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Features of soybean cultivation under the soil and climatic conditions of Western Polissia, Ukraine

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Abstract. The relevance of this study lies in identifying the optimal soybean maturity group for cultivation in Western Polissia under the current thermal conditions of the growing season. The study aimed to provide a comprehensive assessment of the feasibility of soybean cultivation on sod-podzolic and peat soils in Western Polissia. To achieve this aim, a series of field experiments was conducted to examine interactions between the study object and biotic and abiotic factors. Laboratory and mathematical-statistical methods were also applied, including analysis of variance and statistical data processing, to assess the reliability of the research findings. Limited thermal resources were found to be the main constraint on soybean cultivation in Western Polissia. An analysis of current hydrothermal resources, based on data from the meteorological station of the Sarny Research Station, showed that the thermal resources of sod-podzolic soils in Western Polissia were sufficient to produce physiologically mature seed of ultra-early and early-maturing soybean varieties with a growing season of up to 100 days. On peat soils, however, only ultra early varieties with a growing season of up to 85 days can reach physiological maturity. Under favourable conditions on sod-podzolic light loamy soils of Western Polissia, the yields of the ultra-early soybean variety Yunka and the early-maturing variety Astor, bred by Sevita Genetics (Canada), reached 3.67 and 4.36 t/ha, respectively. The application of the microbial inoculant Rizofix in combination with the phosphate-mobilising preparation Rice Pi increased soybean yield by up to 0.67 t/ha. The results also showed that soybean yields on peat soils were unstable and did not exceed 2.64 t/ha, which was associated with a less favourable hydrothermal regime than that of the adjacent sod-podzolic soils. The practical significance of the findings lies in determining the optimal soybean maturity group for cultivation on sod-podzolic and peat soils in Western Polissia, thereby enabling the production of physiologically mature seed under current hydrothermal conditions

Keywords: drained land; sod-podzolic soils; peat soils; hydrothermal conditions; fertilisation system; inoculant; phosphate-mobilising preparation

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INTRODUCTION

The substantial increase in thermal resources during the growing season has led to shifts in the geographical distribution of crops in Ukraine. Economically attractive steppe and forest-steppe crops that were previously uncommon under these conditions, including maize, sunflower and soybean, are becoming increasingly widespread in the northern regions of Ukraine, displacing crops traditionally grown in the area, such as winter rye, perennial grasses and buckwheat, as reported by G.V. Voropay (2020). S.M. Ryzhuk *et al*. (2022) noted that most of the soil cover in Western Polissia consists of sod-podzolic soils characterised by low humus content, high acidity and poor availability of essential nutrients. In addition, these soils generally have a light texture and low water-holding capacity. These characteristics require crop production technologies to be adapted accordingly, particularly fertilisation systems and varietal selection.

In addition to sod-podzolic soils, lowland peat soils account for approximately 30% of the soil cover in Western Polissia and are generally characterised by low phosphorus availability and, in particular, potassium deficiency, according to R.S. Truskavetskyi (2010). Therefore, achieving high yields of cereal and grain legume crops on peat soils requires the application of scientifically justified rates of phosphorus and potassium fertilisers, as well as micronutrients and secondary nutrients such as copper, magnesium and sulphur. Soybean is a strategically important crop in global agriculture and, owing to its high ecological adaptability, is now cultivated under a wide range of soil and climatic conditions, as noted by S.M. Islam *et al*. (2022). Soybean makes a major contribution to global food security because of the high protein and oil content of its seed and its relatively low dependence on nitrogen fertilisation. Unlike other crops widely grown in global agriculture, soybean can improve soil fertility by fixing atmospheric nitrogen and leaving part of it in the soil for subsequent crops in the rotation.

As noted by O. Mazur *et al*. (2025), when properly inoculated, soybean can leave up to 90100 kg/ha of biologically fixed nitrogen in the soil, which justifies its recognition as one of the best preceding crops for most agricultural crops. I. Fedoruk *et al*. (2021) demonstrated the effectiveness of combining an inoculant, Wuxal and the insecticidal-fungicidal preparation Standak Top in a tank mixture, which increased soybean yield by up to 0.6 t/ha. In the study by V. Ratoshniuk *et al*. (2023), soybean grown on sod-medium podzolic soils after grain maize, with complete mineral fertilisation at $N_{60}P_{60}K_{60}$ and foliar application of micronutrient fertilisers under optimal moisture conditions, produced yields of 2.65-3.28 t/ha. V. Moldovan *et al*. (2021) established a significant effect of sowing date on soybean yield under Forest-Steppe conditions; sowing at the optimal time increased yield by 13.8%.

Despite the considerable body of research on the expansion of soybean cultivation, its productivity and individual components of cultivation technology, the selection of varieties from different maturity groups for cultivation on sod-podzolic and peat soils of Western Polissia, taking current thermal resources into account, remains insufficiently studied. Therefore, the study aimed to determine the feasibility and suitability of cultivating soybean varieties belonging to different maturity groups on drained land in Western Polissia under current hydrothermal conditions. The main objectives were to identify the optimal soybean maturity group for cultivation on sodpodzolic and peat soils of Western Polissia under the current thermal conditions of the growing season; to investigate the effectiveness of the microbial inoculant Rizofix and the phosphate-mobilising preparation Rice Pi on sod-podzolic and peat soils; and to determine the effect of drainage depth on soybean yield when grown on sod-podzolic soils.

LITERATURE REVIEW

Based on experimental findings, V.M. Polyovyi *et al*. (2022b) reported that the cultivation of economically attractive crops such as soybean, sunflower and grain maize in Polissia is not always profitable because of the need for high rates of mineral fertilisers. Their yields in this region are generally lower than those obtained in the Forest-Steppe zone, as the limited thermal resources of Polissia do not always allow the crops to realise their full yield potential. At the same time, a study by M.A. Krayna & O.A. Furmanets (2023), conducted in the northern part of Rivne Region, showed that selecting the most adapted varieties and hybrids and applying appropriate agronomic practices can provide stable yields of 3-4 t/ha for sunflower, winter oilseed rape and soybean, and approximately 10-12 t/ha for grain maize. Cultivation technologies should therefore be based on organo-mineral fertilisation systems that use crop residues as a source of organic matter for soil replenishment, together with differentiated application of mineral fertilisers. Summarising their findings, T. Ratoshniuk *et al*. (2026) concluded that the highest economic efficiency of crop production under Polissia conditions is achieved through organo-mineral fertilisation systems in which crop residues are used as organic fertiliser.

Among the new economically attractive crops becoming increasingly widespread in Western Polissia, soybean merits particular attention because, under suitable conditions, it can substantially improve the soil nitrogen regime, as reported by Y.O. Tarariko *et al*. (2025). Similar conclusions were reached by S. Kobak *et al*. (2025), who found that, with effective inoculation, soybean can leave up to 80-100 kg/ha of biologically fixed nitrogen in the soil, which is sufficient to meet the needs of the following crop in the rotation.

J.K. Ladha *et al*. (2022) noted that, in global agriculture, biological nitrogen fixation provides a basis for ecological intensification in cereal production systems.

Since 1990, the area sown to soybean in Ukraine has increased more than twentyfold, reaching 1.4 million ha in 2024, as reported by A.A. Korobko (2021). Within the humid zone, the largest increases in soybean area were recorded in Zhytomyr Region, reaching 99.3 thousand ha, Chernihiv Region, 62.1 thousand ha, and Lviv Region, 53.7 thousand ha. In Rivne Region, the soybean area increased from 23.0 to 86.2 thousand ha, while in Volyn Region it rose from 9.0 to 37.3 thousand ha. Based on current climate change scenarios, T.K. Kostyukevich *et al*. (2021) concluded that favourable agroecological conditions for soybean development are expected in the Forest-Steppe and Polissia zones of Ukraine during 2021-2050, which may ultimately increase total soybean production by at least 15%-20%. During 2021-2026, the area under soybean in Ukraine has remained at approximately 1.5-2.0 million ha, with most production shifting towards the Forest-Steppe and Polissia zones because of climatic factors. Under current climatic conditions, soybean cultivation in the Steppe zone is feasible only with irrigation. Until 2014, the main soybean-producing areas were concentrated in the Forest-Steppe zone (66%), followed by the Steppe (19%) and Polissia (15%). Between 2016 and 2020, the share of soybean area in Polissia increased by 10%, whereas that in the Steppe declined by more than half (Biliavska *et al.*, 2021). According to T.A. Zabarna & V.V. Chereshnyuk (2024), the most favourable conditions for soybean occur when annual precipitation ranges from 500 to 600 mm, with more than 300 mm received during the growing season. Soybean has its greatest water requirement between flowering and full seed filling.

Based on a synthesis of statistical data, S.H. Peretyatko & O.L. Rudik (2021) found that increases in total soybean production have resulted mainly from the expansion of the cultivated area rather than improvements in yield. During 2016-2026, soybean yields in Ukraine ranged from 1.62 to 2.58 t/ha, which is below the crop's potential productivity. With appropriate agronomic practices and favourable growing conditions, some farms are able to achieve stable soybean yields of at least 4-5 t/ha. This disparity indicates the strong influence of weather conditions and the generally insufficient level of crop management applied in soybean production.

In a study by V. Mazur *et al.* (2022), yields among 160 soybean varieties belonging to the medium-early maturity group and grown under the conditions of Kyiv Region ranged from 1.72 to 3.70 t/ha, representing a more than twofold difference. This finding highlights the importance of selecting varieties that are highly adapted to specific soil and climatic conditions. V.S. Kravchenko & S.P. Krykun (2025) found that soybean yields varied considerably between cultivation zones: 1.53 t/ha in the Steppe, 2.31 t/ha in the Forest-Steppe and 2.40 t/ha in Polissia. The Forest-Steppe was identified as providing the most favourable conditions for consistently high yields. The study also showed that the soil and climatic conditions of Ukraine are generally favourable for realising the biological yield potential of medium-maturing soybean varieties.

Soybean is a crop that, under suitable conditions, requires little or no nitrogen fertiliser. Given the substantial increase in fertiliser prices, this characteristic makes soybean an important component of resource-efficient crop production technologies. According to V.V. Lykhochvor & V.F. Petrychenko (2020), soybean plants obtain 60%-80% of their total nitrogen requirement through symbiotic nitrogen fixation. Expanding the area under soybean can therefore substantially improve the soil nitrogen regime and reduce expenditure on nitrogen fertilisers in short-rotation crop systems. The authors also noted that soybean is sensitive to the availability of particular nutrients in the soil, including sulphur, copper, magnesium and boron. Sulphur application can increase soybean yield by up to 0.5 t/ha.

Soybean is a relatively new crop in the northern regions of Ukraine, although climate warming may lead to a substantial expansion of the cultivated area in these regions in the future (Polyovyi *et al.*, 2022a). At the same time, soybean is a crop adapted to monsoon climates; therefore, when planning its cultivation in regions with limited thermal resources, preference should be given to the earliest-maturing varieties, which are more likely to produce physiologically mature seed within a short growing season (Tarariko *et al.*, 2022). In their study, A.M. Rybalchenko & A.Ye. Serdiuk (2023) found that early-maturing soybean varieties produced the highest yields under the conditions of the Left-Bank Forest-Steppe. Based on long-term studies assessing soybean varieties from different maturity groups under varying environmental conditions, O.P. Tkachuk *et al*. (2023) concluded that the earliest-maturing varieties showed the greatest drought tolerance in the Forest-Steppe zone. Summarising long-term data, V.I. Sichkar (2023) noted that a considerable proportion of soybean varieties have insufficient adaptability to the diverse agroclimatic conditions of Ukraine. Ukraine therefore requires a longterm strategy for developing new-generation varieties characterised by greater adaptation to the conditions of specific soil and climatic zones.

MATERIALS AND METHODS

Experimental studies assessing the feasibility and suitability of soybean cultivation in Western Polissia were conducted at the Sarny Research Station of the Institute of Water Problems and Land Reclamation of the National Academy of Agrarian Sciences of Ukraine (IWPLR NAAS) during 2021-2024. The experiments

were carried out on the two most widespread soil types in the region: sod-podzolic and lowland peat soils. The agrochemical properties of the soils were as follows:

- sod-podzolic light loamy soil: humus content, 2.34%; readily hydrolysable nitrogen content (Cornfield method), 147 mg/kg soil; mobile phosphorus and potassium (Kirsanov method), 144 and 156 mg/kg soil, respectively; pH_{salt}, 5.4;
- peat soil: readily hydrolysable nitrogen content (Cornfield method), 750.0 mg/kg soil; mobile phosphorus and potassium (Kirsanov method), 239 and 150 mg/kg soil, respectively; pH_{salt}, 5.2.

Five soybean varieties belonging to different maturity groups were studied in the field experiments. In the first field experiment, conducted during 2021-2023, the following five varieties were evaluated:

- Yunka (Sevita Genetics): growing season of 85 days; required heat units, 2,350 Crop Heat Units (CHU); RM 0.4;
- Astor (Sevita Genetics): growing season of 105 days; required heat units, 2,575 CHU; RM 0.5;
- Niagara (Sevita Genetics): growing season of 108 days; required heat units, 2,600 CHU; RM 0.4;
- Neptun (Sevita Genetics): growing season of 115 days; required heat units, 2,700 CHU; RM 0.9;
- SB_{142} (SB&B Foods Inc.), an American-bred variety: growing season of 123 days; required heat units, 2,750 CHU; RM 0.9.

These soybean varieties were studied on drained peat soils and sod-podzolic light loamy soils. In addition, two experiments with identical designs were conducted to assess the effectiveness of the phosphate-mobilising preparation Rise P and the nitrogen-fixing microbial inoculant RhizoFix Soy, produced by the Canadian brand Lallemand. RhizoFix and Rise P were applied as seed treatments immediately before sowing, at the rates and according to the recommendations specified by the manufacturer. Mineral fertilisers were applied to the sodpodzolic soils at a rate of $N_{60}P_{60}K_{60}$. On the peat soils, mineral fertilisers were applied at $N_{35}P_{60}K_{120}$. Grain maize was the preceding crop in the soybean field experiments. Soil tillage consisted of mulching the field after maize harvest, followed by discing and autumn ploughing. Pre-sowing tillage involved cultivation to a depth of 9-12 cm. The experimental plots measured 50 m^2; treatments were arranged systematically and replicated three times.

In the second field experiment, conducted during 2022-2024 on sod-podzolic light loamy soils, the effect of groundwater table depth on the yield of the Astor soybean variety was investigated. Owing to differences in field topography, the groundwater table during the growing season occurred at depths of 75-85, 85-100 and 100-140 cm below the soil surface, thereby simulating different operating conditions of the drainage network. The sod-podzolic light loamy soils of the experimental plots had a humus content of 2.47%, readily hydrolysable nitrogen content (Cornfield method) of 159 mg/kg soil, and mobile phosphorus and potassium contents (Kirsanov method) of 174 and 187 mg/kg, respectively; pH_{salt} was 5.5. Mineral fertilisers were applied at $N_{60}P_{60}K_{60}$ in the form of nitroammophoska. Soil moisture content and soil water reserves were determined by the gravimetric oven-drying method in the 0-50 cm soil layer, at 10 cm intervals, in triplicate once every ten-day period. Groundwater levels were measured every five days using a measuring tape in observation wells. Yield was determined by complete threshing of the entire harvest area of each plot. The results of the field experiments were statistically processed by analysis of variance using STATISTICA 6.1. Weather conditions were assessed using data from the meteorological station of the Sarny Research Station (n.d.). The authors complied with the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS

One of the main factors limiting soybean cultivation in Western Polissia is the insufficient thermal supply during the growing season. To assess this factor, long-term data from the meteorological station of the Sarny Research Station (n.d.) were analysed. The dates of stable transitions of air temperature across 0°C, 5°C, 10°C and 15°C, together with the duration of the corresponding periods on the drained peatland area, are presented in Table 1.

***Table 1**. Dates of stable air-temperature transitions across 0°C, 5°C, 10°C and 15°C and duration of the corresponding periods (mean for 2007-2024)*

Value	Dates of temperature transition across specified thresholds and duration of the corresponding periods											
	>0°	<0°	days	>5°	<5°	days	>10°	<10°	days	>15°	<15°	days
D_{mean}	24.02	5.12	284	25.03	30.10	217	22.04	3.10	163	12.05	7.09	116
D_{min}	26.01	9.11	254	14.03	6.10	186	4.04	24.09	128	27.04	24.08	100
D_{max}	30.03	31.12	318	11.04	25.11	248	30.04	23.10	188	7.06	18.09	141

***Source:** developed by the author*

The data on stable temperature transitions show that the period with a mean daily temperature above 5°C ranged from 186 to 248 days, with an average duration of 217 days. The period with temperatures above 10°C ranged from 128 to 188 days, averaging 163 days. The period of intensive vegetation (>15°C)

ranged from 100 to 141 days, with an average of 116 days. In most years, the growing season began in the third ten-day period of March, while the period of active vegetation began in the third ten-day period of April. Overall, even the shortest recorded period of active vegetation with a mean daily temperature above 15°C, namely 100 days, is sufficient for ultra-early and early-maturing soybean varieties to reach maturity. Under the maximum recorded duration of this period, even medium-early soybean varieties can reach maturity.

A further limiting factor is the short frost-free period, particularly on peat soils, where the probability of early autumn frosts is considerably higher than on adjacent sod-podzolic soils. According to long-term observations from the meteorological station of the Sarny Research Station of the IWPLR NAAS – the only station in Ukraine's hydrometeorological observation network located directly within a peatland area – the long-term mean duration of the frost-free period at the peatland site where the experiments were conducted is 137 days. At the same time, the frost-free period varied considerably over the past ten years, ranging from 99 to 150 days. Thus, in years with the shortest frost-free period, its duration is sufficient only for ultra-early soybean varieties with a growing season of 85 days to reach maturity. In addition, the soybean growing season is longer in the northern regions of Ukraine because of longer daylight hours and cooler weather, which slow plant development and extend the period from sowing to maturity compared with the southern regions. Weather conditions during the study years, including precipitation and temperature patterns, are presented in Figures 1 and 2.

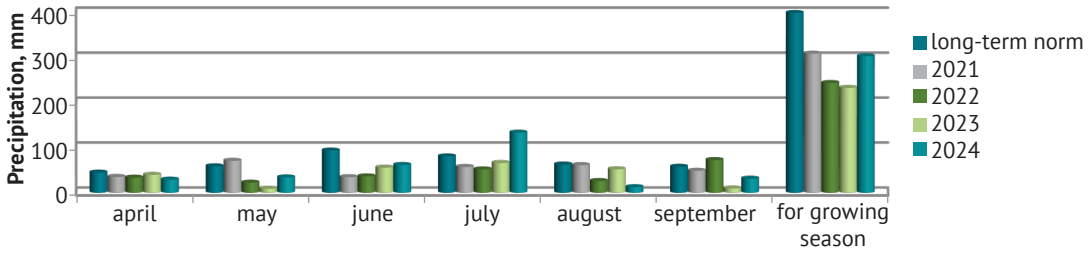

***Figure 1**. Precipitation, mm*

***Source:** developed by the author*

Analysis of weather conditions showed that precipitation during the 2021 growing season amounted to 309.5 mm, which was 90.5 mm below the long-term average. During the 2022 growing season, 244.3 mm of precipitation was recorded, 155.7 mm below the long-term average; in 2023, the corresponding value was 233.3 mm, or 166.7 mm below the long-term average. In 2024, precipitation totalled 304.0 mm, which was 96.0 mm below the long-term average. Overall, precipitation was distributed very unevenly among the months of the growing season throughout the four-year study period. Particularly pronounced variation in rainfall distribution was observed during the summer months. The temperature regime during the 2021-2024 growing seasons was also characterised by substantial month-to-month fluctuations (Fig. 2).

