelyi* tudományos, kutató, fejlesztő munkáját.

IGAZGATÓI TEVÉKENYSÉGE



5. ábra: Ujhelyi Imre igazgatói irodája

Ujhelyi Imre tíz évig (1909-1919 között) volt az akadémia igazgatója (*5. ábra*). Első beszédében programot hirdetett, amelyben kiemelte a fejlesztés fontosságát. Hangsúlyozta, hogy amíg Óvár egyedüli akadémia volt, nem voltak versenytársai és elkényelmesedhetett. „De ma már 5 mezőgazdasági akadémia van” (Debrecen, Kassa, Keszthely, Kolozsmonostor, Óvár), ami versenyhelyzetet jelent. Hangsúlyozta,hogy e nemes versenyben maga is ki akarja venni a részét és a jelszava nem az lesz, hogy „Előre”, hanem az, hogy „Utánam”.

Mivel a vár épület már szűkösnek bizonyult a tanszékek elhelyezésére, új akadémia épület építését kezdeményezte, és 1910. október 15-én elrendelte az építkezés megkezdését. Az „új Akadémia” épület (mai „B” épület) 1913 nyarára készült el (*6. ábra*).

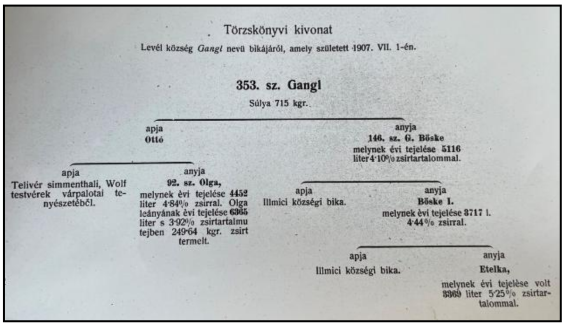
6. ábra: Az új Akadémia épület

TENYÉSZTŐI, TENYÉSZTÉSSZERVEZŐI MUNKÁSSÁGA

Ujhelyi Imre szoros kapcsolatot ápolt a környékbeli gazdákkal, állattartókkal. Elsősorban a szarvasmarha tenyésztésüket, tejgazdaságaikat segítette. Kezdetben kerékpárral, majd lófogattal járta a környéket.
Azt vallotta, hogy a szarvasmarha állomány jobbá tétele érdekében mindenekelőtt *világosan meg kell határozni a tenyészcélt.* Elhatározta, hogy a „Mosony” megyében a különböző fajtákhoz, keresztezésekhez tartozó szarvasmarha állományt szimentáli jellegűvé átalakítja (fajta átalakító keresztezés). Külföldi tanulmányútjai során ugyanis azt tapasztalta, hogy a szimentáli fajta jó tejelő, emellett kiváló hústermelő is.
1896-ban megalapította a *Magyaróvári Szarvasmarhatenyésztő Egyesület*-et, majd 1897-ben a Földművelésügyi Minisztérium jóváhagyta az egyesület alapszabályát.

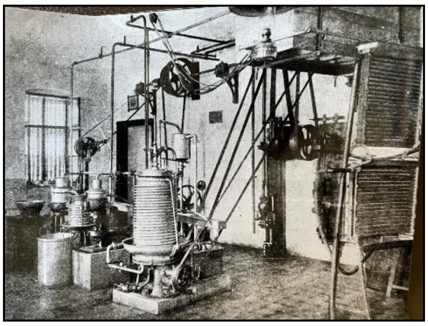
Ebben többek között az alábbiak szerepeltek:

1. Egységes eljárás alkalmazása a tenyészállatok megválasztásánál.
2. Megfelelő bikák beszerzése és a tenyészállatok rendszeres törzskönyvelése minek alapján a leszármazás hitelesen kimutatható (*7. ábra*).
3. Előadások, állatszemlék tartása.
4. Állatok és teremékek értékesítésének előmozdítása és közvetítése.