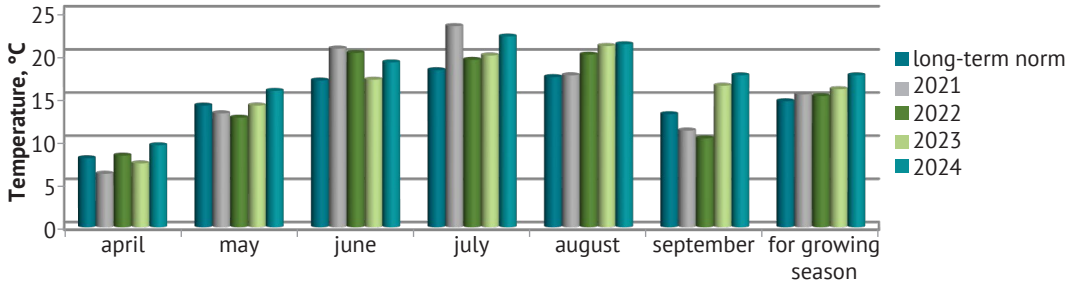

***Figure 2**. Mean monthly air temperature during the 2021-2024 growing seasons*

***Source:** developed by the author*

The temperature regime during the 2021 growing season resulted in the onset of vegetation occurring 2-3 weeks later than in previous years. April and September were unusually cold, with mean monthly air temperatures 1.8°C and 1.9°C below the long-term averages, respectively, whereas temperatures during the remaining months of the growing season, from May to August, were considerably higher. Overall, the mean air temperature during the 2021 growing season was 15.4°C, which was 0.8°C above the long-term average. Mean monthly air temperatures differed substantially from the long-term averages across individual months of the growing season.

The 2022 growing season was characterised by a prolonged and cold spring. May was particularly cold, with the mean monthly air temperature 1.4°C below

the long-term average. In June, July and August, mean monthly temperatures exceeded the long-term averages by 3.2°C, 1.2°C and 2.6°C, respectively. September, however, was unusually cold, with the mean monthly temperature 2.8°C below the long-term average.

The temperature regime during the 2023 growing season was characterised by a cold start, with the mean monthly air temperature in April 0.6°C below the long-term average. Temperatures in May and June were close to the long-term averages, whereas mean monthly air temperatures from July to September were considerably higher. The 2024 growing season was characterised by mean monthly air temperatures above the long-term averages. July, August and September were particularly warm, with mean monthly temperatures exceeding the long-term averages by 3.9°C, 3.8°C and 4.3°C, respectively.

In Ukraine, the thermal resources of soybean-growing regions are traditionally assessed using accumulated active or effective temperatures. However, as noted by S.M. Kalenska & R.V. Hovenko (2022), the sum of active temperatures is a generalised indicator that does not allow the thermal requirements of a crop to be assessed with sufficient accuracy. For many spring crops, accumulated effective temperatures are therefore more commonly used. However, this indicator does not always account for diurnal temperature patterns, particularly absolute minimum and maximum temperatures, which can substantially affect plant development. Western Polissia is characterised by relatively wide fluctuations between minimum and maximum daily air temperatures. As early as August, night-time minimum temperatures frequently fall below 10°C, particularly on peatlands (Tarariko *et al.*, 2022). Therefore, for the northern regions of Ukraine, including minimum air temperatures in assessments of thermal resources provides a more accurate representation of local climatic conditions.

Soybean varieties of American and, particularly, Canadian origin, which have become increasingly widespread in Ukraine in recent years, are classified into maturity groups according to their required CHU, a system used to determine the amount of accumulated heat required for a crop to reach full maturity. The CHU system was developed by American researchers, and its method of calculating accumulated heat units provides a more accurate practical characterisation of the thermal regime of a region (Kalenska & Hovenko, 2022). Canadian soybean varieties are assigned to maturity groups according to the total number of heat units required from sowing to full crop maturity. The calculated accumulated CHU values for sod-podzolic and peat soils are presented in Table 2.

***Table 2**. Accumulated CHU on peat and sod-podzolic soils during 2021-2024*

Soil type	Period	Accumulated heat units, CHU			
		2021	2022	2023	2024
Peat soil	May-September	2,602	2,538	2,743	3,060
	frost-free period	2,280	2,092	2,236	2,845
Sod-podzolic soil	May-September	2,966	2,893	3,127	3,488
	frost-free period	2,630	2,567	2,596	2,864

***Source:** developed by the author*

The data in Table 2 show substantial differences in CHU values between sod-podzolic and peat soils. These differences are attributable to the specific thermal properties of peat soils, including low thermal conductivity and high moisture content, as well as to microclimatic conditions and differences in the duration of the frost-free period. In addition, minimum nighttime temperatures on peat soils are considerably lower than those recorded on adjacent mineral soils.

Accumulated CHU values varied substantially among the study years on both sod-podzolic and peat soils. On sod-podzolic soils, accumulated CHU ranged from 2,893 to 3,488 during MaySeptember and from 2,567 to 2,864 during the frost-free period. On peat soils, CHU values ranged from 2,538 to 3,060 during May-September and from 2,092 to 2,845 during the frost-free period. Overall, thermal conditions during the growing season differed considerably among the study years, making it possible to identify the optimal soybean maturity group for cultivation under the conditions of Western Polissia.

Under conditions of substantial climate warming, crop productivity depends to a considerable extent on moisture availability, particularly the distribution of precipitation, groundwater table depth and soil moisture content. Averaged over the three-year study period, groundwater levels ranged from 67 to 117 cm below the soil surface on sod-podzolic soils and from 56 to 111 cm on peat soils. Monitoring of soil water reserves during 2021-2023 showed that, on sod-podzolic soils, water reserves ranged from 49.0 to 91.4 mm in the 0-30 cm soil layer and from 113.8 to 173.1 mm in the 0-50 cm layer. On peat soils, the corresponding values ranged from 113.8 to 173.0 mm in the 0-30 cm layer and from 243.1 to 324.6 mm in the 0-50 cm layer. The effects of the nitrogen-fixing preparation RhizoFix and the phosphate-mobilising preparation Rise P on soybean yield under cultivation on drained sod-podzolic soils are presented in Table 3.

***Table 3**. Soybean yield on drained sod-podzolic soils, mean for 2021-2023*

Variety	Growing season, days	Required heat units, CHU	Yield, t/ha			
			without preparations	RhizoFix	Rise P	RhizoFix + Rise P
Yunka	85	2,350	3.87	4.33	4.21	4.55
Astor	105	2,575	3.15	3.46	3.49	3.85
Niagara	108	2,600	2.74	3.09	3.03	3.23
Neptun	120	2,700	2.59	2.87	2.84	3.12
Sb_{142}	124	2,750	2.39	2.65	2.62	2.77
$LSD_{0.5}$, t/ha			0.043	0.056	0.061	0.059

***Source:** developed by the author*

Overall, the results showed a substantial yield advantage of the early-maturing varieties Yunka and Astor over the later-maturing varieties Niagara, Neptun and Sb_{142}. Over the three-year study period, application of the microbial inoculant RhizoFix increased soybean yield by 0.26-0.46 t/ha, depending on the variety. Application of the phosphate-mobilising preparation Rise P increased yield by 0.23-0.34 t/ha. In treatments combining the RhizoFix inoculant with the phosphate-mobilising preparation Rise P, soybean yield increased by 0.38-0.70 t/ha. The effects of the nitrogen-fixing preparation RhizoFix and the phosphate-mobilising preparation Rise P on soybean yield on drained peat soils are presented in Table 4.

***Table 4**. Soybean yield on drained peat soils, mean for 2021-2023*

Variety	Growing season, days	Required heat units, CHU	Yield, t/ha			
			without preparations	RhizoFix	Rise P	RhizoFix + Rise P
Yunka	85	2,350	2.11	2.21	2.58	2.64
Astor	105	2,575	1.99	2.04	2.30	2.39
Niagara	108	2,600	1.94	1.99	2.26	2.33
Neptun	120	2,700	1.60	1.65	1.80	1.97
Sb_{142}	124	2,750	1.46	1.50	1.67	1.73
$LSD_{0.5}$, t/ha			0.038	0.042	0.034	0.045

***Source:** developed by the author*

Comparison of the data in Tables 3 and 4 shows that the yields of all soybean varieties studied were lower on peat soils than on sod-podzolic soils. The difference was particularly pronounced for the latest-maturing varieties in the study, namely Neptun and Sb_{142}. These experimental findings indicate that only ultra-early soybean varieties with a growing season of up to 85 days are suitable for cultivation on peat soils. Growing later-maturing varieties on such soils involves a greater risk because thermal resources may be insufficient for the crop to reach maturity. One of the main reasons for the lower soybean yields on peat soils compared with sod-podzolic soils is their less favourable hydrothermal regime, particularly the shorter frost-free period, which is, on average, 15-20 days shorter than on adjacent sod-podzolic soils. In most cases, the first autumn frosts on peat soils occur as early as the first ten-day period of September, as observed in 2021 and 2022, whereas on adjacent sod-podzolic soils they occurred in the third ten-day period of September.

The findings indicate that the earliest-maturing soybean varieties are the most suitable for cultivation on peat soils. The yield of the ultra-early Yunka variety ranged from 2.11 to 2.64 t/ha across the experimental treatments, whereas yields of the other varieties ranged from 1.46 to 2.39 t/ha. It should be noted that RhizoFix showed relatively low effectiveness on peat soils, with yield increases not exceeding 0.1 t/ha. The phosphate-mobilising preparation Rise P was considerably more effective, increasing yield by 0.20-0.47 t/ha. Combined application of RhizoFix and Rise P increased yield by 0.26-0.53 t/ha, depending on the variety. The low effectiveness of the nitrogenfixing microbial inoculant RhizoFix on peat soils can be attributed to their high nitrogen availability, which appears to suppress nitrogen fixation. Nevertheless, the use of nitrogen-fixing microbial inoculants specifically on peat soils requires further experimental investigation.

As reported by V.F. Petrychenko *et al.* (2016), soybean is sensitive to moisture availability and responds negatively to water deficiency, particularly during seed filling and development. In crop production systems on drained land, regulation of the soil water regime, particularly groundwater table depth, is an important management component (Tarariko *et al.*, 2022). During 2022-2024, the effect of groundwater table depth on the yield of the Astor soybean variety was studied on sod-podzolic soils (Table 5).

***Table 5**. Yield of the Astor soybean variety depending on groundwater table depth on sodpodzolic soils*

Study year	Yield, t/ha			Yield increase among groundwater table treatments, t/ha	
	Groundwater table depth, cm			85-100 cm up to 100-140 cm	75-85 cm up to 100-140 cm
	100-140 cm	85-100 cm	75-85 cm		
2022	2.81	3.63	4.11	0.82	1.30
2023	2.52	3.44	3.81	0.92	1.29
2024	2.49	3.03	3.41	0.54	0.92

***Source:** developed by the author*

The results showed that soybean yield was significantly affected by groundwater table depth. On plots where the groundwater table was 100-140 cm below the soil surface, soybean yield ranged from 2.49 to 2.81 t/ha. At a groundwater table depth of 85-100 cm, yield ranged from 3.03 to 3.63 t/ha, while at 75-85 cm it ranged from 3.41 to 4.11 t/ha. These findings indicate that, when soybean is grown on sod-podzolic soils, the optimal groundwater table depth during the growing season is 75-85 cm below the soil surface. Lowering the groundwater table to a depth of 100-140 cm during the period of active soybean growth results in a substantial reduction in yield.

DISCUSSION

A distinctive feature of the soil cover in Western Polissia is that approximately 70% of the area is occupied by sod-podzolic soils and their variants. Most are low-humus soils with a light texture, low water-holding capacity and poor availability of major plant nutrients (Voropay, 2020). In Western Polissia, sod-podzolic light loamy soils are the most suitable for soybean cultivation because they are more fertile and retain moisture more effectively than their sandy loam counterparts, as noted by Y.O. Tarariko *et al*. (2025). In the present study, under a comparable fertilisation regime and with the application of the nitrogen-fixing microbial inoculant RhizoFix and the phosphate-mobilising preparation Rise P, the Yunka variety produced yields exceeding 4.0 t/ha on sod-podzolic light loamy soils over the four-year study period.

Soybean cultivation on peat soils remains insufficiently studied. Despite the specific hydrothermal conditions of peatlands, including shorter growing and frost-free periods than on adjacent mineral soils, as well as low availability of phosphorus, potassium and certain micronutrients, these soils are characterised by high nitrogen availability and sufficient moisture reserves, both of which are critically important for soybean cultivation (Truskavetskyi, 2010). Climatic conditions have a substantial effect on soybean yield formation and seed quality. A.M. Rybalchenko & A.Ye. Serdiuk (2023) demonstrated that soybean yield in the Left-Bank Forest-Steppe of Ukraine depends directly on the genetic characteristics of the variety, weather conditions in a particular year and plant adaptation to hydrothermal factors.

The present findings show that the yield of the same soybean variety differed substantially between soils of mineral origin, represented by sod-podzolic soils, and soils of organic origin. Overall, in every study year, soybean yield was higher on sod-podzolic soils than on peat soils, regardless of maturity group. This indicates that hydrothermal conditions have a pronounced effect on soybean growth and development even within the same geographical area when the crop is grown on different soil types. On peat soils, the hydrothermal regime is less favourable for soybean cultivation, particularly during the spring and autumn periods.

V.F. Petrychenko *et al*. (2016) found that the use of nitrogen-fixing microbial inoculants in soybean cultivation can eliminate the need for nitrogen fertiliser application. In the studies by I. Fedoruk *et al*. (2021) and O. Mazur *et al*. (2025), inoculant application increased soybean yield by up to 0.5 t/ha. According to S. Kobak *et al*. (2025), the optimal time for inoculant application is when the soil warms to above 12°C-14°C in spring. The present findings show that, under favourable conditions on sod-podzolic soils, the combined application of nitrogen-fixing microbial inoculants and phosphate-mobilising preparations can increase soybean yield by up to 0.6 t/ha.

In experiments conducted at the balance lysimeter station of the Institute of Agriculture of Polissia of the NAAN, V. Ratoshniuk *et al*. (2023) found that, on sod-podzolic loamy sand soils under natural moisture conditions, soybean grain yield ranged from 2.33 to 2.65 t/ha when the Nano-Mineralis nanofertiliser was applied against a background of $N_{60}P_{60}K_{60}$ with split nitrogen application and incorporation of crop residues. Foliar application of the Nano-Mineralis micronutrient fertiliser increased soybean yield by 13.1%-28.6%. Artificial water regulation increased soybean yield by 23%. In the present study, artificial water regulation increased soybean yield by up to 53.1%, further demonstrating the high sensitivity of this crop to the drainage regime.

CONCLUSIONS

The experimental findings indicate that, under the current thermal conditions of the growing season, early-maturing soybean varieties with a growing season of up to 100 days are the most suitable for cultivation on sod-podzolic soils in Western Polissia. On peat soils, current thermal resources are sufficient to ensure reliable maturation only of ultra-early soybean varieties with a growing season of up to 85 days. Application of

the microbial inoculant RhizoFix in combination with the phosphate-mobilising preparation Rise P increased soybean yield, with the greatest effect observed on sod-podzolic soils. On peat soils, the effectiveness of the inoculant was considerably lower, probably because of the naturally high nitrogen availability of these soils.

On peat soils, the nitrogen-fixing microbial inoculant RhizoFix showed low effectiveness in soybean crops, increasing yield by no more than 0.1 t/ha. The phosphate-mobilising preparation Rise P was more effective on peat soils, increasing soybean yield by up to 0.47 t/ha. For soybean cultivation on sod-podzolic soils, the optimal groundwater table depth during the growing season was found to be 75-85 cm below the soil surface, whereas lowering the groundwater table to 100-140 cm resulted in a substantial reduction in yield.

The experimental findings also indicate that the hydrothermal conditions of peat soils are less favourable for soybean cultivation than those of sod-podzolic soils. Overall, soybean yield on peat soils is unstable and depends strongly on the weather conditions of a particular year. Further comprehensive experimental research is therefore required to assess soybean cultivation on peat soils in Western Polissia. Promising areas for future research include evaluating the effectiveness of phosphate- and potassium-mobilising preparations, biologically derived plant growth stimulants, and foliar micronutrient application on peat soils, as these aspects remain insufficiently studied under such conditions.

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CONFLICT OF INTEREST

None.

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Особливості вирощування сої в ґрунтово-кліматичних умовах зони Західного Полісся України

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Анотація. Актуальність дослідження полягає у встановленні оптимальної групи стиглості сої для вирощування в зоні Західного Полісся відповідно до сучасних показників теплозабезпеченості вегетаційного періоду. Метою роботи було дати комплексну оцінку можливості вирощування сої на дерново-підзолистих та торфових ґрунтах зони Західного Полісся. Для досягнення мети досліджень був проведений комплекс польових дослідів для вивчення взаємодії об'єкта досліджень із біотичними та абіотичними факторами, лабораторні, математико-статистичні – для проведення дисперсійного аналізу і статистичної обробки даних з метою оцінювання достовірності отриманих результатів досліджень. Встановлено, що основними обмежуючими чинниками, що ускладнюють вирощування сої в зоні Західного Полісся є обмежені теплові ресурси. Аналіз сучасних показників гідротермічних ресурсів на прикладі метеопосту Сарненської дослідної станції показав, що на дерново-підзолистих ґрунтах зони Західного Полісся на дерново-підзолистих ґрунтах теплових ресурсів достатньо для одержання фізіологічно стиглого зерна ультра ранніх та ранньостиглих сортів сої з тривалістю вегетаційного періоду до 100 днів, а на торфових ґрунтах – тільки ультра ранніх сортів з тривалістю вегетаційного періоду до 85 днів. На дерново-підзолистих легкосуглинкових ґрунтах зони Західного Полісся за сприятливих умов урожайність ультра раннього сорту сої – Юнка та ранньостиглого – Астор селекції Sevita genetics (Канада) становила 3,67 та 4,36 т/га. Застосування мікробного інокулянту Різофікс у поєднанні з фосфор мобілізуючим препаратом Райс Пі дозволило підвищити урожайність сої до 0,67 т/га. Результати проведених досліджень показали, що урожайність сої на торфових ґрунтах є нестабільною і не перевищувала 2,64 т/га, що пов'язано з менш сприятливим гідротермічним режимом порівняно з прилеглими дерново-підзолистими ґрунтами. Практичне значення отриманих результатів полягає у встановленні оптимальної групи стиглості сої для вирощування на дерново-підзолистих та торфових ґрунтах в зоні Західного Полісся, що дозволяє одержувати фізіологічно-стигле зерно за сучасних показників гідротермічних ресурсів

Ключові слова: осушувані землі; дерново-підзолисті ґрунти; торфові ґрунти; гідротермічні умови; система удобрення; інокулянт; фосфоро-мобілізуючий препарат

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Characteristics of rooting in rose cuttings (*Rosa* spp.) depending on cultivar and morphometric parameters under greenhouse conditions

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Abstract. The relevance of this study stems from the need in ornamental horticulture for high-quality, uniform and cultivar-specific rose planting material, which can be produced under controlled microclimatic conditions. Rooting of cuttings is a crucial stage in vegetative propagation; however, its effectiveness depends on the biological characteristics of the cultivar and the parameters of the harvested shoot. The aim of this study was to determine the characteristics of rooting of semi-hardwood rose cuttings depending on cultivar and morphometric parameters under greenhouse conditions. The cultivars Jude the Obscure, The Pilgrim and Abraham Darby were studied. For each cultivar, cuttings 25, 40 and 60 cm in length were used; the number of internodes, shoot diameter, length of the lower cut, percentage of rooted cuttings, average root length and average root system mass were determined. The cuttings were planted in a sterile substrate of peat and perlite in a 1:1 ratio at an air temperature of 22-25°C, relative

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humidity of 85-95%, diffused light and regular fine-mist irrigation. It was found that as the length of the cuttings increased from 25 to 60 cm, the number of internodes, the diameter of the shoots and the area of the lower cut all increased; however, the maximum length did not always result in the highest survival rate. The best rooting rates for all cultivars were achieved using 40 cm-long cuttings: for Jude the Obscure the rooting rate was 82%, for The Pilgrim 76%, and for Abraham Darby 86%. Cuttings 60 cm in length formed a longer and more robust root system; in particular, for Abraham Darby, the average root length reached 7.4 cm and the root mass was 0.94 g, although the rooting percentage was lower than for the 40 cm cuttings. The lowest results were observed when using 25 cm-long cuttings. Based on a range of indicators, the Abraham Darby cultivar proved to be the most promising for propagation by cuttings. The practical value of this study lies in substantiating the feasibility of using 40 cm-long semi-hardwood cuttings to increase the yield of high-quality rose planting material under greenhouse conditions

Keywords: ornamental horticulture; English roses; semi-hardwood shoots; substrate; root formation; planting stock; cuttings

INTRODUCTION

Ornamental horticulture requires techniques that ensure a consistent supply of uniform planting stock with a high degree of preservation of cultivar characteristics. For roses, this issue is particularly important, as their ornamental value is determined not only by the colour and shape of the flower, but also by vigour, repeat flowering, resilience to growing conditions and the ability to retain typical cultivar characteristics during propagation. O.Yu. Bondarenko *et al.* (2024), analysing the range of cultivated plants in botanical collections, emphasised the importance of selecting adapted ornamental crops for landscaping, whilst H.V. Pantsyreva (2019) substantiated the prospects for using flowering ornamental plants in the design of park plantings. I.L. Denysko (2022) demonstrated the potential for introducing David Austin roses into the Right-Bank Forest-Steppe region of Ukraine and noted their high ornamental value and adaptive potential. H. Gill *et al.* (2025) demonstrated that certain ornamental traits of roses, in particular the characteristics of flower colour change, are genetically determined; thus, it is important to use propagation methods that ensure the preservation of cultivar identity. A. Kalisz *et al.* (2023) also drew attention to the varietal specificity of roses, identifying significant differences between cultivars in the content of bioactive compounds in the petals.

Vegetative propagation by cuttings is one of the most practical methods for obtaining uniform planting stock of roses. P.V. Bezvikonnyi *et al.* (2023) found that the application of growth biostimulants affects the rooting of green cuttings of the wrinkled rose under protected ground conditions. E.K. Blythe *et al.* (2004) demonstrated that the method of applying auxin and the use of a surfactant can alter the rooting efficiency of rose cuttings. A. Muraleedharan *et al.* (2020) also noted that the rooting of rose cuttings depends on the hormonal preparation used, whilst N. Ghazijahani *et al.* (2017) demonstrated that rhizogenesis in soft rose cuttings can be regulated by treating the mother plants with organic acids. I. Mohammed *et al.* (2024) confirmed that the response of rose cuttings to indolebutyric acid and an anti-transpirant depends on the rose cultivar, the method of application and the characteristics of the cutting. These results indicate that rooting is not only a technical process but also a cultivar-dependent one.

A. Ait Hida *et al.* (2022), studying cuttings of *Rosa damascena* Mill., demonstrated that the origin of the cutting material and auxin treatment significantly affect the rooting percentage. Similar conclusions regarding the importance of auxin regulation of root formation are also presented in the studies by S. Ercişli *et al.* (2005), A. Kazankaya *et al.* (2005) and I. Mohammed *et al.* (2024), which emphasise the role of indolebutyric acid, the substrate, the physiological state of the cutting and the technical conditions of rooting. *In vitro* studies have also confirmed the importance of growth regulators for root formation and subsequent regeneration in roses (Chhalgri *et al.*, 2020; Kosenko *et al.*, 2021; El Malahi *et al.*, 2025). Furthermore, R.J. Morales-Orellana *et al.* (2022) demonstrated that localised laser damage to tissues can stimulate the formation of adventitious roots in rose cuttings, highlighting the complexity of the physiological mechanisms of rhizogenesis. O.V. Kobets (2013), using green cuttings of berry crops as an example, also demonstrated the importance of growth regulators and the conditions under which mother plants are maintained for the rooting process. Thus, existing studies have confirmed the importance of growth regulators; however, the question of the optimal length of cuttings and their morphometric parameters for specific rose cultivars remains insufficiently detailed. The scientific problem lies in the fact that most existing studies examine the influence of substrates, auxins or the origin of cuttings in isolation, whilst a comprehensive assessment of cultivar characteristics and the morphometric parameters of cuttings under controlled greenhouse conditions remains limited. It is therefore important to identify those parameters of cuttings that ensure not only high survival rates but also the formation of a sufficiently developed root system in the cultivars Jude the Obscure, The Pilgrim and Abraham Darby.

The aim of the study was to investigate the effect of cultivar and the morphometric parameters of cuttings on their rooting under greenhouse conditions and to determine the optimal cutting parameters for producing high-quality rose planting stock. To achieve this aim, the study involved analysing the biological characteristics of the cultivars under investigation, determining the morphometric parameters of the cuttings, assessing their impact on the rooting percentage, investigating root system development, and establishing the optimal cutting parameters for the effective vegetative propagation of roses under greenhouse conditions. The scientific novelty of this work lies in the comparative assessment of the rooting of cuttings from three rose cultivars with different morphometric parameters under controlled greenhouse conditions.

MATERIALS AND METHODS

The study was conducted in June-July 2025 in the greenhouse of the "Amitys" Horticultural and Landscape Centre. The study focused on semi-hardwood cuttings of roses (*Rosa* spp.) of the cultivars Jude the Obscure, The Pilgrim and Abraham Darby, rooted under greenhouse conditions. The study was conducted in accordance with the principles of the Convention on Biological Diversity (1992). The experimental design involved the study of two factors: rose cultivar and cutting length. Factor A comprised three cultivars: Jude the Obscure, The Pilgrim and Abraham Darby; factor B comprised three cutting lengths: 25, 40 and 60 cm. The experiment was set up in triplicate. The treatments were arranged randomly within each replicate in the greenhouse, which minimised the impact of variations in light, humidity and temperature.

Cuttings were taken from well-developed, healthy semi-hardwood shoots in 2025. In each treatment, the length of the cutting, the number of internodes, the shoot diameter and the length of the lower cut were determined. The lower cut was made at a 45° angle immediately below a bud, whilst the upper cut was made straight, 1-2 cm above the top bud. The lower leaves were removed, and the upper leaves were partially shortened to reduce moisture evaporation, in line with general methodological approaches to the propagation of ornamental crops by cuttings (Bezvikonnyi *et al.*, 2023; Mohammed *et al.*, 2024). The morphometric parameters of the cuttings are presented in Table 1.

***Table 1**. Morphometric characteristics of rose cuttings depending on cultivar*

Cultivar	Variant No.	Cutting length, cm	Number of internodes, no.	Shoot diameter, mm	Length of basal cut, cm
Jude the Obscure	1	25	2	3.4	2.0
	2	40	5	4.5	3.5
	3	60	7	5.6	5.0
The Pilgrim	1	25	2	3.2	2.0
	2	40	4	4.3	3.4
	3	60	6	5.3	4.8
Abraham Darby	1	25	3	3.7	2.2
	2	40	5	4.8	3.7
	3	60	7	5.9	5.1

***Source:** compiled by the authors*

Before planting, the base of the cuttings was treated with "Kornevin", the active ingredient of which is indolebutyric acid (IBA). The working solution was prepared immediately before use at a rate of 1 g of the product per 1 litre of water. The lower part of the cuttings was immersed in the solution to a depth of 2-3 cm and left for 12 hours, after which the cuttings were planted in a sterile substrate of peat and perlite in a 1:1 ratio. The planting depth was 2-3 cm. In the greenhouse, the air temperature was maintained at 22-25°C, relative humidity at 85-95%, with diffused lighting and regular moistening of the substrate. Fine-mist irrigation was used to maintain high humidity, and ventilation was carried out to prevent the development of fungal diseases and rotting of the cuttings.

Records were taken on days 14, 21, 28 and 35 after planting. The rooting period lasted 35 days. A cutting was considered rooted if it had at least three adventitious roots longer than 1.0 cm and the above-ground part remained viable. The rooting percentage was determined as the proportion of rooted cuttings out of the total number of cuttings planted in each treatment. The average root length was determined by measuring the developed roots on the rooted cuttings. Statistical analysis of the results was carried out using standard methods of variance analysis. For each experimental treatment, the arithmetic mean of the studied parameters was calculated.

RESULTS AND DISCUSSION

Analysis of the morphometric parameters of rose cuttings showed that, in all the cultivars studied, as the cutting length increased from 25 to 60 cm, the number of internodes, shoot diameter and length of the lower cut increased in a regular pattern. This trend indicates an increase in the reserve of plastic substances in longer cuttings and a potentially larger area for root formation, which is consistent with data on internode

lengths and shoot growth parameters in roses reported by S. Demotes-Mainard *et al.* (2013). In Jude the Obscure, the number of internodes ranged from 2 to 7, and the shoot diameter from 3.4 to 5.6 mm. This indicates a gradual increase in the physiological potential of the cuttings as their length increased. The The Pilgrim cultivar had slightly lower morphometric parameters compared with other cultivars: the number of internodes was 2-6, and the shoot diameter was 3.2-5.3 mm. Such cuttings remained suitable for rooting but required stable temperature and humidity conditions (Rubtsova *et al.*, 2020; Denysko, 2025).

The highest morphometric parameters were observed in the Abraham Darby cultivar: shoot diameter ranged from 3.7 to 5.9 mm, and the number of internodes ranged from 3 to 7. This indicates better-developed shoots and a greater reserve of nutrients, which may have a positive effect on root system development. In terms of morphometric characteristics, the cuttings of the Abraham Darby cultivar were the most robust; Jude the Obscure had slightly lower values, whilst The Pilgrim had the lowest. Cuttings of an average length of 40 cm were the most balanced for subsequent rooting, as they combined a sufficient number of internodes and shoot diameter without an excessive risk of moisture loss (Ouyang *et al.*, 2019; Mohammed *et al.*, 2024). The results of cutting rooting, depending on cultivar and morphometric parameters, are presented in Table 2.

***Table 2**. Rooting performance of rose cuttings depending on cultivar and morphometric parameters under greenhouse conditions*

Cultivar	Variant No.	Cutting length, cm	Rooted cuttings, %	Mean root length, cm	Mean root system mass, g
Jude the Obscure	1	25	65	4.2	0.48
	2	40	82	6.5	0.75
	3	60	78	7.1	0.88
The Pilgrim	1	25	61	3.9	0.43
	2	40	76	6.1	0.68
	3	60	72	6.6	0.79
Abraham Darby	1	25	69	4.6	0.54
	2	40	86	6.9	0.82
	3	60	81	7.4	0.94

***Source:** compiled by the authors*

Root formation efficiency depended on both the cultivar and the length of the cuttings. For all the cultivars studied, the lowest rooting rates were observed for cuttings 25 cm in length. This can be explained by the smaller number of internodes, limited reserves of plastic substances and weaker physiological potential for root system formation, which is consistent with data on the influence of the origin and physiological state of cuttings on rhizogenesis (Ait Hida *et al.*, 2022; Mohammed *et al.*, 2024). The highest percentage of rooted cuttings across all cultivars was observed when using 40 cm-long cuttings. For the Jude the Obscure cultivar, this figure was 82%, for The Pilgrim 76%, and for Abraham Darby 86%. Thus, cuttings of medium length exhibited the most favourable balance between nutrient reserves, the number of internodes and the level of transpiration losses. It was precisely this length that ensured better survival rates and more stable root formation, confirming the importance of considering cutting length and methods to reduce water loss during rooting (Mohammed *et al.*, 2024).

Cuttings 60 cm in length were characterised by a greater average root length and a higher root system mass compared with shorter variants. In the Abraham Darby cultivar, the average root length was 7.4 cm and the root system mass was 0.94 g, which was the highest value among all variants. At the same time, the rooting percentage for 60 cm-long cuttings was lower than that for the 40 cm variant. This may be due to greater water loss and increased stress on the cutting during the period prior to the formation of a fully developed root system, as previously noted by S. Demotes-Mainard *et al.* (2013) and P.V. Bezvikonnyi *et al.* (2023).

Varietal differences were also clearly evident. Overall, the Abraham Darby showed the best results, with a rooting percentage of 69-86%, an average root length of 4.6-7.4 cm, and a root system mass of 0.54-0.94 g. This indicates its superior ability for vegetative propagation and the formation of a well-developed root system. The Jude the Obscure also showed high rooting rates, particularly with 40 cm-long cuttings. The The Pilgrim showed slightly lower results, but followed the general pattern: the best rooting was observed in cuttings of medium length, a finding also reported by O.L. Rubtsova *et al.* (2020), I.L. Denysko (2022) and A. Ait Hida *et al.* (2022).

The results obtained confirm that the rooting process of rose cuttings under greenhouse conditions is cultivar-specific and depends to a large extent on the morphometric parameters of the cuttings. The most consistent rooting rates were observed when using cuttings of an average length of 40 cm, which provided the optimal combination of the number of internodes, shoot diameter and physiological potential for root formation. Shorter cuttings were characterised by a lower rooting percentage due to a smaller reserve of

nutrients, whilst longer cuttings formed a more robust root system but had a slightly lower survival rate due to higher moisture loss (Ercişli *et al.*, 2005; Bezvikonnyi *et al.*, 2023; Mohammed *et al.*, 2024).

Thus, the success of rose cuttings in greenhouse conditions depends not only on maintaining an optimal microclimate, but also on the correct selection of the cultivar and the characteristics of the cuttings. For practical purposes, it is most advisable to use semi-hardwood cuttings 40 cm in length, as these ensure the highest rooting rate and the development of a sufficiently well-developed root system. This makes it possible to increase the yield of high-quality rose planting stock for ornamental horticulture, landscaping and flower production.

The results obtained are consistent with the findings of P.V. Bezvikonnyi *et al.* (2023), who established the positive effect of growth biostimulants on the rooting of green cuttings of *Rosa rugosa* Thunb. in protected soil. A common finding is the confirmation that controlled growing conditions and the stimulation of root formation enhance the efficiency of cuttings. At the same time, the present study focuses not only on the application of the stimulant but also on the comparison of cultivars and cutting lengths.

I. Mohammed *et al.* (2024) investigated the response of rose cuttings to indolebutyric acid and an anti-transpirant and demonstrated that reducing water loss is a key factor in successful rooting. This explains the results obtained in the treatment with 60 cm-long cuttings: they formed a larger root mass but had a lower rooting percentage compared with 40 cm-long cuttings, presumably due to an increased transpiration load. A. Ait Hida *et al.* (2022) demonstrated that the origin of *Rosa damascena* Mill. cuttings and the exogenous application of auxin significantly influence the rooting percentage. A similar pattern was observed in the present study: the cultivars Jude the Obscure, The Pilgrim and Abraham Darby responded differently to identical cuttings conditions, indicating cultivar-specific characteristics in the root formation process. S. Ercişli *et al.* (2005) determined the importance of the substrate and IBA concentration for the formation of adventitious roots in *Rosa dumalis* cuttings. The results obtained in this study confirm the advisability of using a light, aerated substrate of peat and perlite, whilst supplementing previous findings with information on the role of the cuttings' morphometric parameters.

A. Kazankaya *et al.* (2005) demonstrated that the rooting efficiency of *Rosa canina* L. cuttings depends on the time of collection and the concentration of IBA. In this study, the time of collection was standardised, which allowed to focus on varietal differences and cutting length. This allows to consider cutting length as an independent technological factor in the vegetative propagation of roses. I. Skoroplyas (2016) investigated the rooting of rose cuttings on different substrates at the Kremenets Botanical Garden and emphasised the importance of the substrate's physical properties for rhizogenesis. In this study, the substrate was the same for all treatments; thus, differences between cultivars and cutting lengths can be attributed primarily to the morphophysiological characteristics of the shoots. S. Demotes-Mainard *et al.* (2013) developed a model of leaf and internode growth in roses that accounts for inter-plant variability. Their results explain why, even within a single crop, different cultivars may have varying morphometric potential. In this study, the Abraham Darby exhibited the highest values for shoot diameter and number of internodes, accompanied by the best overall rooting performance. I.L. Denysko (2022) noted the potential of David Austin's rose cultivars for the conditions of the Right-Bank Forest-Steppe of Ukraine. These findings are complemented by a practical aspect: for cultivars of this group under greenhouse conditions, 40 cm long semi-hardwood cuttings were the most effective. Consequently, the patterns identified can be used to improve the technology for producing planting material for English roses. Thus, the research results confirm that the effectiveness of rose cuttings is determined by a combination of three factors: cultivar-specific characteristics, the morphometric parameters of the cuttings, and controlled microclimatic conditions.

CONCLUSIONS

Research has shown that the rooting of rose cuttings (*Rosa* spp.) under greenhouse conditions depended on cultivar characteristics and the morphometric parameters of the cuttings. The most significant factors were cutting length, the number of internodes and shoot diameter, which determined the reserve of plastic substances, the intensity of root formation and the cuttings' ability to take root. For all the cultivar studied – Jude the Obscure, The Pilgrim and Abraham Darby – the highest rooting percentage was observed when using semi-hardwood cuttings 40 cm in length. It was precisely these cuttings that provided the most balanced ratio between the number of internodes, the physiological potential of the shoots and the level of transpiration losses.

Cuttings 25 cm in length were characterised by lower rooting rates, which is attributed to a smaller number of internodes, a smaller shoot diameter and a limited supply of nutrients. In contrast, 60 cm-long cuttings formed a longer and more robust root system; however, their survival rate was slightly lower compared with cuttings of medium length. This suggests that an excessive increase in cutting length does not always ensure higher propagation efficiency, as it may be accompanied by increased water loss and a greater physiological stress on the plant material. Among the cultivars studied, Abraham Darby exhibited the best overall rooting performance, which can be explained by better shoot development, a larger cutting diameter and a higher potential for root system formation. The

Jude the Obscure cultivar also demonstrated a high capacity for rooting, particularly when using 40 cm-long cuttings. The The Pilgrim cultivar showed slightly lower performance, but still followed the general trend favouring cuttings of medium length.