7. ábra: Törzskönyvi lap

Az egyesület kezdetben 22 taggal indult, majd 1918-ra már 2286 tagot számlált. Az alapítással megkezdődött a tenyésztési és tejelési adatok rendszeres gyűjtése és megindult mosonmegyei tájfajta kialakítása.
A törzskönyvezéshez, teljesítmény ellenőrzéshez elengedhetetlen volt *az állatok egyedi megjelölése.* Ujhelyi minden nyilvántartásba vett állat szarvába maga sütötte be a „M” (Mosony) jelet és a sorszámot.
Dániai mintára megalakította a *Tejelellenőrző Szakosztály*-t. Az ellenőrzést kiterjesztette a tejhozam mérésére, a tej zsírtartalmának meghatározására (*8. ábra*). Erre *Gerber féle* eljárást alkalmazott, amit igyekezett szélesebb körben elterjeszteni. Ellenőrizte továbbá a tehenek takarmányait, takarmányozását is.



8. ábra: A levéli tejszövetkezet tejháza

Fontosnak tartotta az összegyűjtött adatok folyamatos értékelését (adatfeldolgozás), a legjobb egyedek kiválogatását (tenyészkiválasztás). Követte azt az ősi tenyésztési elvet, hogy „párosítsd a legjobbat a legjobbal”, ezért a kiváló teheneket külföldről vásárolt tenyészbikákhoz párosította (célpárosítás), leányivadékaikat ellenőrizte (ivadékvizsgálat). A Miesbachból és Bonyhád vidékéről vásárolt állományt Bajorországból behozott tenyészbikákkal fedeztette.
Hangsúlyt fektetett a *küllemi bírálatra.* Ennek során mindig megbeszélték az állatok *„jó”* és *„rossz”* tulajdonságait. Bevezette a *szarvasmarha díjazásokat*, amely nagy hatással volt a tenyésztőkre. Tenyészállat árveréseket szervezett, amelyekre a Fekete Sas Vendéglő és Szálloda udvarán került sor. Céltudatos tenyésztői tevékenysége eredményeként a környéken, a megyében jelentősen emelkedett az egy tehénre jutó tejtermelés. Például az óvári tehenészetben, amely a legjobb volt, a tehenenkénti tejhozam 1895-ben 1838-liter, 1905-ben 2515-liter volt, 1915-ben pedig már elérte a 4062 litert (*9. ábra*). Fontosnak tartotta a gazdák, az állattartók rendszeres továbbképzését, ezért folyamatosan előadásokat, tanfolyamokat tartott számukra. Az értékesítés, tejfeldolgozás elősegítése érdekében *tejszövetkezeteket* szervezett.

9. ábra: Az óvári tehenészet tejháza

EGYÉB SZAKMAI, FEJLESZTŐ TEVÉKENYSÉGE

Kezdeményezésére 1892-ben megalakult az *Állatgyógyászati állomás*, amely egyrészt a hallgatók gyakorlati oktatását, másrészt a helybéli és környékbeli szegényebb gazdák állatainak gyógyítását is szolgálta.
Nagy hangsúlyt fektetett az állategészségügyi kutatásokra, amelynek akkoriban elsősorban a tuberkulózis elleni védekezés volt a fő feladata. Munkájának eredménye a *Bang-Ujhelyi féle* eljárás a szarvasmarha-gümőkor elleni védekezésben, időállónak bizonyult.
Ugyancsak kezdeményezte a *Tejgazdasági Kísérleti Állomás* létesítését (*10. ábra*), amely 1903-ban kezdte meg működését. Irányításával készült az „Óvári sajt” és az „Ilmici sajt”. Fontos hangsúlyt fektetett az egyéb állatfajok tenyésztésére is. Tenyészbaromfi, kecske akciókat szervezett, szorgalmazta a hússertés tenyésztés bevezetését, közvetítette a yorkshire fajtát.