Thus, for effective vegetative propagation of roses under greenhouse conditions, it is advisable to use semi-hardwood cuttings 40 cm in length, which ensure the highest survival rate and sufficient root system development. Maintaining optimal temperature and humidity conditions, using a light, well-aerated growing medium, and applying root-forming stimulants also help to improve the efficiency of cuttings. Future research should focus on clarifying the effects of different concentrations of auxin preparations, substrate composition and the timing of cutting collection for the rose cultivars under study.

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Особливості укорінення живців троянд (*Rosa* spp.) залежно від сорту та морфометричних параметрів у тепличних умовах

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Анотація. Актуальність дослідження зумовлена потребою декоративного садівництва у якісному, однорідному та сортово-типовому садивному матеріалі троянд, який можна отримувати в умовах контрольованого мікроклімату. Укорінення живців є важливим етапом вегетативного розмноження, однак його ефективність залежить від біологічних особливостей сорту та параметрів заготовленого пагона. Метою роботи було встановити особливості укорінення напівздерев'янілих живців троянд залежно від сорту та морфометричних показників у тепличних умовах. Досліджували сорти Jude the Obscure, The Pilgrim та Abraham Darby. Для кожного сорту використовували живці довжиною 25, 40 і 60 см, визначали кількість міжвузлів, діаметр пагона, довжину нижнього зрізу, відсоток укорінених живців, середню довжину коренів і середню масу кореневої системи. Живці висаджували у стерильний субстрат із торфу та перліту у співвідношенні 1:1 за температури повітря 22-25°C, відносної вологості 85-95 %, розсіяного освітлення та регулярного дрібнодисперсного зрошення. Встановлено, що зі збільшенням довжини живців від 25 до 60 см зростали кількість міжвузлів, діаметр пагонів і площа нижнього зрізу, однак максимальна довжина не завжди забезпечувала найвищу приживлюваність. Найкращі показники укорінення у всіх сортів одержано за використання живців довжиною 40 см: у Jude the Obscure укорінення становило 82 %, у The Pilgrim 76 %, у Abraham Darby 86 %. Живці довжиною 60 см формували довшу і масивнішу кореневу систему, зокрема у Abraham Darby середня довжина коренів досягала 7,4 см, а маса кореневої системи – 0,94 г, проте відсоток укорінення був нижчим, ніж у варіанті 40 см. Найнижчі результати спостерігали за використання живців довжиною 25 см. За комплексом показників найбільш перспективним для живцювання був сорт Abraham Darby. Практична цінність роботи полягає в обґрунтуванні доцільності використання напівздерев'янілих живців довжиною 40 см для підвищення виходу якісного садивного матеріалу троянд у тепличних умовах

Ключові слова: декоративне садівництво; англійські троянди; напівздерев'янілі пагони; субстрат; коренеутворення; садивний матеріал; живці

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Silvicultural and mensurational structure of *Pinus nigra* Stands in Ukraine based on the 2011 state forest inventory data

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Abstract.The study aimed to identify the territorial, forest-site, silvicultural, and mensurational patterns governing the formation of Crimean pine and Austrian pine stands in Ukraine. The analysis was based on a compartment-level database of the State Forest Inventory as of 2011. Structured queries in the Microsoft SQL Server database management system, weighted mean calculations, and regression analysis of age-related changes in stand mensurational characteristics were applied. The total area of the studied stands amounted to 134.1 thousand ha, of which 99.8% was occupied by Crimean pine (*P. nigra* var. *pallasiana*) and 0.2% by Austrian pine (*P. nigra* var. *austriaca*). Most Crimean pine stands were concentrated in the southern and eastern regions of Ukraine, whereas Austrian pine stands had a local distribution, predominantly in the western part of the country. Very dry and dry forest-site conditions accounted for 84.8% of the total area of Crimean pine stands, primarily in dry fairly fertile site types and dry poor site types. Austrian pine occurred more frequently in fresh fairly fertile and fertile site types. Artificially established and pure stands predominated in the structure of both taxa. Under dry site conditions, artificially established stands accounted for 91.5% of Crimean pine stands and 98.5% of Austrian pine stands. The highest site-quality classes, mean heights, mean diameters, growing stock volumes, and proportions of merchantable timber were generally recorded in fairly fertile and fertile site types. By

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contrast, the productive potential of stands growing in dry poor site types was constrained by moisture deficiency and low soil fertility. The diversity of associated tree species increased with increasing site trophicity: *P. sylvestris* predominated in poor site types, whereas the contribution of broadleaved hardwood species increased in fairly fertile and fertile site types

Keywords: Crimean pine; Austrian pine; forest-site types; growing stock volume; productivity; merchantable timber; growth dynamics

INTRODUCTION

Black pine (*Pinus nigra* J.F. Arnold) is an ecologically and intraspecifically differentiated coniferous species whose natural range encompasses the mountainous regions of Southern and Central Europe, the Balkan Peninsula, the Mediterranean region, and Asia Minor. The spatial fragmentation of its range and the long-term isolation of individual populations have led to the formation of several geographical subspecies and ecotypes differing in morphological traits, growth rates, drought tolerance, and responses to site conditions. The eastern part of this taxonomic complex includes Pallas pine, also known as Crimean pine, which is most commonly classified as *P. nigra* subsp. *pallasiana* (Lamb.) Holmboe, whereas the name *P. pallasiana* D. Don is used less frequently.

The silvicultural importance of black pine is determined by its ability to form stands on dry, rocky, nutrient-poor, eroded, and anthropogenically disturbed lands. Owing to the plasticity of its root system, relatively efficient water use, and tolerance of adverse soil conditions, the species is widely used for erosion-control afforestation, the stabilisation of sands and slopes, the reclamation of disturbed lands, and the establishment of protective forest plantations. M.E. Lucas-Borja *et al.* (2022), investigating Spanish black pine along an elevation gradient, demonstrated that afforestation success depends strongly on plantation-site conditions and seed origin, with severe drought at low-elevation sites substantially reducing seedling survival. Z. Vacek *et al.* (2023), based on a systematic review of European studies, also confirmed the considerable potential of black pine for forest restoration, timber production, and climate-change adaptation in forestry. At the same time, these authors revealed substantial variation in cultivation outcomes depending on seed provenance, stand age and density, and local environmental conditions.

Current research on *P. nigra* increasingly focuses on identifying relationships among stand structure, climate, and productivity dynamics. S. Versace *et al.* (2022), studying populations of *P. nigra* subsp. *laricio* in Corsica, Sardinia, Sicily, and Calabria, further confirmed that resistance, recovery, and resilience following drought events depend on the local environment and tree age. According to their findings, older trees showed greater resistance to individual drought periods, although responses differed among populations. The importance of geographic origin for black pine growth has recently been demonstrated by G. Giovannelli *et al.* (2026) in common-garden trials involving 16 provenances from four subspecies. The authors found that provenance effects on radial growth were stronger than subspecies effects and recorded substantial phenotypic plasticity and genotype-by-environment interactions among contrasting sites.

An equally important research direction concerns the effects of stand density and silvicultural interventions on the response of black pine plantations to drought. From the perspective of timber utilisation, A. Dias *et al.* (2020) analysed the physical, chemical, and mechanical properties of *P. nigra* wood from six Portuguese sites. The authors found that its mechanical properties were broadly comparable to those of *P. pinaster*, while several wood characteristics indicated potential advantages for industrial use. These findings provide additional grounds for considering black pine not only as a protective or land-reclamation species but also as a potentially valuable timber-producing species.

These findings demonstrate the need for a comprehensive approach to assessing black pine stands. Their silvicultural potential cannot be substantiated solely on the basis of total area or stand survival. Their distribution by forest site conditions, origin, age, species composition, relative density, and site-quality class must also be considered, together with the dynamics of mean height, mean diameter, growing stock, and timber merchantability. Identifying these relationships makes it possible to distinguish realised productivity from the potential productive capacity of the species and to determine the conditions under which its cultivation is both ecologically and economically justified. In Ukraine, black pine in the broad taxonomic sense is represented primarily by Crimean pine and by substantially smaller areas of Austrian pine stands. Crimean pine occurs naturally in the Crimean Mountains, whereas in the Steppe, Forest-Steppe, and partly in the Polissia zones, it is grown predominantly in artificially established stands. Austrian pine is an introduced taxon whose cultivation centres are located mainly in the western, central, and north-eastern regions of the country.

The analysed dataset covers their distribution across administrative regions and forest site conditions, the proportions of natural and artificially established stands, pure and mixed stands, site-quality classes, growing stock, mean heights and diameters, the proportion

of merchantable timber, and the composition of associated tree species. The adaptive capacity of Crimean pine under the steppe conditions of Ukraine has also been assessed through physiological indicators. V. Bessonova & T. Yusypiva (2021) found that tree and shoot growth, needle surface development, and needle water content in anti-erosion plantations varied markedly with forest-growth conditions, with the lowest values generally occurring under arid and semi-arid slope conditions. Their findings demonstrate that physiological adaptation to drought does not eliminate the growth constraints associated with limited water availability.

Despite considerable scientific interest in the ecology, climatic sensitivity, introduction, and productivity of *P. nigra*, most studies have been conducted on individual experimental sites, regional networks of sample plots, or within a single subspecies. In Ukraine, the relationships among the territorial distribution of Crimean and Austrian pine, forest site conditions, stand origin and species composition, age structure, productivity, and timber merchantability remain insufficiently investigated. Addressing this knowledge gap is particularly relevant in the context of adapting forest management to increasing climatic aridity, restoring degraded lands, and scientifically substantiating the expansion of the range of tree species used in protective afforestation. The aim of the study was to provide a comparative assessment of Crimean pine and Austrian pine stands in Ukraine and to determine how their distribution, stand structure, and productivity vary in relation to forest site conditions.

To achieve this aim, the following objectives were established to assess the regional distribution of stand areas and determine their forest-site and age structure, origin, and proportions of pure and mixed stands; to analyse stand productivity and merchantability, as well as the dynamics of mean height, mean diameter, and growing stock in relation to site conditions; to determine the species composition of associated tree species in Crimean pine and Austrian pine stands. The scientific novelty of the study lies in the development of an integrated nationwide assessment of black pine stands by simultaneously combining spatial, forest-typological, age-related, coenotic, and mensurational characteristics. Unlike local studies of individual populations or experimental plantations, the present study compares Crimean pine and Austrian pine stands within a unified information framework in terms of their area, origin, species composition, productivity, and the qualitative structure of growing stock.

LITERATURE REVIEW

Scientific research on black pine encompasses its taxonomy, natural and secondary distribution, introduction, forest-site affinity, growth, productivity, natural regeneration, health condition, and economic value. Comparisons among published findings are complicated by inconsistent interpretations of the intraspecific structure of *P. nigra*. Different sources use the names *P. nigra* var. *austriaca*, *P. nigra* subsP. *nigra*, *P. nigra* subsP. *pallasiana*, and *P. pallasiana* D. Don. These differences in taxonomic approaches have also affected forest inventory records, in which Crimean pine and Austrian pine may have been registered as separate tree species, varieties of black pine, or, in some cases, mistakenly assigned to Scots pine.

One of the first comprehensive studies of introduced black pine stands in Ukraine was conducted by T.B. Skrobach (2006). The author characterised the distribution of the species in the lowland and mountainous parts of western Ukraine, its bioecological properties, silvicultural and mensurational characteristics, health condition, seed production, and capacity for natural regeneration. The findings provided a positive assessment of the effectiveness of black pine introduction and substantiated its potential for use in forest plantations and phytomeliorative stands. At the same time, it was emphasised that the longevity and productivity of the species are determined by the correspondence of specific sites to its ecological requirements rather than solely by its generally recognised drought tolerance.

Environmental differentiation within the natural Crimean range of *P. nigra* subsP. *pallasiana* was examined by N.M. Devi *et al.* (2023) along an elevational transect on Mount Ai-Petri. Using four tree-ring chronologies, the authors demonstrated substantial differences in climate–growth relationships along the altitudinal gradient. These differences were associated not only with climatic variation but also with topography, soil, and bedrock characteristics. Precipitation during the growing season, particularly in July, was identified as an important factor affecting radial growth. The study therefore confirms that even within a relatively compact natural range, Crimean pine growth is strongly site dependent and should be interpreted within a combined climatic-edaphic framework.

The complex intraspecific differentiation of European black pine has also been investigated using genomic approaches. S. Olsson *et al.* (2020) developed transcriptomic resources representing major biogeographical regions of the natural range and used nuclear orthologous genes and single-nucleotide polymorphisms to examine evolutionary relationships within *P. nigra*. Their results supported the existence of two broad geographical population groups while also demonstrating that conventional subspecific classifications do not fully reflect the genetic structure of the species. These findings emphasise the need for caution when interpreting the taxonomic identity and provenance of introduced stands solely from historical planting records or conventional forest inventory classifications.

The adaptation of black pine to conditions within its secondary range was investigated by M. Soroka & T. Yuskevych (2011). In the Holohory region, the authors recorded successful seed regeneration and the

formation of a third generation of black pine without direct human intervention, which was interpreted as evidence of its complete naturalisation. Phytosociological surveys showed that the species had formed an ecological niche similar to that of natural black pine forests belonging to the eastern ecological grouP. Nevertheless, the capacity of this introduced species for autonomous spread requires monitoring near natural steppe and meadow-steppe communities, because successful naturalisation from a forestry perspective does not always correspond with the objectives of conserving native vegetation.

The climatic sensitivity of Crimean pine within its natural range was assessed by I. Koval (2013). A dendrochronological analysis of a 110-year-old stand on the southern slope of the Crimean Mountains revealed differences in the responses of earlywood, latewood, and total annual ring width to temperature and precipitation. Latewood was the most sensitive component to climatic variation. Reduced precipitation during the warm season and increasing summer water deficits resulted in decreased radial growth. Thus, even in natural stands of the subspecies *pallasiana*, drought tolerance does not prevent productivity losses under prolonged shortages of available moisture.

The phenological characteristics of introduced black pine under the conditions of the Right-Bank Forest-Steppe were studied by S. Adamenko *et al*. (2018). The authors identified an early onset of vegetation and a pronounced dependence of shoot growth intensity on air temperature. Needle growth began later than shoot elongation, while growth intensity increased from the lower part of the crown towards the apex. The correspondence of seasonal rhythms to the local climate indicates a sufficient level of species adaptation; however, phenological observations alone do not characterise the long-term productivity and stability of established stands.

The importance of planting-material provenance for the adaptation of black pine to contrasting environmental conditions was investigated by V. Ivetić *et al*. (2021). The authors compared seedlings originating from southern Greek and northern Serbian provenances and assessed their tolerance to freezing, heat, and drought. Seedlings from the northern provenance showed the highest tolerance to severe freezing, although differences among provenances were not statistically significant, while the combined effects of heat and drought caused greater foliar damage than drought alone. The authors emphasised that the use of black pine in reforestation and restoration should not be based on the search for a single universally adapted provenance but should consider genetic diversity and the correspondence of reproductive material to projected environmental conditions. These findings highlight the importance of provenance selection when black pine is introduced beyond its natural range.

The productivity of semi-arid Crimean pine stands was assessed by S. Bulut *et al*. (2023) using an integrated approach combining field measurements, biogeochemical modelling, remote sensing, and machine-learning techniques. Net primary productivity showed significant temporal relationships with vegetation indices, temperature, and solar radiation, while the integration of satellite-derived texture characteristics with support vector machine modelling provided high predictive accuracy. The study demonstrates that Crimean pine productivity is spatially and temporally variable and is controlled by the interaction of stand characteristics, climatic factors, and environmental conditions. It also highlights the potential of combining conventional forest inventory data with remote-sensing information for assessing the productive capacity of black pine stands over larger areas.

The interaction between forest management and climatic stress in black pine stands was examined by E. Collado *et al*. (2026) across several Mediterranean regions in Spain and Slovenia. Based on dendrochronological, mensurational, and soil data from managed and unmanaged stands, the authors found that silvicultural treatments, particularly moderate thinning, generally enhanced radial growth and reduced tree drought stress. The effects varied with stand age, climatic conditions, and regional context and were particularly pronounced in warmer and drier areas. These results demonstrate that stand structure and management intensity are important determinants of black pine growth responses under increasing climatic aridity.

The influence of ecological regionalisation on Crimean pine growth was quantified by M. Seki & O.E. Sakici (2022) using data from 274 sample plots and 293 stem analyses in north-western Türkiye. The authors found significant ecoregional differences in dominant-height, tree-number, basal-area, and stand-volume growth. Ecoregion-specific models provided more reliable predictions than a single regional model, whereas ignoring ecological differentiation resulted in systematic biases in estimates of stand characteristics. The findings demonstrate that growth and yield assessment of *P. nigra* subsp. *pallasiana* should explicitly account for ecological regionalisation rather than assuming uniform stand development across contrasting environments.

A. Dias *et al*. (2022) analysed the long-term growth of introduced black pine stands in Portugal located near the western limit of its current distribution. Six stands aged 50-90 years showed differences in diameter-growth dynamics that did not form a clear latitudinal or longitudinal gradient. Low mortality and the satisfactory condition of most stands indicated the high adaptive capacity of the species, while differences among growth trajectories confirmed the influence of local site conditions and, potentially, the provenance of planting material. The proposed models may be used to predict diameter growth when planning new forest plantations.

Mensurational modelling of natural even-aged black pine stands was performed by D.I. Raptis *et al.* (2021). Based on 3,442 pairs of height and diameter observations, the authors developed nonlinear mixed-effects models describing the relationship between these variables. The inclusion of dominant height and dominant diameter as predictors improved the accuracy of tree-height estimates. Such models are of practical importance for calculating growing stock and aboveground biomass and demonstrate that the interpretation of mean mensurational characteristics should account for between-site variability and the structure of the individual stand.

The regeneration dynamics of black pine forests following severe disturbance were analysed by S. Martín-Alcón & L. Coll (2016) in *P. nigra* subsP. salzmannii forests affected by a large wildfire in north-eastern Spain. The authors found that post-fire trajectories were determined jointly by pre-fire vegetation structure, burn severity, the proximity of unburned patches, topography, and site quality. Pine regeneration was favoured near surviving forest patches, whereas transitions towards shrub-dominated vegetation occurred more frequently on xeric sites. These findings demonstrate that the long-term persistence and structural development of black pine forests depend strongly on disturbance history and site context and that their regeneration trajectories can be influenced by silvicultural management.

The structural development and natural regeneration of old-established black pine plantations were investigated by A. Bricca *et al.* (2025) in the eastern European Alps. The authors analysed the effects of climatic, topographic, and local environmental conditions together with interactions among the tree, shrub, herbaceous, and regeneration layers. They found that plant diversity and regeneration were influenced not only by site conditions but also by the structure of the upper vegetation layers, with tree composition exerting cascading effects on shrub, herbaceous, and juvenile woody communities. Old-established black pine plantations were characterised by relatively high plant diversity but limited natural regeneration, while the course of their passive transition towards more natural forest communities depended on environmental conditions and interactions among vegetation layers. These findings demonstrate that the long-term structural development of black pine plantations cannot be interpreted solely from the characteristics of the dominant tree species but requires consideration of stand structure, regeneration processes, and site-specific environmental filters.

A synthesis of the available scientific literature indicates that regional patterns of introduction, physiological adaptation, climatic sensitivity, natural regeneration, and black pine growth have been investigated most extensively. Nevertheless, most studies are based on a limited number of sample plots or focus on an individual region, taxon, or aspect of stand functioning. Studies simultaneously comparing the territorial distribution, forest site conditions, origin, species composition, age structure, site quality, growing stock, mean height and diameter, and proportion of merchantable timber in Crimean pine and Austrian pine stands throughout Ukraine remain insufficient. The analysis of a nationwide forest inventory dataset makes it possible to extend existing regional findings and develop an integrated understanding of the silvicultural and mensurational structure of black pine stands.

MATERIALS AND METHODS

The analysis was based on the 2011 database of the Ukrderzhlisproekt Production Association (2012), which currently represents the most recent statistically reliable source of nationwide forest inventory information (Information from the State Forest Cadastre, 2019). The use of more recent nationwide data is constrained by the absence of a complete repeated forest inventory covering the entire territory of Ukraine and by restricted or unavailable access to forests located in temporarily occupied territories. Consequently, the results should be interpreted as representing the pre-war baseline condition of *P. nigra* stands rather than their current state. Nevertheless, this temporal limitation also gives the dataset particular value as a reference point for assessing subsequent changes and for planning post-war forest restoration and management. Since 2011, the actual condition, area, and structure of these stands may have been altered by wildfires, military activities, forest damage associated with hostilities, and logging or other disturbances in territories beyond the effective control of Ukrainian forest authorities. These factors should therefore be taken into account when extrapolating the results to the present-day condition of black pine stands. The study included the entire population of forest-covered inventory compartments managed by all categories of forest users, including those located within the temporarily occupied territories of Ukraine. Database queries and data analysis were performed using Microsoft SQL Server. At the first stage, the total population of inventory compartments dominated by the two black pine taxa-Crimean pine and Austrian pine-was identified using the "Count" query mode. Data grouping was performed using the operators *s* to calculate the total area and *g* to group the target variable, including administrative region, forest site conditions, and age grouP. This procedure was used to identify the most widely represented forest site types, the analysis of which encompassed the largest number of observations, i.e. forest inventory compartments. In the same query mode, mean site-quality classes were calculated for individual edatopes using the *v* operator to obtain the area-weighted mean site-quality class and the *g* operator to group records by forest site conditions

(Ukrderzhlisproekt Production Association, 2006). At the second stage, the distribution of stand area by species composition and origin was determined for the most widespread forest site types using the "Count" mode. The data were grouped using the *s* operator to sum stand areas and the *g* operator to classify records by forest site conditions, stand origin, pure or mixed stand status, and associated tree species. Forest site types were classified according to the Alekseev-Pogrebnyak edaphic grid, which differentiates forest site conditions along gradients of soil fertility (trophic status) and moisture regime (Krasnov *et al.*, 2009). Area-weighted mean mensurational characteristics were also calculated for the subsequent analysis of their age-related dynamics. The *v* operator was used to calculate the mean diameter, mean height, growing stock per hectare, and proportion of merchantable trees, whereas the *g* operator was used to group the data by forest site conditions and age class. Relationships between stand age and the principal mensurational characteristics of Crimean pine stands – mean diameter, mean height, and growing stock per hectare – within the most widely represented forest site types were assessed using regression analysis. Model coefficients were estimated by the least-squares method. Goodness of fit was evaluated using the coefficient of determination, R^2, which indicates the proportion of variation in the mean mensurational characteristics explained by changes in age class. Statistical processing and graphical presentation of the results were performed in Microsoft Excel 2024.

RESULTS AND DISCUSSION

The total area of Crimean pine and Austrian pine stands in Ukraine is 134.1 thousand ha; however, the proportion of the two studied taxa is highly uneven. Crimean pine accounts for 99.8% of the total area, whereas Austrian pine represents only 0.2%. This marked disparity indicates that black pine stands in Ukraine are represented predominantly by Crimean pine, while the data on Austrian pine describe only local centres of its introduction. The regional distribution of the stands is also distinctly asymmetric (Table 1). Kherson Oblast and the Autonomous Republic of Crimea account for 56.4% of the total area of Crimean pine stands, while their combined share with Mykolaiv and Odesa oblasts reaches 73.7%.

Table 1. *Regional distribution of black pine stand area by taxon*

Oblast / Region	Austrian pine, ha	Crimean pine, ha	Total, ha
Autonomous Republic of Crimea	16.4	36,916.5	36,932.9
Vinnytsia Oblast	–	3,578.5	3,578.5
Volyn Oblast	–	44.0	44.0
Dnipropetrovsk Oblast	–	1,562.8	1,562.8
Donetsk Oblast	–	6,324.7	6,324.7
Zhytomyr Oblast	1.3	7.5	8.8
Zakarpattia Oblast	8.2	0.7	8.9
Zaporizhzhia Oblast	–	5,681.8	5,681.8
Ivano-Frankivsk Oblast	24.3	6.2	30.5
Kyiv Oblast	–	143.0	143.0
Kirovohrad Oblast	23.9	976.0	999.9
Luhansk Oblast	–	7,701.0	7,701.0
Lviv Oblast	74.2	1.2	75.4
City of Kyiv	–	0.6	0.6
City of Sevastopol	–	6,961.8	6,961.8
Mykolaiv Oblast	–	13,922.7	13,922.7
Odesa Oblast	–	9,184.0	9,184.0
Poltava Oblast	–	206.3	206.3
Rivne Oblast	1.0	1.1	2.1
Sumy Oblast	3.0	28.6	31.6
Ternopil Oblast	98.5	25.6	124.1
Kharkiv Oblast	2.6	551.5	554.1
Kherson Oblast	–	38,528.2	38,528.2
Khmelnytskyi Oblast	4.5	977.4	981.9
Cherkasy Oblast	–	150.7	150.7
Chernivtsi Oblast	27.9	273.5	301.4
Chernihiv Oblast	2.1	17.2	19.3
Total for Ukraine	287.9	133,773.1	134,061.0

Source: *developed by the authors*

The concentration of most Crimean pine stands in southern Ukraine reflects the long-standing use of this taxon for the afforestation of sandy areas, dry slopes, eroded soils, and low-productivity lands. This is consistent

with the conclusions of S.Ayan *et al.* (2021), who identified *P. nigra* subsp. *pallasiana* as one of the principal tree taxa used for afforestation in semi-arid steppe regions and on anthropogenically transformed lands in Türkiye. At the same time, the authors emphasised that the success of such plantations depends on matching the provenance of planting material to local environmental conditions.

Austrian pine exhibits a different spatial pattern, with its largest stand areas occurring in Ternopil, Lviv, Chernivtsi, and Ivano-Frankivsk oblasts. The concentration of this taxon in western Ukraine is associated with the history of its introduction and the establishment of forest plantations during the periods when the region formed part of Austria-Hungary and Poland. A similar pattern was identified by T.V. Yuskevych *et al.* (2011), who summarised data on the distribution of black pine and Crimean pine in the forests of western Ukraine. The researchers also noted that the actual area of black pine stands may have been underestimated because some stands were incorrectly classified as Scots pine in forest inventory records.

The distribution of stand area by forest site conditions confirms the pronounced ecological differentiation of the studied taxa (Table 2). In Crimean pine stands, 84.8% of the total area occurs under very dry and dry forest site conditions. The largest areas are concentrated in dry fairly fertile site types (C_1) and dry poor site types (A_1), which together account for more than two-thirds of the total area occupied by this taxon. This distribution characterises Crimean pine as a taxon that has been widely used under conditions of moisture deficiency and low to moderate soil fertility.

***Table 2**. Distribution of black pine stand area by forest site conditions*

Forest-site types	Austrian pine, ha	Crimean pine, ha
A_0	-	2,340.9
A_1	18.0	30,959.3
A_2	9.6	6952.6
A_3	-	59.9
B_0	-	3,058.4
B_1	2.4	10,450.1
B_2	12.8	3,780.2
B_3	2.7	88.0
C_0	-	4,532.8
C_1	26.7	57,793.2
C_2	100.8	7,473.4
C_3	24.9	132,6
D_0	-	254,2
D_1	26.0	4,003.3
D_2	63.6	1,867.9
D_3	0.4	26.3
Total	287.9	133,773.1

Note: *A_0 – very dry, poor; A_1 – dry, poor; A_2 – fresh, poor; A_3 – moist, poor; A_4 – wet, poor; A_5 – very wet, poor; B_0 – very dry, fairly poor; B_1 – dry, fairly poor; B_2 – fresh, fairly poor; B_3 – moist, fairly poor; B_4 – wet, fairly poor; B_5 – very wet, fairly poor; C_0 – very dry, fairly rich; C_1 – dry, fairly rich; C_2 – fresh, fairly rich; C_3 – moist, fairly rich; C_4 – wet, fairly rich; C_5 – very wet, fairly rich; D_0 – very dry, rich; D_1 – dry, rich; D_2 – fresh, rich; D_3 – moist, rich*
Source: *developed by the authors*

The forest-site spectrum of Austrian pine is shifted towards fresh and moist conditions, which account for 74.6% of its total stand area. Its stands are most widely represented in fresh fairly fertile site types and fresh fertile site types. Thus, the differences between the two taxa concern not only the extent of their distribution but also their predominant ecological niches: Crimean pine is associated mainly with drier sites, whereas Austrian pine occurs more frequently on better-moistened and more fertile sites. However, a large stand area within a particular forest site type is not a direct indicator of its optimality for species growth. The predominance of Crimean pine in C_1 and A_1 largely reflects the scale of artificial afforestation undertaken on dry lands. A study by S. Gülsoy & T. Çinar (2019) in Anatolian black pine stands showed that site quality is determined by the combined effects of elevation, slope position, aspect, soil characteristics, and water availability. As summer drought intensified, productivity declined even within the natural range of the subspecies *pallasiana*.

The physiological capacity of Crimean pine to respond to different levels of moisture availability was confirmed by V. Bessonova & S. Yakovlieva-Nosar (2022). In erosion-control plantations in Dnipropetrovsk Oblast, the authors identified seasonal changes in the concentrations of soluble sugars and starch in needles depending on forest site conditions. These

responses characterise mechanisms of adaptation to water deficit but do not imply uniformly high productivity throughout the entire xerophytic range of the species. The obtained results provide grounds for distinguishing between the ecological resilience and productive efficiency of the species. The ability of Crimean pine to form stands under very dry and dry conditions determines its protective and phytomeliorative importance. Nevertheless, its growth potential can be most fully realised on sites offering a more favourable combination of moisture availability and soil fertility.

The age structure of the stands reflects differences in the history of their establishment and subsequent management (Fig. 1). In Crimean pine, most of the stand area is occupied by second-age-class young stands and middle-aged stands (Fig. 1a). This structure resulted from the large-scale artificial afforestation of the southern and eastern regions of Ukraine during the second half of the twentieth century. The relatively small proportion of mature and overmature stands indicates the limited representation of older age cohorts in the present-day forest estate.

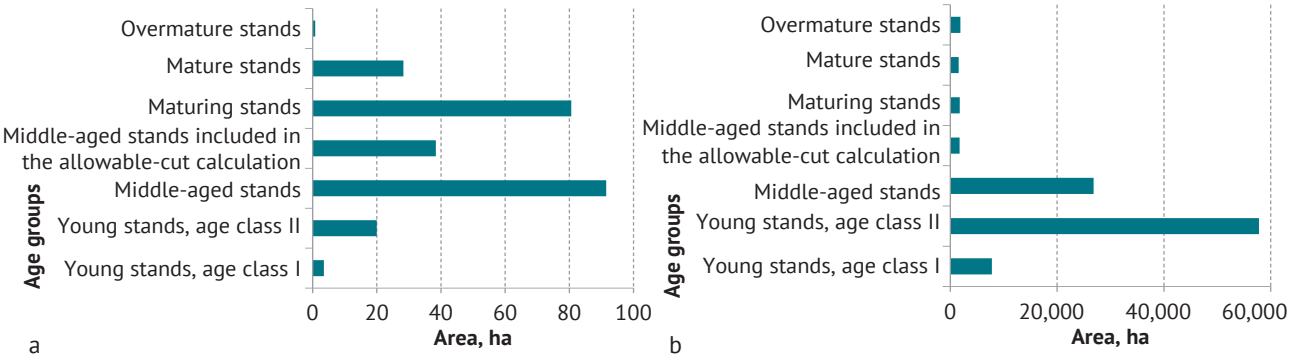

***Figure 1**. TAge structure of black pine stands by taxon*
***Note:** a – Austrian pine; b – Crimean pine*
***Source:** developed by the authors*

Austrian pine stands are dominated by middle-aged and maturing age groups (Fig. 1b). This pattern corresponds to the localised nature of the taxon's introduction and the survival of plantations established during different historical periods. Differences in age structure should be taken into account when comparing mean height, mean diameter, growing stock, and timber merchantability, since a higher mean value for one taxon may result not only from its biological characteristics but also from the greater representation of a particular age grouP. The analysis of stand origin in the four principal dry forest site types revealed the predominance of artificially established stands (Table 3).

***Table 3**. Distribution of black pine stand area by taxon and origin in dry edatopes*

Forest site type	Austrian pine, ha		Crimean pine, ha	
	Artificial	Natural	Artificial	Natural
A_1	18.0	–	20,400.2	45.8
B_1	2.4	–	7,458.9	1,027.7
C_1	26.7	–	38,922.0	5,440.3
D_1	23.6	1.1	3,138.8	16.0
Total	70.7	1.1	69,919.9	6,529.8

***Source:** developed by the authors*

Artificially established stands account for 91.5% of the analysed Crimean pine area and 98.5% of the Austrian pine area. Natural Crimean pine stands are most widely represented in B_1 and C_1, where their share exceeds 12%. Under the edaphically contrasting conditions of A_1 and D_1, the proportion of naturally originated stands is minimal. This structure suggests that the natural regeneration of Crimean pine is most successful not under the poorest pine-site conditions, but in dry relatively poor and fairly fertile site types, where moisture deficiency is combined with a more adequate level of soil nutrient availability. In their study of Crimean pine forests, Y.V. Pluhatar *et al.* (2010) also identified substantial differences between natural and artificially established stands in species composition, age structure, relative density, site-quality class, growing stock, and the proportion of merchantable timber. The authors emphasised the need for a differentiated assessment of the realised and potential productivity of stands of different origins.

Pure stands predominate within A_1, B_1, C_1, and D_1, accounting for approximately 74% of the area for both taxa (Table 4). However, the internal structure of this

proportion differs between them. Crimean pine has the highest proportion of pure stands in dry poor site types, whereas the contribution of mixed stands increases with increasing site trophicity. This pattern indicates a broader range of associated tree species under more fertile site conditions.

***Table 4**. Distribution of black pine stand area by taxon and species composition in dry edatopes*

Forest site type	Austrian pine, ha		Crimean pine, ha	
	Pure	Mixed	Pure	Mixed
A_1	5.5	12.5	17,525.4	2,742.9
B_1	–	2.4	6,035.3	2,451.0
C_1	26.2	0.5	30,571.2	13,560.6
D_1	21.6	3.1	2,299.7	854.7
Total	53.3	18.5	56,431.6	19,609.2

***Source:** developed by the authors*

For Austrian pine, the ratio between pure and mixed stands varies considerably among forest site types. In A_1 and B_1, the taxon occurs predominantly as a component of mixed stands, whereas pure plantations prevail in C_1 and D_1. However, the limited total area occupied by Austrian pine restricts the extent to which this pattern can be generalised across all regions of Ukraine. The predominance of even-aged, artificially established, and pure stands distinguishes most Ukrainian plantations from natural old-growth black pine forests. T.A. Nagel & M. Cerioni (2023) found that natural black pine stands in South-Eastern Europe generally exhibit uneven-aged structures and include broadleaved and shade-tolerant associated species. The contribution of such species increases on more productive sites, whereas black pine maintains long-term dominance primarily on steep, rocky slopes. The prevalence of pure plantations has practical implications for their long-term stability. G.-M. Tudoran *et al*. (2023), studying black pine outside its natural range in the Romanian Carpathians, documented a deterioration in the condition of dense monodominant stands caused by defoliation, insufficient spring–summer precipitation, and competition for soil moisture. The authors considered the development of stable mixed stands involving locally adapted tree species more promising than the maintenance of extensive monocultures.

The composition of associated tree species changes consistently with increasing trophicity of forest site conditions (Table 5). In dry poor pine-site types, Scots pine predominates among the associated species in Crimean pine stands, while Dnieper birch also makes a substantial contribution. These species are adapted to the ecological constraints of sandy soils and limited moisture availability. The contribution of other associated species in A_1 is comparatively low. In dry relatively poor site types, species diversity increases through the inclusion of sessile oak, downy oak, and Stankewicz's pine. In dry fairly fertile site types, the principal associated species are downy oak and sessile oak, with black locust, Scots pine, and wild cherry also present. This composition reflects the greater nutrient availability of the soils and the potential for the formation of stands with more complex species structures. In dry fertile site types, the areas occupied by individual associated species are smaller, although their species composition is the most diverse. Alongside Scots pine and black locust, pedunculate oak, field elm, and Norway maple also occur. The increasing contribution of broadleaved species under more fertile conditions is consistent with the natural successional trajectory of these sites.

***Table 5**. Distribution of mixed Crimean pine stand area in dry edatopes by subdominant tree specie*

Forest site type	Subdominant tree species	Area, ha
A_1	Black locust (*Robinia pseudoacacia* L.)	698.2
	Dnieper birch (*Betula borysthenica* Klokov)	1,989.2
	Silver birch (*Betula pendula* Roth)	89.1
	Scots pine (*Pinus sylvestris* L.)	5,919.8
	Black poplar (*Populus nigra* L.)	815.0
B_1	Black locust (*Robinia pseudoacacia* L.)	584.8
	Downy oak (*Quercus pubescens* Willd.)	311.9
	Sessile oak (*Quercus petraea* (Matt.) Liebl.)	877.4
	Scots pine (*Pinus sylvestris* L.)	2,182.5
	Stankewicz's pine (*Pinus stankewiczii* (Sukaczev) Fomin)	279.1
C_1	Black locust (*Robinia pseudoacacia* L.)	1,918.6
	Downy oak (*Quercus pubescens* Willd.)	5,248.5
	Sessile oak (*Quercus petraea* (Matt.) Liebl.)	5,111.2

Table 5. Continued

Forest site type	Subdominant tree species	Area, ha
C_1	Scots pine (*Pinus sylvestris* L.)	1,626.6
	Wild cherry (*Prunus avium* (L.) L.)	1,080.9
D_1	Black locust (*Robinia pseudoacacia* L.)	192.7
	Field elm (*Ulmus minor* Mill.)	132.3
	Pedunculate oak (*Quercus robur* L.)	201.9
	Norway maple (*Acer platanoides* L.)	164.6
	Scots pine (*Pinus sylvestris* L.)	158.5

Source: *developed by the authors*

In Austrian pine stands within A_1 and B_1 forest site types, Scots pine is the predominant associated tree species (Table 6). In C_1 and D_1, the species spectrum expands to include Norway maple, European ash, honey locust, northern white cedar, and American sycamore. However, owing to the limited area occupied by Austrian pine, these species combinations are predominantly local and partly reflect the specific characteristics of individual forest plantation sites. The observed increase in the contribution of broadleaved species under more fertile site conditions is consistent with the findings of T.A. Nagel & M. Cerioni (2023), who documented the development of shade-tolerant and late-successional species beneath the canopy of black pine on productive sites. The principal difference is that the natural old-growth forests examined by these authors had a more complex uneven-aged structure, whereas artificially established even-aged stands predominate in Ukraine. A common pattern is the increasing role of broadleaved species with rising site productivity. From a silvicultural perspective, the admixture of oak species, maple, elm, ash, and other locally adapted tree species may promote the development of a more complex vertical stand structure, enhance biological stability, and improve the differentiation of soil resource use. At the same time, the proportion of associated species should be regulated according to the intended function of the stand, because on productive sites they may gradually displace the light-demanding black pine. The distribution of mean site-quality classes confirms that the productivity of both taxa depends on site trophicity and moisture conditions. Austrian pine achieves its highest productivity in fresh fertile, fresh fairly fertile, and moist fairly fertile site types. In dry poor, dry fairly fertile, and certain moist site types, its stands are predominantly assigned to site-quality classes III-IV (Fig. 2).