10. ábra: Tejgazdasági Kísérleti Állomás (1903)

UJHELYI IMRE HAGYATÉKA, EMLÉKEZETE

Oktatói, kutató, vezetői, tenyésztőszervezői munkája mellett folyamatosan publikált. Több, mint 320 tudományos és népszerűsítő írása maradt ránk, amelyek különböző hazai és külföldi szaklapokban jelentek meg. Ez az akkori technikai feltételek közepette, és figyelembe véve, hogy mindössze 57 évet élt, rendkívül kimagasló szakirodalmi munkásságnak tekinthető.
Az 1936. május 31 és június 2. között tartott „Óvári Gazdanapok” rendezvényen az akadémia épülete mellet került sor *Ujhelyi Imre* szobrának leleplezésére, amely szobor Pátzay Pál szobrászművész alkotása *(11. ábra).* Emellett szülőfalujában Dunapatajon, Levél községben, Budapesten, Kaposvárott, Szentlőrincen, Csermajorban és másutt és áll *Ujhelyi Imre* szobor. Az óvári vár belső falán pedig kő relief is őrzi emlékét.
Mosonmagyaróvár város utcát és általános iskolát nevezett el *Ujhelyi Imréről*. Nevét viseli a Szentlőrinci Mezőgazdasági Szakközépiskola és viselte az egykori Csermajorban működött Tejipari Szakközépiskola is. A Földművelésügyi Minisztérium az egykori Magyar Agrártudomány Egyesület kezdeményezésére *Ujhelyi Emlékplakett (Ujhelyi Díj)* kitűntetést alapított, amelyet első ízben a szarvasmarha tenyésztésben, törzskönyvezésben, és az állategészségügyben nyújtott kiemelkedő tevékenységért ítéltek oda. Emlékére megalakult és működött az Ujhelyi Imre szabadegyetem.

11. ábra: Szoboravatás (1936)

Ujhelyi Imre eredményei nemcsak a ránk maradt épületekbe, szobrokba, intézményekbe, irodalmi forrásmunkákba épültek be, hanem közvetlen hasznosultak hazánk és a világ állattenyésztésében. Közvetítették *Ujhelyi* szellemét a közelmúlt és napjaink munkájához, irányt mutatva a mai állattenyésztési kutatásokhoz, fejlesztésekhez. Azt vallotta, hogy "Mindig a közérdek, főleg a kisember érdeke vezetett".
Az egykori tanítvány, majd munkatárs *Schandl József* akadémikus (1957) szerint *„Azt, hogy állattenyésztésünk 10-15 év alatt behozta fél évszázados lemaradását, elsősorban Újhelyi Imrének köszönhetjük*.”

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Szajkó László öröksége – oktatás, kutatás egysége az állattenyésztésben

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Szajkó László 1922. május 2-án született Eleken. Középiskolai tanulmányait Budapesten végezte, majd Mosonmagyaróváron *1946-ban* szerezte meg a Magyar Agrártudományi Egyetemen a diplomáját. *1948-ban* tanári képesítést szerzett. *1959-ben* Gödöllőn *summa cum laude* doktorált és *1967-ben* nyújtotta be, majd védte meg kandidátusi értekezését. A MTA doktora fokozatát *1990-ben* szerezte meg (*1. ábra*).

1. ábra: Szajkó László tudományos diplomája és tudományos fokozatai

1942-44 között tanulmányai mellett – megszakításokkal – 13 hónapot töltött nagyüzemi gyakorlatban, ahol főleg állattenyésztési feladatokat végzett.
Oktatói, szakmai munkáját 1944 derekán kezdte meg Magyaróváron, Baintner professzor tanszékén demonstrátorként, ahol kutatómérnökként dolgozott.
Az oklevél megszerzése után, 1946-tól – álláshely hiányában – kinevezésre nem- számíthatott, mégis a tanszéken maradt, ahol a tízezres kísérleti keltető üzem vezetését végezte. Kísérleteket folytatott az akkor még kevésbé tisztázott keltetés alatti tojássúly-csökkenés és a gép páratartalma és hőfoka közötti összefüggések tisztázására. Vizsgálta fajtatiszta és keresztezett baromfi-állományok tojásainak életképességét és keltethetőségét.
Megállapította három tyúkfajtánál az optimális keltető tojások súlyát.