Table 6*. Distribution of mixed Austrian pine stand area in dry edatopes by subdominant tree species*

Forest site type	Subdominant tree species	Area, ha
A_1	Scots pine (*Pinus sylvestris* L.)	18.0
B_1	Scots pine (*Pinus sylvestris* L.)	2.4
C_1	Black locust (*Robinia pseudoacacia* L.)	2.0
	Norway maple (*Acer platanoides* L.)	1.2
	Scots pine (*Pinus sylvestris* L.)	0.6
	Northern white cedar (*Thuja occidentalis* L.)	3.2
	European ash (*Fraxinus excelsior* L.)	0.1
D_1	Honey locust (*Gleditsia triacanthos* L.)	3.1
	Norway maple (*Acer platanoides* L.)	2.3
	American sycamore (*Platanus occidentalis* L.)	0.1
	Scots pine (*Pinus sylvestris* L.)	5.2
	European ash (*Fraxinus excelsior* L.)	3.5

Source: *developed by the authors*

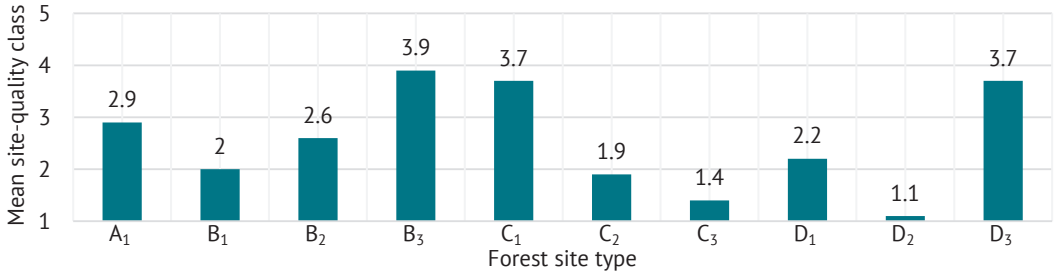

Figure 2*. Mean productivity of Austrian pine stands in relation to forest site conditions*
Source: *cdeveloped by the authors*

Crimean pine occurs across a considerably broader range of forest site conditions; however, its high-site-quality stands are likewise concentrated mainly in fresh and moist fertile site types and in moist fairly fertile site types. Productivity declines in very dry poor, relatively poor, fairly fertile, and fertile site types. The area-dominant C_1 site type does not provide the highest mean site quality, confirming the distinction between the extent of species distribution and the optimality of site conditions for realising its growth potential (Fig. 3).

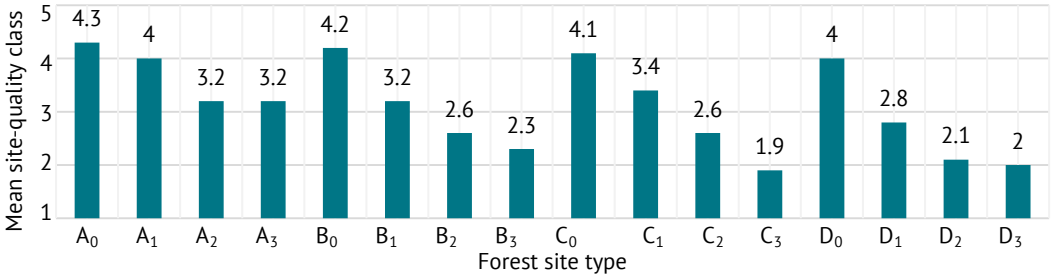

***Figure 3**. Mean productivity of Crimean pine stands in relation to forest site conditions*
***Source:** developed by the authors*

Similar patterns were identified by L.I. Tereshchenko *et al.* (2019) in their survey of Austrian pine stands in Kirovohrad, Kharkiv, and Sumy oblasts. The species was generally inferior to Scots pine in height, but in certain stands it exceeded Scots pine in diameter and was characterised by better stem quality and vitality. The authors confirmed the potential of Austrian pine for protective afforestation on eroded lands, while also recording substantial variability in performance among individual study sites. Thus, the site-quality structure does not confirm the universal superiority of either taxon. Crimean pine is characterised by a broader ecological range and an ability to persist under arid conditions, whereas Austrian pine attains higher productivity mainly in fresh and relatively fertile site types. For forest management planning, this indicates the need to assess the protective effectiveness and timber productivity of the stands separately.

The dynamics of mean growing stock in Crimean pine stands are generally characterised by an increase from young stands to middle-aged, maturing, and mature stands (Fig. 4). At the same time, the rate of growing-stock accumulation varies substantially depending on forest site conditions. In dry poor site types, growing stock remains lower than in dry fairly fertile and fertile site types, particularly in older age classes. This confirms that limited soil nutrient availability in A_1 constrains the realisation of productive potential even over a prolonged growth period.

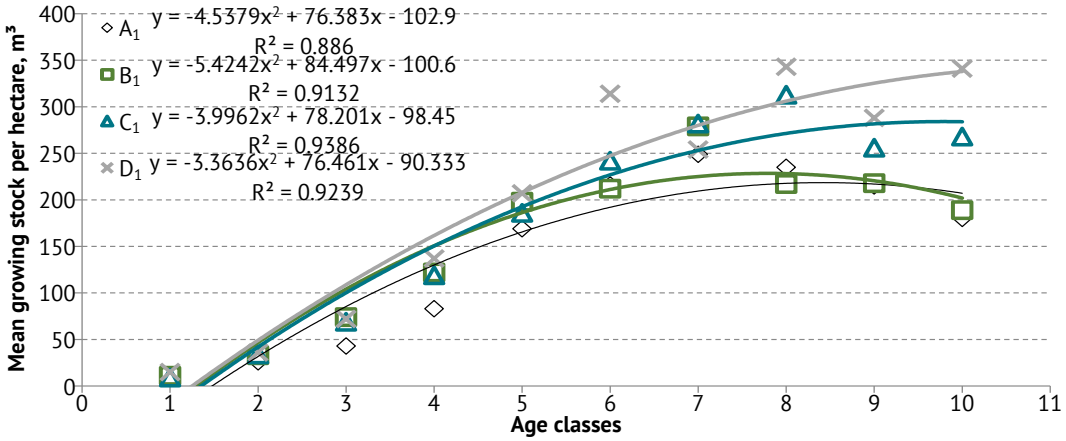

***Figure 4**. Dynamics of mean growing stock in Crimean pine stands under dry edaphic conditions*
***Source:** developed by the authors*

The highest mean growing stocks of Crimean pine were recorded in D_1 and C_1. In the older age classes, individual values exceed 300 $m^3 \cdot ha^{-1}$. Growing stock fluctuates among the older age classes and does not form a completely monotonic sequence. These variations cannot be attributed solely to the biological ageing of the stands. Growing stock is influenced by relative density, species composition, the intensity of thinning and sanitary interventions, natural mortality, management history, and the number of forest inventory

compartments represented within each age grouP. Because the data comprise aggregated indicators from different stands, the resulting series characterises the age gradient of the stand population rather than the continuous developmental trajectory of a single stand.

D. Candel-Pérez *et al.* (2022) found that the growth of *P. nigra* along a latitudinal gradient depends on the combined effects of climate, age, tree diameter, and stand structure. The positive effect of spring precipitation varied according to stand density and tree-size differentiation; therefore, climatic responses cannot be interpreted independently of mensurational structure. A comparison of northern and southern black pine populations conducted by Ş.C. Izmir *et al.* (2024) also revealed spatial heterogeneity in climate-driven growth. Southern populations of *P. nigra* subsP. *pallasiana* exhibited certain indications of greater drought resilience; however, their growth remained dependent on the seasonal distribution of precipitation and the duration of water deficit. The graphical representation of age-related changes in mean height and diameter confirms the patterns identified for growing stock (Fig. 5, 6).

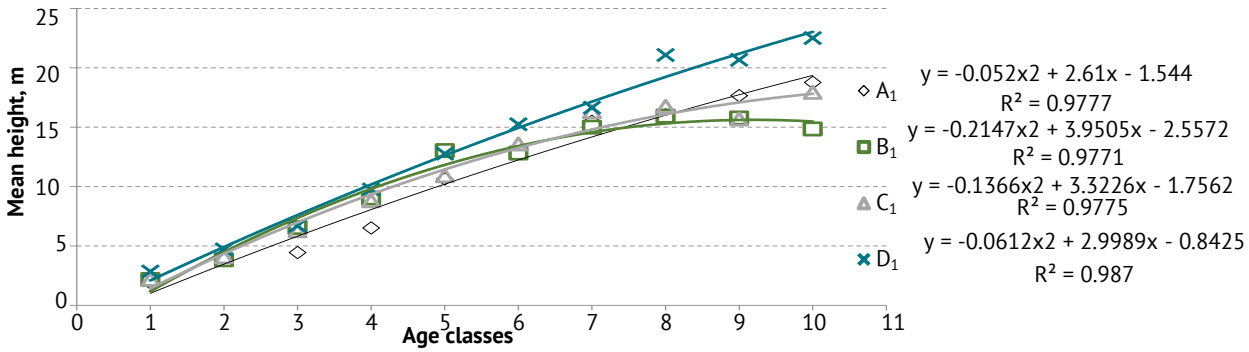

Figure 5. *Dynamics of mean height in Crimean pine stands under dry edaphic conditions*
Source: *developed by the authors*

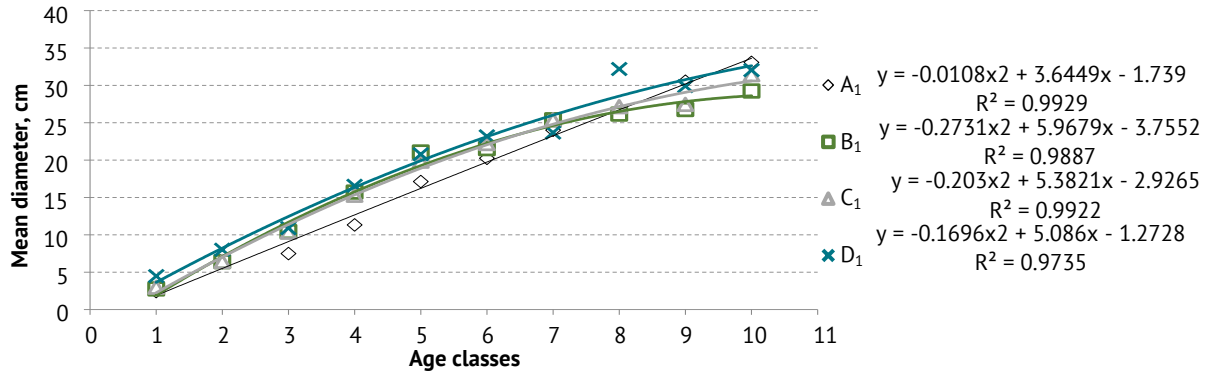

Figure 6. *Dynamics of mean diameter in Crimean pine stands under dry edaphic conditions*
Source: *developed by the authors*

In poor site types, the dynamics of both characteristics proceed more slowly, whereas larger mean tree dimensions are attained in fairly fertile and fertile site types. In the older age groups, height increment gradually slows, while diameter continues to increase, although the mean values exhibit some fluctuations. For Crimean pine, the greatest heights and diameters are characteristic of D_1 and C_1. Under D_1 conditions, mean height reaches 23 m in age class X, while mean diameters in C_1 and D_1 exceed 32 cm. Thus, soil fertility substantially influences the dimensional structure of stands, whereas the drought tolerance of the species primarily ensures stand persistence under harsh conditions but does not eliminate constraints on growth.The proportion of merchantable timber generally increases with age, although the pattern of this change depends to some extent on forest site conditions (Table 7). In young stands, the yield of merchantable timber is low because small-diameter stems predominate. In middle-aged and maturing stands, increasing mean diameter and the natural pruning of lower branches contribute to improved merchantability. For Crimean pine, the most consistent increase in the proportion of merchantable timber is observed in C_1 and D_1. In older age classes, values exceeding 60-70% are attained in these site types. In dry poor and relatively poor site types, the pattern is less stable, which may be associated with greater branchiness, uneven relative density, and an unfavourable soil water regime.

***Table 7**. Dynamics of the mean proportion of merchantable timber under dry edaphic conditions, %*

Age class	Forest site type			
	A_1	B_1	C_1	D_1
1	–	–	–	–
2	27	27	7	9
3	24	24	27	25
4	34	36	37	37
5	44	47	48	43
6	55	52	56	53
7	56	46	69	58
8	62	52	72	63
9	62	53	67	56
10	–	43	71	62

***Source:** developed by the authors*

A. Zeidler *et al.* (2024) investigated the physical and mechanical properties of wood from introduced pine species growing on reclaimed lands in Central Europe. Black pine was characterised by high wood density and potential suitability for producing higher-value products. At the same time, the authors emphasised that wood quality depends on age, site conditions, and climate, and that the species should be introduced as a component of diverse stands rather than extensive pure plantations.

The results of the present study complement this work by characterising the merchantable structure of the growing stock. The proportion of merchantable timber reflects the silvicultural yield of timber assortments, whereas wood density and mechanical strength indicate its technological quality. An integrated assessment of these characteristics is necessary to determine the actual economic value of Crimean pine.

CONCLUSIONS

The two black pine taxa in Ukraine were found to exhibit clearly differentiated spatial and silvicultural structures, reflecting two distinct models of land use rather than two variants of the same productivity pattern. Of the 134.1 thousand ha of Pinus nigra stands, 99.8% were established to be represented by Crimean pine, with 73.7% of its area concentrated in Crimea and Kherson, Mykolaiv, and Odesa oblasts, whereas Austrian pine was shown to occur only locally, mainly in western Ukraine. Crimean pine was found to be strongly associated with xeric sites, with 84.8% of its area occurring under very dry and dry forest site conditions, while Austrian pine was concentrated mainly in fresh and moist, more fertile sites. This divergence was found to be consistent with the age structure of the two taxa – Crimean pine is dominated by second-age-class young and middle-aged stands, whereas Austrian pine is represented mainly by middle-aged and maturing stands – and with their origin and structure: in the principal dry site types, artificially established stands were shown to account for 91.5% of Crimean pine and 98.5% of Austrian pine stands, and pure stands were found to occupy approximately three-quarters of the area of both taxa.

It was established, however, that stand productivity is governed more strongly by site quality than by the extent of taxon distribution. The highest site-quality classes and the greatest mean tree dimensions and growing stocks were found to be associated with fairly fertile and fertile site types, whereas dry poor sites were shown to constrain the realisation of growth potential. For Crimean pine, the most favourable growth patterns were recorded in C_1 and D_1: in older age classes, mean growing stock was found to exceed 300 $m^3 \cdot ha^{-1}$, mean height reached 23 m in D_1, mean diameter exceeded 32 cm in C_1 and D_1, and the proportion of merchantable timber generally reached more than 60-70%. Austrian pine likewise showed its highest productivity on fresh and relatively fertile sites. The same fertility-driven pattern was revealed to underlie the composition of associated tree species, which becomes progressively more diverse with increasing site trophicity: Scots pine was identified as the principal associated species on the poorest dry sites, whereas the contribution of oaks and other broadleaved species was found to increase in fairly fertile and fertile site types – in Crimean pine stands expressed particularly through the increasing importance of sessile and downy oak, followed by maple, elm, and other broadleaved species on richer sites. Austrian pine was shown to exhibit a similar tendency, although its associated-species combinations are more local because of the limited area occupied by this taxon. Taken together, these findings indicate that drought tolerance primarily enables stand persistence under adverse conditions, whereas high timber productivity – and the formation of more compositionally complex mixed stands – requires more favourable soil fertility and moisture availability.

These findings suggest that Crimean and Austrian pine should not be evaluated by a single productivity criterion: their management should account for differences in ecological niche, stand structure, and functional role, with greater emphasis on protective functions under poor xeric conditions and on combining protective and timber-production objectives on more fertile sites. It should be noted that the conclusions regarding

Austrian pine, whose area amounts to only 0.2% of the total, were derived from a substantially smaller dataset and should therefore be interpreted with corresponding caution. Further research should focus on developing regional models of stand growth and productivity, assessing the resistance of pure and mixed stands to drought, fire, pests, and diseases, and refining forest inventory data through field surveys and remote-sensing methods.

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CONFLICT OF INTEREST

None.