1946-47-ben az Országos Termelési Bizottság Magyaróvári Kirendeltségénél dolgozott, ahol a földreform realizálása kapcsán a meg nem művelt területek szerződéses hasznosításával foglalkozott és közben az egyetemen kutatómunkát folytatott.
1948-1952-ig a Földművelésügyi Minisztérium Szakoktatási Főigazgatóságán, mint állattenyésztési tanulmányi előadó és osztályvezető-helyettes dolgozott. Részt vett az egyetem és a középiskolák tananyag reformjában és az új egyetemi jegyzetek és a középiskolai tankönyvek megírásában, illetőleg szerkesztésében.
Négy év minisztériumi szolgálat után *1952-ben a Magyaróvári Mezőgazdasági Technikumhoz* tanárként helyezték át. Ekkor oktató tevékenységét szakmailag és didaktikailag kiemelkedőnek ítélték, és ezért megbízták több *országos bemutató tanítás* tartásával és tagja lett az Országos Tanulmányi Bizottságnak. Már ekkor megbízták a főiskola újra szervezésének ügyeivel.

2. ábra: Anatómiagyakorló, laboratóriumok az 1960/70-es években

1952-től kezdte meg a mai *Állattenyésztéstani Tanszék* megszervezését. Olyan szertárat és laboratóriumot épített ki, amelyet az anatómia, az állattenyésztés, a tejgazdaságtan és takarmányozástan oktatása terén dolgozó tanárok számára országosan is bemutattak. *1953-tól*, az Agrártudományi Főiskola újraműködésétől kezdve, mint egyetemi docens, majd egyetemi tanár, Magyaróváron az Állattenyésztési Tanszéket vezette 1987-ig (*2. ábra*).

3. ábra: Szajkó László dolgozószobájában

Az első években háromszemélyes tanszéki létszám mellett a hármas tárgykörhöz tartozó témák előadását egyedül tartotta (állattenyésztés, takarmányozástan és tejgazdaságtan). A tanszék megindulásától kezdve azon fáradozott, hogy Magyaróvár szervesen bekapcsolódjon az országos állattenyésztési kutatásokba (*3. ábra*). Hamarosan tagja lett a tudományos kutatások Szarvasmarha-tenyésztési és Baromfitenyésztési Témakollektívájának. Kutató tevékenységét, az akkori követelményeknek megfelelően, főleg tájjellegű kérdésekben folytatta.
Szarvasmarha takarmányozási kérdések közül a *Fertő-táj, a Hanság és a Szigetköz ásványianyag ellátottságát, a táj sajátosságából fakadó ásványi anyagok hiányát vizsgálta.* Az akkor oly gyakori *táplálkozási hiányosság okozta* szarvasmarha *meddőség* okainak feltárására felmérte a környék gazdaságainak takarmányozási körülményeit, valamint a foszfor és kalcium kiegészítés hatását vizsgálta.

4. ábra: A baromfi telep bejárata

1954-től a tanszéki kollégákkal együtt részt vett a baromfitenyésztés fejlesztésében, az akkor olyan sürgetően fontos *mintafalvak* kialakításában, és az ott található elöregedett, fajtátlan állományoknak lecserélésében a Főiskola telepének sárga magyar *tífuszmentes állományára* (*4. ábra*). Ugyanekkor (1952-54) felismerte a *baromfikeresztezések* előremutató jelentőségét és azért több fajtával keresztezéseket végezett *tojástermelésre és húselőállításra* egyaránt.
1954-től az OTÁF felkérésére tervezetet dolgozott ki a környéken lévő *10 állami gazdaság szarvasmarha-állományának központos rendszerű, évi 8 bikára vonatkozó utódellenőrzésére.* Részt vett a megyei és a dunántúli bika-állomány elbírálásában, kijelölésében, kiválogatásában.
1955 óta végzett a *szarvasmarhák fehérjehiányának kiegészítésére karbamid etetési kísérleteket.*
1963-ban kezdte meg a baromfitenyésztési témák között vizsgálni a *"fajtakérdés* összefüggését a háztáji tenyészetekben". Ebből a témából nőtt ki az az akció, amit a SZÖVOSZ-szal együtt folytattak Fejér megyében és megszülettek azok az eredmények, melynek nyomán kezdetben kialakult az országban lefolytatott háztáji tojóhibrid forgalmazás (*5. ábra*).