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Лісівничо-таксаційна структура насаджень *Pinus nigra* в Україні за даними державного обліку лісів станом на 2011 рік

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Анотація. Метою дослідження було встановити територіальні, лісотипологічні та лісівничо-таксаційні закономірності формування насаджень сосни кримської та сосни австрійської в Україні. Аналіз виконано за повидільною базою даних державного обліку лісів станом на 2011 рік із застосуванням структурованих запитів у системі керування базами даних Microsoft SQL Server, розрахунку середньозважених показників і регресійного аналізу вікової динаміки таксаційних характеристик. Загальна площа досліджуваних насаджень становила 134,1 тисячі гектарів, з яких 99,8 % припадало на P. nigra subsp. pallasiana та 0,2 % – на *P. nigra* subsp. *austriaca*. Основний масив сосни кримської зосереджений у південних і східних регіонах, тоді як насадження сосни австрійської мають локальне поширення переважно у західній частині країни. У дуже сухих і сухих типах лісорослинних умов зосереджено 84,8 % площі сосни кримської, насамперед у сухих сугрудах і сухих борах. Сосна австрійська частіше траплялася у свіжих сугрудах і грудах. У структурі обох таксонів переважали штучні та чисті деревостани; у сухих умовах частка штучних насаджень становила 91,5 % для сосни кримської та 98,5 % для сосни австрійської. Найвищі класи бонітету, середні висоти, діаметри, запаси та частка ділової деревини формувалися переважно у сугрудах і грудах, тоді як у сухих борах лісорослинний потенціал обмежувався дефіцитом вологи та низькою родючістю ґрунтів. Видовий склад супутніх порід ускладнювався зі зростанням трофності місцезростань: у борах домінувала *P. sylvestris*, а в сугрудах і грудах збільшувалася участь твердолистяних порід

Ключові слова: сосна кримська; сосна австрійська; типи лісорослинних умов; стовбуровий запас; продуктивність; ділова деревина; динаміка росту

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Dimensions of perceived value in the Honduran wood industry

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Abstract. Forestry firms in Honduras exhibit significant weaknesses in value creation. This paper aimed to identify how economic, social, and shared value are perceived within Honduras's secondary broadleaf-wood industry, and to propose measures to strengthen value creation in the sector. To this end, the analysis of contingency tables, Pearson's chi-square test, Cramer's V coefficient, and the Mann-Whitney U test (with effect size estimates) were applied to survey data from 17 hardwood processing enterprises in four forest regions of Honduras. The 44 indicators were grouped into three categorical variables (B1, C1, C3) and three quantitative variables (EV, SV, ShV), and reliability and validity were assessed using Cronbach's alpha, HTMT, and Kendall's τb correlations. The effect size was very large (V = 0.78) for the EV–SV pair, where a significant association was found, $\chi^2(4) = 22.00$, $p = 0.0002$. For the SV–ShV pair, the association was also significant ($\chi^2(6) = 13.00$, $p = 0.041$) with an effect size of V = 0.60. This indicated a close relationship between economic, social, and shared value within the study sample. These constraints negatively affect the implementation of marketing practices, quality control, traceability, and market access. Also, the absence of seals of origin reduces competitiveness in both national and international markets. To address these limitations, the authors proposed strengthening the use of local raw materials to improve product quality, expanding marketing knowledge, training personnel, and enhancing quality-control systems. The results obtained can serve as a basis for developing national training programmes aimed at strengthening the entrepreneurial and technical capacity of the forestry sector and for incorporating their content into environmental licensing processes

Keywords: shared value; economic value; social value; environmental value; secondary forest industry; broadleaved wood

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INTRODUCTION

There are approximately 200 timber companies and more than 7,000 carpentry workshops in Honduras (Forest Conservation Institute, 2022), divided in four forest regions that work with 48 tree species, eleven of which account for 94% of the total processed volume. Mahogany (*Swietenia macrophylla King*) is particularly important, representing 47.8% of total exports (Forest Conservation Institute, 2023). Despite the sector's relevance, secondary forestry small and medium-sized enterprises (SMEs) in Honduras have not reached a level of development comparable to that of the primary industry mainly due to strong deforestation that has climatic, social, and economic consequences that must be alleviated (OIMT, 2025). Thus, in 2006, the International Tropical Timber Agreement was signed to combat deforestation and protect broadleaved forests that cover 4,160,619 hectares, equivalent to 72.37% of Honduras's total forest, including mixed forests (Forest Conservation Institute, 2022). A study by S.A. Saravia-Maldonado *et al.* (2024) of the Talguá River watershed in Honduras confirmed that human-induced pressure on forest resources directly leads to a decline in water quality and the degradation of ecosystem services that support local communities. But these measures are not enough, as they are unaware of the timber industry's perceived value. The perceived value in the industry can be fostered by applying educational policies focused on increasing empowerment, legitimacy, and social learning in the labour force.

As R. Reyes *et al.* (2001) noted, the Honduran secondary forestry industry suffers from limited training in administrative and marketing areas, which undermines business performance and contributes to stagnation in the acquisition of technical skills and in the development of export capacity. According to A. Rodríguez-Zunino & R. Kometter (2012), informality remains one of the sector's main challenges, as many SMEs are not registered on official commercial records. This situation results in small-scale production, inadequate machinery, deficiencies in quality control, the absence of specialised training and technical assistance, and reduced managerial capacity among entrepreneurs. Y. Sun *et al.* (2025) showed that the secondary forestry industry's lack of horizontal innovation (product diversification) combined with vertical upgrading (quality enhancement) negatively affects export performance. As a result, M. Shang *et al.* (2025) found that the secondary forestry industry in Honduras needs to enhance technical production and management capabilities, which positively affects wood product quality and competitiveness, in order to impulse sustainable human development (Mendieta, 2010).

Along with the problems of informality and inefficient resource management, T.W. Gillespie *et al.* (2000) reported that tropical timber forests in Central America have been reduced to less than 0.1% of their original extension on the Pacific side, due to excessive logging and economic and administrative impediments that are limiting the development of the forestry sector in Guatemala, Nicaragua and Costa Rica, including the deficient business advisory services for the forest timber sector in Central America. Applied to the Honduran forest, the concept of value in the business environment can be understood from a triple perspective: a) economic value, when financial benefit is generated (Riva & García, 2018); b) social value, if there is a positive impact on society (Menghwar & Daood, 2021) and c) environmental value, when industrial activity improves the environment (Hernández-Perlines & Ibarra Cisneros, 2018). Thus, according to N. Díaz & C.A. Castaño (2013), shared value is formed by the interaction of the economic, social and environmental values, and defines products, markets and productivity in the value chain. As a result, H. Niccolas Morales *et al.* (2013) argued that shared value develops local clusters that benefit society, as it lays the groundwork for a wood-based bioeconomy (Hug *et al.*, 2024).

As E. Fernández (2012) noted, value creation is closely related to business ethics and, above all, to corporate social responsibility, which C. D'Souza *et al.* (2024) described as emphasising ethics as a central aspect that shapes the social impact of commercial activity, where cross-laminated timber, the most widely used mass timber product, has been increasingly used as an alternative to traditional building materials due to its lower environmental impact (Bremner *et al.*, 2026). G.J. Ceballos & D.M. Chaparro (2023) described ethical leadership as an engine that promotes circular economy practices within shared value, thus creating a sustainable business environment in which wood is adopted as an alternative to carbon-intensive materials in the construction industry, with the support of public administration (Saravia-Maldonado *et al.*, 2024; Lobensteiner & Losacker, 2026). L. Blümel *et al.* (2023) also emphasised that a successful transition of supply chains to a circular bioeconomy requires consideration not only of economic, social, and environmental factors, but also of infrastructure barriers, which are often overlooked by traditional models of strategic analysis.

P.C.M. Neessen *et al.* (2021) showed that the creation of social value leads companies to incorporate social externalities into their business model in order to maximise their profitability and have a social impact. Thus, according to B. Mei *et al.* (2024), in the forestry industry it is essential to enhance profitability and social impact in order to improve environmental conditions and corporate image, which in turn affects financial results. A. Crane *et al.* (2014) noted that this impact is maximised when all stakeholders (internal and external) of the organisation are satisfied, especially customers, mainly if forests are sustainably managed, as wood modifications are non-fossil and

non-toxic, so circular strategies are incorporated by increasing wood reuse (Van den Auwelant *et al.*, 2025; Hosseini *et al.*, 2025). In short, the social value generated by the forestry industry is combined with environmental value necessary to preserve the ecosystem, which in turn influences socio-economic aspects related to quality of life and the creation of wealth that is sustainable over time.

The goal of this research was to analyse the secondary forestry industry that uses broadleaved wood in Honduras to propose strategies to create value in the industry. Perceived value in private SMEs has evolved from a profit-focused perspective to the creation of multidimensional models that integrate social and environmental dimensions.

MATERIALS AND METHODS

Data were collected through interviews with 17 secondary broadleaved-wood industries located across the four forest regions of Honduras (Table 1). All ethical requirements were followed during the survey (Goodyear *et al.*, 2007). For confidentiality reasons linked to environmental impact (4 indicators), job security (3 indicators) and reputation (3 indicators) where no information could not be obtained, the original set of 54 indicators was reduced to 44.

***Table 1**. Forest regions and the number of secondary broadleaf wood industries in Honduras*

Forest Region	Number of secondary industries	Geographical location	Population
Comayagua	1	La Libertad, Comayagua	28,906
North-West	7	San Pedro Sula, Choloma	1,040,063
Atlantis	8	La Ceiba, Esparta, San Francisco	250,310
Aguan Valley	1	Olanchito	31,843
Total	**17**		**1,351,122**

***Source:** compiled by the authors based on the Forest Conservation Institute (2023), and the National Institute of Statistics of Honduras (n.d.)*

These indicators were grouped according to their contribution to value creation and the measurement approach used, resulting in three categorical variables (B1, C1, C3), each with differentiated levels or conditions (Table 2), and three quantitative variables: Economic Value (EV), Social Value (SV), and Shared Value (ShV), all measured using discrete low-variability ordinal scales (Table 3). Environmental value showed no variability in the dataset and was therefore excluded from inferential analysis. Since all cases reported the same value, it was not possible to apply statistical tests or estimate associations with other dimensions. Therefore, the environmental dimension reflects only a homogeneous perception within the set of companies studied and does not allow for comparative or explanatory inferences. The environmental results described only a uniform pattern of response, with no inferential support. Given that the normality tests (Shapiro-Wilk) indicated $p < 0.05$ in all variables and that EV, SV and ShV present ordinal scales with repeated values, non-parametric methods suitable for small samples and discrete data were chosen. Thus, the Mann-Whitney U test was used to compare independent groups, Kendall's τ-b for ties in correlations, χ^2 for contingency analysis, and Cramer's V to evaluate associations and effect sizes. The study, of an exploratory-descriptive nature and based on the complete universe of secondary broadleaf wood industries in Honduras ($N = 17$), does not pursue broad population inferences, but rather to characterise the sector and support the formulation of strategies. The selected methods are robust in contexts of low sampling power and were complemented with VS MPR to strengthen interpretation. Finally, it is explicitly recognised that the results are associative and exploratory, and that the sample size limits generalisation without compromising the relevance of the analyses applied.

***Table 2**. Operational definitions of the categorical variables B1, C1, and C3*

Variable	Definition	Level	Description of the level
B1 – Business formalisation	Classifies SMEs according to their degree of administrative and legal formalisation.	**B1 = 01**	Low formalisation: SMEs not registered in official commercial records, lacking updated forest permits, or operating with informal accounting practices.
		B1 = 02	High formalisation: SMEs legally registered, with valid forest permits, structured accounting, and compliance with administrative regulations.
C1 – Technical and productive capacity	Differentiates SMEs based on their level of equipment, process standardisation, and technical skills.	**C1 = 01**	Basic capacity: limited machinery, predominantly manual processes, low standardisation, and minimal technical training.
		C1 = 02	Advanced capacity: semiautomated or automated machinery, standardised processes, quality control, and trained personnel.

Table 2. Continued

Variable	Definition	Level	Description of the level
C3 – Market orientation	Classifies SMEs according to their primary market focus and commercial diversification.	**C3 = 01**	Local market: SMEs selling mainly to local or regional markets with low commercial diversification.
		C3 = 02	External or diversified market: SMEs exporting or selling to large national buyers, distributors, or exportoriented channels.

Source: *compiled by the authors*

Table 3*. Operational definitions of the quantitative variables EV, SV, and ShV*

Variable	Definition	Scale type	Description of measurement
EV	Measures the extent to which SMEs generate or prioritise economic outcomes derived from their activities.	Discrete quantitative scale	Scores reflect the degree of economic performance, efficiency, and financial contribution associated with the firm's operations. Higher scores indicate stronger economic value creation.
SV	Assesses the importance assigned by SMEs to social outcomes, including community wellbeing, labour conditions, and social cohesion.	Discrete quantitative scale	Scores represent the level of commitment to socially oriented practices. Higher scores indicate greater prioritisation of social benefits and collective wellbeing.
ShV	Captures the degree to which SMEs integrate economic and social objectives simultaneously, aligning business performance with community benefits.	Discrete quantitative scale	Scores reflect the firm's capacity to generate mutual benefits for business and society. Higher scores indicate stronger alignment between economic gains and social impact.

Source: *compiled by the authors*

The EV, SV, ShV, and ENV dimensions were constructed from 44 indicators grouped by their contribution to economic, social, shared, and environmental value. Each indicator was scored on a discrete ordinal scale (min 1, max 3), and the final score for each dimension was the sum of its associated indicators. As a result, EV ranged from 8 to 12, SV from 27 to 32, and ShV from 8 to 11. The ENV dimension showed no variability, as all firms reported the same level of environmental compliance, which reflects the homogeneity of regulatory requirements in the Honduran forestry sector. For this reason, ENV was excluded from inferential analysis. The use of ordinal summed scales is consistent with exploratory research in small industrial populations and supports the application of non-parametric statistical methods.

To evaluate the association between the categorical variables, a contingency table analysis was performed, complemented by Pearson's chi-square test and Cramer's V as a measure of effect size. Before selecting the statistical tests, the normality assumption was evaluated using the Shapiro-Wilk test due to the small sample size. In all cases, the results showed p-values 0.05, indicating that normality of the data distribution could not be assumed. The presence of repeated values confirmed the discrete and non-normal nature of the dependent variables. Due to the lack of normality and the small sample size, the Mann-Whitney U test was used as a nonparametric test, as it is suitable for comparing differences in quantitative variables between two independent groups. Among the available categorical variables, C1 was selected as the grouping factor because it showed a more balanced distribution across its levels (01 and 02), thereby improving the stability of the analysis compared to other variables with very unequal group sizes. For each dependent variable (EV, SV, ShV), the distributions between the two levels of C1 were compared.

Given the ordinal nature of the variables and the small sample size (N = 17), reliability and validity were assessed using methods appropriate for discrete data. Internal consistency was evaluated using Cronbach's α. Although the final dataset included 44 indicators, each construct (EV, SV, ShV) was measured using multiple items, which allowed the computation of Cronbach's α and HTMT ratios. Discriminant validity was assessed using the Heterotrait-Monotrait ratio (HTMT), computed from the correlation matrix. Associations between the three quantitative variables were evaluated using Kendall's τ-b, which is appropriate for ordinal data with ties. Group comparisons across levels of C1 (Technical and Productive Capacity) were conducted using the Mann-Whitney U test. Effect sizes were estimated using rank-biserial correlation and the Vovk-Sellke Maximum p-Ratio (VS-MPR). Because ShV showed zero variance in Group 1, the Mann-Whitney test could not be computed for this variable. All analyses were conducted using the statistical software JASP version 0.96.0, and Jamovi 2.7.24.0.

RESULTS AND DISCUSSION

Table 4 presented descriptive statistics by group for the SV, EV, and ShV variables, comparing levels of the C1 factor. A consistent pattern is observed across all three variables: Group 2 showed higher mean values and wider ranges than Group 1, indicating systematic differences between the two levels.

***Table 4**. Group descriptives*

	Group	N	Mean	SD	SE	CV	Mean rank	Sum rank
SV	1	8	28.000	1.069	.378	.038	6.250	50
	2	9	29.667	1.323	.441	.045	11.444	103
EV	1	8	9.500	1.604	.567	.169	5.250	42
	2	9	11.667	.500	.167	.043	12.333	111
ShV	1	8	8.000	.000	.000	.000	6.000	48
	2	9	9.222	1.093	.364	.119	11.667	105

***Note:** SD – Standard Deviation, SE – Standard Error, CV – Coefficient of Variation*
***Source:** compiled by the authors*

Regarding SV, Group 1 obtained a mean of 28.00, while Group 2 had a higher mean of 29.667. Average ranks were also higher in Group 2 than in Group 1, suggesting that Group 2 participants consistently scored higher on SV. In terms of EV, Group 1 had a mean of 9.500, compared with a significantly higher mean in Group 2, which was 11.667. The mid-ranges clearly reflect this difference (5.250 in Group 1 vs 12.333 in Group 2), indicating that Group 2 consistently ranks highest in EV. Finally, in ShV, Group 1 obtained an average of 8.000, while Group 2 reached an average of 9.222. The average range was also higher in Group 2 than in Group 1, indicating a clear trend towards higher shared values in the second group. In addition to the analysis of descriptive variables, a contingency table analysis (Table 5) was performed to evaluate the association between the categorised variables Environmental Value (ENV), EV, SV, and ShV. For each pair of variables, Pearson's chi-square test was applied, complemented by Cramer's V statistic as a measure of effect size.

***Table 5** Contingency tables and results for each pair of dimensions*

Pair of dimensions	Contingence table	Pearson's χ^2	df	p	Cramer's V
ENV × EV	07: (08 = 4, 11 = 8, 12 = 6)	0	0	1.000	-
ENV × SV	07: (27 = 4, 29 = 12, 32 = 2)	0	0	1.000	-
EV × SV	08:(27 = 4); 11:(29 = 8); 12:(29 = 4, 32 = 2)	22.00	4	.0002	.78
SV × ShV	27:(08 = 4); 29:(08 = 8, 09 = 2, 10 = 2); 32:(10 = =1, 11 = 1)	13.00	6	.041	.60

***Note:** the ENV variable did not present variability, so it was not possible to evaluate inferential associations*
***Source:** compiled by the authors*

The analysis of each variable pair showed no evidence of association between ENV and either EV or SV. For both pairs (ENV-EV and ENV-SV), the chi-square statistic was $\chi^2(0) = 0$ with $p = 1.000$, indicating identical distributions across categories and complete independence between the variables. Because the contingency tables had no degrees of freedom, Cramer's V could not be computed. These results indicate that ENV, EV, and SV operate as independent dimensions within the response pattern. The absence of variability in ENV and the parallel distributions observed suggest that respondents conceptualise ENV, EV and SV as separate constructs, with no perceptual overlap or mutual reinforcement. This structural independence has practical implications. It suggests that decisions or attitudes related to environmental sustainability, economic performance, and social cohesion are compartmentalised rather than integrated. Consequently, interventions or policies aiming to promote sustainable development cannot assume that strengthening one dimension will automatically influence the others.

In the EV and SV pair, a significant association was observed, $\chi^2(4) = 22.00$, $p = .0002$. The effect size was very large ($V = .78$), indicating a strong relationship between the two variables. Finally, in the SV and ShV pair, the relationship was also significant, $\chi^2(6) = 13.00$, $p = .041$. The effect size was large ($V = .60$), suggesting a substantial association between the variables: when SV increases, so does ShV. This result is consistent with models that position SV as an antecedent of collective value. The environmental dimension, as it lacks variability, is outside the model. This may be due to a homogeneous perception of environmental performance or to limitations of the measuring instrument. Internal consistency, as measured by Cronbach's alpha, was $\alpha = .862$, indicating high reliability (Table 6). Distinction validity was confirmed by HTMT coefficients ranging from .591 to .798 – all values below the threshold of .85 (Table 7).

Table 6. *Reliability and convergence validity*

Construct	Cronbach's α	AVE	Interpretation
EV–SV–ShV (3item scale)	**.862**	1.00	High internal consistency

Source: *compiled by authors*

Table 7. *Discriminant validity (HTMT ratios)*

Pair	HTMT	Interpretation
EV – SV	.798	Acceptable (< .85)
EV – ShV	.591	Acceptable
SV – ShV	.704	Acceptable

Source: *compiled by authors*

The Shapiro-Wilk test confirmed that the EV distribution deviated from the normal distribution ($W = .868$, $p = .020$), and the Brown-Forsythe test revealed heterogeneity of variances across groups ($F(1, 15) = 43.24$, $p < .001$), confirming the appropriateness of using the Mann-Whitney U test (Table 8). For the ShV variable, this test could not be applied due to zero variance in Group 1 (all values are identical), which makes it impossible to rank the data. The Mann-Whitney test showed significant differences in EV between C1 levels ($U = 6.000$, $p = .002$). The effect size, estimated by biserial correlation of ranges, was very large ($r = .833$), indicating that the C1 = 02 group had significantly higher scores than the C1 = 01 group. The VS-MPR index showed that the evidence in favour of the alternative hypothesis is more than 25 times greater than that in favour of the null hypothesis. The results suggest that the C1 factor ("Technical and productive capacity") has a substantive impact on how people prioritise economic value obtained in the forestry industry in Honduras.