5. kép: Az Állattenyésztési Tanszék kollektívája 1969-ben

Legfőbb kutatási területe azonban a szarvasmarha tenyésztés volt. Tanszéki munkatársaival *a gépi fejés bevezetése érdekében* genetikai, élettani és műszaki vizsgálatokat folytattak. A vizsgálatok alapján a fejés előkészítésre és a gépi fejés technológiájára dolgoztak ki útmutatást.
A tehénállomány gépi fejhetőségének megállapítási módszerét továbbfejlesztette, a vizsgálatokra műszert dolgozott ki (Országos Találmányi Hivatal: SA-1230/148.212 sz.), amelyet szabadalomként elfogadtak, ez pedig az *UBEROGRÁF* volt (*6., 7. ábra*).

6. ábra: Uberográf készülék bemutatása

A találmányra és a kísérleti eredményekre felfigyeltek: a szovjet Tudományos Akadémia, a csehszlovák törzskönyvezési szakemberek, Jugoszlávia egyes főiskolái, az NSZK Grub-i és más kutató intézetei, a franciaországi INRA kutatóintézet szakemberei, de érdeklődtek Egyiptomból, Ausztráliából, Ausztriából, NDK-ból és más országokból is *(1961-1965).*

SZABADALMI OKIRAT

7. ábra: Szabadalmi okirat

A szarvasmarha-tenyésztésben *a borjúnevelés területén* tanulmányozta négy külföldi országban (Franciaország, NSZK, NDK, CSSR) *a borjak és később a tejelő tehenek kölcsönös káros szopásának kérdéseit. (1963-1966).* Munkatársaival olyan elhelyezési megoldást dolgozott ki, amelynek hatására a borjúnevelésnek ez a káros hátránya nem jelentkezik. *A Lajta-Hansági Állami Gazdaság két 160-as nagyüzemi borjúnevelőjét ennek alapján* rendezte be. A borjúnevelés során *acidofill-tej itatását* kísérletezték ki a Tejkísérleti Intézettel és azt jó sikerrel alkalmazták a káros emésztési tünetek megszüntetésére *(1962).*

Munkája, kutatásai során mindvégig állami programos kutatásokban vett részt. Fő témáját a gépi fejhetőségre vonatkozó genetikai- fiziológiai, műszaki és munkaszervezési területen interdiszciplináris jelleggel folytatta. Az előző eredmények alapján az Országos Gépkísérleti Intézettel közösen sikerült olyan új adatrögzítő berendezés megtervezése, amely alkalmas a fejési sebesség és a fejési folyamatok minden részletének rögzítésére. A MÉM-MI tervei alapján elkészítette az új elektronikus berendezést *(Electro-Uberotester).* A készülék adatai számítógépre átvihetők, lehetővé teszi a modern értékelést, mind a kutatási, mind a gépi fejés üzemi, kritikai elemzése és értékelése szempontjából.

Számos előadást, kerekasztal konferenciát tartott kutatóknak, hallgatóknak Lipcsében, Csehszlovákiában, NSZK-ban a Weihenstefan-i egyetemen.

Munkásságát több száz tudományos és ismeret-terjesztő cikk, egyetemi jegyzet, tankönyv, szakkönyv fémjelzi. Két szabadalmát ismerték el. Félszáz disszertáció elkészítésének volt irányítója, vizsgáztatója, bírálója. Emellett a hallgatók is számíthattak mindig segítőkészségére, évente 3-4 diplomamunka irányítását is vállalta.
TMB megbízásából több mint 20 alkalommal vett részt, mint bizottsági elnök, vagy tag, illetőleg mint opponens kandidátusi és akadémiai doktori munkák elbírálásában. Az *MTA VEAB Állattenyésztési Munkabizottságának elnöke volt* (*8. ábra*).

8. ábra: Szajkó László a doktori bizottság elnöke

Végül, mint ny. egyetemi tanár, tudományos szaktanácsadóként dolgozott a Pannon Agrártudományi Egyetem Mosonmagyaróvári Mezőgazdaságtudományi Karának Állattenyésztési Intézetében. Az Állattenyésztéstan tárgyban három speciális blokkban, továbbá fakultatív tárgyakban tartott előadásokat, illetőleg az *oktatás irányítója volt* (*9. ábra*).

9. ábra: Szajkó László egész élete során lelkes ebtenyésztő, galambász, prémes-állattenyésztő és amatőr fotós volt

Az Állattenyésztéstani Tanszéket 32 éven át vezette. Ez idő alatt a személyi feltételek keretében négy mezőgazdasági tudomány kandidátusa és két tudomány doktora fokozatot szereztek munkatársai.
Állami- és társadalmi megbízások keretében több országos, egyetemi és kari bizottságban fejtette ki tevékenységét.
Több alkalommal volt tudományos dékán- és rektorhelyettes.
Az MTA-MÉM Állattenyésztési Bizottságának állandó tagja, VEAB Állattenyésztési Munkabizottság elnöke, a MAE Országos Állattenyésztők Társaságának vezetőségi tagja, Egyetemi Doktori Bizottság tagja, Egyetemi Nemzetközi Kapcsolatok Bizottság tagja, Kari Külföldi Kapcsolatok Bizottság elnöke, Gyakorlati Oktatási Bizottság tagja, Gazdasági és Fejlesztési Bizottság tagja, Európai Állattenyésztők Szövetsége magyarországi Bizottságának delegált tagja, Nyúltenyésztők Világszövetségének tagja, MTA-VEAB Klub tagja, az Állattenyésztő Professzorok Klub tagja.
Az MTA Állattenyésztési és Takarmányozási Bizottságának tagja és az MTA-VEAB Állattenyésztési Bizottságának elnöke volt, tagja volt a PATE Doktori (PhD) Bizottságának és a Mosonmagyaróvári Kar Tudományos Bizottságának.

Munkássága eredményeként az alábbi kitüntetésekben részesült:
1954: "Kiváló Állattenyésztő"
1961: "Mezőgazdaság Kiváló Dolgozója"
1965: "Munka Érdemrend Ezüst Fokozata"
1966: "Ujhelyi Imre" Emlékérem
1978: "Kiváló Munkáért"
1984: "Ujhelyi Imre" Emlékérem
1985: "Pro Re Rustica Promovenda" Emlékérem
1986: "Wilhelm Kirchner - Ehrenplaketten" (Lipcse)
1987: "Welmann Oszkár" emlékérem

Szajkó László professzorra ismerői, barátai, kollégái, tanítványai úgy emlékeznek, mint aki a professzortól elvárható szakmai, emberi tulajdonságok mindegyikével rendelkezett. Kiváló volt a kapcsolatteremtő képessége, diplomáciai érzéke. Vezetése alatt a társintézményekkel példaértékű volt a szakmai együttműködés, amit utódai tovább ápoltak. Tökéletes vezető volt, soha nem korlátozta kollégái szakmai előmenetelét, empátiával viseltetett nem szakmai problémáik iránt is.
Családjában négy gyermeke az ő nyomdokait követte. Mind a négyen agrármérnöki diplomát szereztek, és tanári pályán kamatoztatták tudásukat, édesapjuk tanári tartását és nagyságát követve.

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