Table 8. *Mann-Whitney U test*

	U	p	VS-MPR	Rank-biserial correlation	SE rank-biserial correlation
SV	14.000	.015	5.977	.611	.281
EV	6.000	.002	25.189	.833	.281

Note: *VS-MPR – Vovk-Sellke Maximum p-Ratio*
Source: *compiled by authors*

Regarding SV, the Mann-Whitney U test indicated significant differences in SV scores between the two levels of factor C1 ($U = 14.000$, $p = .015$). The effect size, estimated by biserial correlation of ranges, was large ($r = .611$), suggesting that the C1 = 02 group had consistently higher SV scores than the C1 = 01 group. The VS-MPR index showed that the evidence in favour of the alternative hypothesis is approximately 6 times greater than that in favour of the null hypothesis. The results suggest that the C1 factor ("Technical and productive capacity") has a substantive impact on how people prioritise EV and SV, implying that groups defined by this factor do not respond similarly to initiatives aimed at collective well-being. In practical terms, this means that any intervention, programme, or policy that seeks strengthening socially and economically oriented attitudes or behaviours should differentiate its strategies according to the level of C1, since both groups start from different sensitivities. The associations between value dimensions were calculated using Kendall's τb correlations (Table 9) that revealed strong and statistically significant associations between EV and SV and between EV and ShV. The association between SV and ShV was moderate but significant ($\tau b = .583$, $p = .011$) (Table 8). These results indicate that the three dimensions form a coherent value system in which increases in one dimension tend to be accompanied by increases in the others.

Table 9. *Kendall's τb correlation matrix*

		EV	SV	ShV
EV	τb	—		
	p-value	—		
SV	τb	.791	—	
	p-value	<.001	—	
ShV	τb	.776	.583	—
	p-value	<.001	.011	—

Source: *compiled by authors*

In short, any public or private-public policy applied to the forestry industry in Honduras must focus on strengthening socially and economically oriented environmental attitudes towards forests, and it should differentiate its strategies by the level of technical and productive capacity achieved. It is therefore necessary to launch environmental awareness campaigns by Honduran public administrations at their different levels (local, regional, and national) to preserve a natural wealth, much of which is currently at risk of ecological damage. K. Rusanen *et al*. (2024) observed that sustainable value creation in the forest sector has been studied from multiple approaches, but with a clear predominance of the economic dimension, while environmental and social values remain underdeveloped; they further noted that the literature addresses the issue mainly at the conceptual level, highlighting circularity, but with little empirical evidence, and that the most widely used theoretical frameworks fail to fully capture the needs of a sustainable transition. This imbalance mirrors the pattern observed in the present study: among the three value dimensions examined, EV and SV emerged as statistically robust and strongly associated, whereas ENV showed no variability and could not be examined inferentially, reinforcing the broader concern that environmental value remains comparatively underexplored in empirical forest-value research.

To enrich the analysis, I. Grundel *et al*. (2022) argued that the Landscape Resource Analysis enables the identification of tangible and intangible values in forest areas through collaborative processes that facilitate dialogue among actors with potentially conflicting interests. As a result, social learning is promoted, and local perspectives, normally absent from traditional forest planning, are made visible. M. Arena *et al*. (2024) described how innovation ecosystems generate ShV through a model that integrates inputs, internal processes, and outputs: inputs include actors, structure, relationships, and governance, which shape the ecosystem's diversity and potential; internal processes encompass strategies and formal and informal mechanisms with varying levels of openness. The same authors revealed key relationships between these elements and highlight how heterogeneity and governance influence the speed, intensity, and resilience of the value created. This four-sphere structure broadly parallels the tripartite EV–SV–ShV model used in the present study, although M. Arena's *et al*. (2024) explicit "innovative" output dimension has no direct counterpart in the indicators applied here – a gap that future instruments could address. Linked to values, C. D'Souza *et al*. (2024) described Corporate Social Responsibility as an ethical commitment grounded in values and a business strategy that can drive innovation and sustainable value, especially regarding environmental issues. Alongside the fight against environmental deterioration, M. Usman *et al*. (2026) showed that technological and productive capacities affect the economic performance of companies through green innovation, while J.I. Dorrego-Viera *et al*. (2026) linked similar capacities to the forest-based bioeconomy.

The results provided descriptive and associative evidence regarding the relationships among these value dimensions and the differences observed between groups. Given the small sample size and the ordinal nature of the data, these results should be interpreted as indicative of systematic differences in the observed indicators rather than as evidence of causal effects. These positive associations among EV, SV, and ShV lend indirect empirical support to the conceptual integration proposed by D. D´Amato & J. Korhonen (2021), who argued that the union of these values is necessary to move towards an economy based on renewable processes that respect biodiversity, meaning that the green economy, circular economy, and the bioeconomy come together – though, as K. Laktuka *et al*. (2024) added, only if knowledge-based strategies increase the value added in forests' products and services offered to the market. This pattern reflects co-variation among the measured indicators but does not imply directional or causal relationships. As noted above, the absence of variability in ENV precludes any inferential conclusions about this dimension.

Overall, the findings indicate that technical and productive capacity (C1) is associated with differences in the economic and social value indicators reported by firms. However, due to the exploratory nature of the study, the small sample size, and the use of non-parametric methods, the results should be understood as descriptive patterns within the studied population rather than generalisable or causal conclusions. The associations identified among EV, SV, and ShV highlighted the interrelated behaviour of these dimensions in the dataset, but further research with larger samples would be required to examine these relationships in greater depth.

CONCLUSIONS

The central implication of this study is that technical and productive capacity, rather than compliance with environmental requirements alone, appears to be the factor most closely associated with how Honduran secondary forestry firms create economic and social value. This suggests that current sector policy, which is largely oriented towards environmental licensing, audits, and monitoring, may be overlooking the lever that most directly shapes value creation on the ground. Given the exploratory nature of the study and its small sample size, these findings should be read as an indication of where policy attention could be usefully redirected, rather than as definitive proof of what drives value creation across the sector. The secondary broadleaf forestry industry in Honduras currently prioritises environmental compliance but pays comparatively little

attention to the business indicators that drive economic value and to the corporate social responsibility practices that build social value as a bridge towards shared value. Addressing this gap does not require abandoning environmental requirements, but complementing them with support for local raw material use, product quality, marketing knowledge, personnel training, and quality control – the areas most closely linked to the value dimensions found to be strongest in this sample.

Based on these findings, the following recommendations are proposed. National training programmes should be developed to strengthen the entrepreneurial and technical capacities of forest industries, integrating this content into environmental licensing processes. Complementary to this, the regulatory framework for traceability should be updated and strengthened, promoting digital tracking systems and seals of origin that guarantee the legality and sustainability of forest products, complemented by fiscal, financial, and technological incentives for microenterprises and cooperatives that use regional raw materials and improve their production processes. Inter-institutional coordination between the Forest Conservation Institute and municipalities should also be optimised through integrated digital platforms for audits, procedures, and monitoring, alongside a national forestry marketing strategy that strengthens digital marketing, product design, and market access to position Honduran products nationally and internationally. Finally, public-private partnerships for innovation should be promoted through applied research, international certifications, and technological improvements in broadleaved wood transformation, together with a national system of sustainability and shared value indicators to measure the sector's economic, social, and environmental performance and support evidence-based decision-making.

Together, these recommendations seek to strengthen the competitiveness of the Honduran forestry industry, promote the sustainable use of natural resources, and generate tangible benefits for local communities, thereby contributing to a more balanced and resilient development model that benefits society. As future research, the study will be expanded to other countries, allowing to observe whether the same problems occur in other forestry-based environments, especially in Central America. Also, future research should expand the sample, refine the measurement of environmental performance, and incorporate longitudinal or comparative designs to broaden the analytical scope.

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CONFLICT OF INTEREST

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Аспекти сприйманої цінності в деревообробній галузі Гондурасу

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Анотація. Лісогосподарські підприємства в Гондурасі демонструють значні недоліки у сфері створення вартості. Мета даної роботи полягала у визначенні того, як економічна, соціальна та спільна цінність сприймаються у галузі переробки листяної деревини Гондурасу, а також у розробці пропозицій щодо заходів для посилення створення вартості в цьому секторі. З цією метою до даних опитування 17 підприємств з переробки твердої деревини у чотирьох лісових регіонах Гондурасу було застосовано аналіз таблиць співвідношень, критерій хі-квадрат Пірсона, коефіцієнт V Крамера та U-критерій Манна-Уїтні (з оцінками розміру ефекту). 44 показники було згруповано у три категоріальні змінні (B1, C1, C3) та три кількісні змінні (EV, SV, ShV), а надійність і валідність оцінювали за допомогою коефіцієнта альфа Кронбаха, HTMT та кореляцій τb Кендалла. Розмір ефекту виявився дуже великим (V = 0,78) для пари EV–SV, де було зафіксовано значущий зв'язок, $\chi^2(4) = 22{,}00$, p = 0,0002. У парі SV–ShV зв'язок також був значущим ($\chi^2(6) = 13{,}00$, p = 0,041) з розміром ефекту (V = 0,60). Це вказало на тісний взаємозв'язок між економічною, соціальною та спільною цінністю в межах досліджуваної вибірки. Підприємства лісової галузі Гондурасу стикаються зі структурними слабкостями, пов'язаними з вирубкою лісів, неформальністю, технічним застаріванням та обмеженим рівнем освіти. Ці обмеження негативно впливають на впровадження маркетингових практик, контроль якості, простежуваність та доступ до ринку. Крім того, відсутність знаків походження знижує конкурентоспроможність як на національних, так і на міжнародних ринках. Для усунення цих обмежень автори запропонували активізувати використання місцевої сировини з метою підвищення якості продукції, розширити знання в галузі маркетингу, провести навчання персоналу та вдосконалити системи контролю якості. Отримані результати можуть слугувати основою для розробки національних навчальних програм, спрямованих на зміцнення підприємницького та технічного потенціалу лісового сектору, а також для включення їхнього змісту до процесів екологічного ліцензування

Ключові слова: спільна цінність; економічна цінність; соціальна цінність; екологічна цінність; вторинна лісова промисловість; листяна деревина

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Patterns and growth dynamics of the plantation sector in South Sumatra, Indonesia

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Abstract. The plantation sector is a crucial pillar of South Sumatra Province's economic structure, as it contributes significantly to the Gross Regional Domestic Product. Therefore, an in-depth study of its growth dynamics and shifts in regional structure is necessary. This study aimed to identify production characteristics, area, commodity growth, and changes in the plantation sectoral structure across regencies/cities in South Sumatra. Using secondary data from Central Statistics Indonesia and the Plantation Office for 2021-2025, this study applied quantitative descriptive methods through percentage analysis, growth analysis, and a shift-share approach to examine the competitive position of each plantation commodity. The analysis showed that palm oil, rubber, and coffee are the dominant commodities in both production and spatial distribution, while coconut and cocoa make more limited contributions. The growth analysis for 2021-2025 indicated that coconut (0.025) and coffee (0.023) recorded positive growth, while palm oil (-0.019), rubber (-0.053), and cocoa (-0.021) experienced negative growth. Shift-share analysis further revealed that palm oil (C_{ij} = 2,161,960.89), rubber (C_{ij} = 374,948.27), and cocoa (C_{ij} = 337.51) possessed positive regional competitive advantages, whereas coconut (C_{ij} = -249.30) and coffee (C_{ij} = -6,770.39) exhibited negative competitive values and remained concentrated in limited production areas. These findings indicate a dualistic plantation structure in

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South Sumatra, where a limited number of commodities function as regional growth drivers while others remain stagnant and require revitalisation. The results provide an empirical basis for local governments to strengthen leading commodities, improve plantation productivity, and formulate differentiated commodity development policies according to regional potential and competitiveness. These findings provide a strategic basis for local governments to strengthen the development of leading commodities, increase area productivity, and design differentiated policies according to the potential and dynamics of each district

Keywords: leading potential; structural transformation; shift-share; Gross Regional Domestic Product; plantation structure; plantation productivity; commodity development

INTRODUCTION

South Sumatra Province is a key region in the Indonesian economy, marked by significant potential in the plantation sector (Ciptawaty *et al.*, 2020). The plantation sector has long been the backbone of the local economy, as South Sumatra's agro-climate supports the development of strategic commodities such as palm oil, rubber, coffee, and sugarcane. In the 2019-2023 South Sumatra Provincial Medium Term Development Plan (MTDP), the agriculture, forestry, hunting, fisheries, and plantation sectors are listed as among the most significant contributors to the province's Gross Regional Domestic Product (GRDP) (South Sumatra Province, 2019).

According to data from the Central Statistics Agency (CSA) of South Sumatra Province, the South Sumatra economy is showing a stable growth trend. In 2024, the provincial economy is projected to grow by 5.03% based on GRDP (CSA South Sumatra, 2025). Furthermore, in the first quarter of 2025, South Sumatra's contribution to Sumatra Island's total GRDP was recorded at 13.58%, according to the provincial fiscal report (Ministry of Finance of the Republic of Indonesia, 2025). This data demonstrates South Sumatra's strategic role in the regional economy and the importance of its leading sectors (basic sectors) within the local economic structure.

The plantation sector is one of the main drivers of regional economic development in South Sumatra, accounting for a substantial share of agricultural output and supporting employment, exports, and rural livelihoods. However, recent changes in plantation commodity performance, spatial concentration, and regional competitiveness have created uneven development among districts. Understanding the patterns and growth dynamics of plantation commodities is therefore essential for identifying regional competitive advantages, evaluating structural transformation, and providing evidence-based guidance for sustainable regional development and investment policies, including Musi Banyuasin, Banyuasin, East OKU, and Lahat. This confirms that plantation activities dominate the local economy and provide a source of prosperity for rural communities. However, the development of the plantation sector in South Sumatra has not been evenly distributed spatially. Structural inequalities exist: some regencies have experienced rapid growth in plantation output, making significant contributions to the provincial economy.

The plantation sector has become one of the most strategic components of Indonesia's regional economy because it contributes substantially to employment, export earnings, rural development, and regional gross domestic product. South Sumatra is among the country's leading plantation provinces, with oil palm, rubber, coffee, coconut, and cocoa serving as the dominant commodities. Although these commodities have long supported regional economic growth, recent changes in commodity prices, land-use dynamics, productivity, and regional competitiveness have altered the spatial distribution of plantation development. These changes have increased the need to understand how plantation growth differs across districts and commodities, particularly in the context of regional development planning and sustainable agricultural transformation.

The existing studies have investigated various aspects of plantation development in Indonesia, but important research gaps remain. A. Syahza *et al.* (2021) demonstrated that sustainable plantation commodities contribute significantly to regional economic development, although their study focused primarily on sustainable commodity development without analysing spatial differences in regional competitiveness. M.F. Ali *et al.* (2021) examined the dynamics of rubber production and concluded that international price volatility strongly influences plantation performance; however, the study did not investigate regional structural change at the subnational level. P. Wang *et al.* (2021) highlighted the importance of governance and institutional capacity in improving agricultural competitiveness, but their analysis was not specifically directed toward plantation-based regional economies. J.D. Merfeld & P. Brummund (2022) showed that sectoral productivity differences strongly influence regional economic performance, yet they did not evaluate how plantation commodities contribute differently across local administrative regions. Later, T.H. Masitah *et al.* (2023) reported that labour quality, production area, and investment significantly determine oil palm productivity in Indonesia, whereas their analysis was limited to productivity determinants rather than regional structural dynamics.

Studies conducted by Indonesian researchers also reveal similar limitations. T. Feninda (2023) reported that oil palm plantations substantially contribute to

South Sumatra's regional economy but did not compare the performance of multiple plantation commodities across districts. J. Barkah & M. Rojali (2024) demonstrated that oil palm expansion promotes regional economic growth and poverty reduction; nevertheless, their study concentrated on Kalimantan and did not evaluate structural changes in South Sumatra. M.A.R. Mauladi *et al.* (2022) analysed coffee supply-chain management in West Java and highlighted institutional and marketing constraints, although the study did not examine the regional competitiveness of plantation commodities using spatial economic approaches. Overall, previous studies have mainly focused on individual commodities, productivity determinants, supply chains, or economic contributions, while comprehensive analyses integrating plantation production, plantation area, commodity growth, and structural change across all districts within a province remain limited. Using a descriptive-analytical framework, this study sought to objectively present the condition of the plantation sector, thereby providing a basis for assessing its development and the challenges it faced.

This study addresses these research gaps by integrating descriptive analysis, growth analysis, and shift-share analysis to evaluate the patterns and growth dynamics of the plantation sector across all regencies and cities in South Sumatra Province during the 2021-2025 period. Unlike previous studies that examined individual commodities separately, this research simultaneously analyses plantation production, cultivated area, commodity growth, and structural competitiveness to identify leading commodities, regional growth patterns, and structural transformation. The findings are expected to provide stronger empirical evidence for regional economic planning, commodity development strategies, and sustainable plantation policy in South Sumatra.

MATERIALS AND METHODS

This study used a quantitative descriptive method to provide an empirical understanding of the dynamics of the plantation sector in South Sumatra Province. This approach was chosen because it can systematically describe phenomena by presenting characteristics, trends, and variations in data related to the sector's growth and contribution. A quantitative approach was applied to process numerical data derived from the area and production of various plantation commodities. This data was analysed using shift share analysis to identify growth patterns, contribution levels, and shifts in the structure of the plantation sector within the regional economy. Through quantitative analysis, this study produced a comprehensive and relevant understanding that supported the formulation of sustainable plantation development policies in South Sumatra Province.

This research was conducted in South Sumatra Province, which comprises 17 regencies/cities with diverse economic and spatial characteristics. This area was selected based on regional economic growth dynamics and differences in sectoral structures across regions, making it relevant for analysis in the context of economic geography. This diversity provided a strong foundation for examining variations in regional performance and identifying factors influencing shifts in the regional economic structure. The research took place from February to December 2025, encompassing a series of systematic stages, from data collection and quantitative and qualitative analysis to the interpretation of results based on the theoretical framework. All stages culminated in the preparation of a final report that contained the key findings and their implications for regional development policy.

Data type and source. This research utilised secondary data sourced from official government institutions. The primary data included commodity types, commodity area, and plantation commodity production volumes. All data were obtained from the 2025 publications of the CSA of South Sumatra Province. Furthermore, the CSA data was validated by comparing it with data from the South Sumatra Provincial Plantation Office for 2025. This validation was conducted to ensure consistency in statistical figures across agencies and to reduce potential bias arising from differences in data collection methods. The integration of these two data sources enabled this research to produce more comprehensive findings and to more accurately depict the actual conditions of the plantation sector.

Data collection in this research was conducted using a documentation study method. Documentation studies allow researchers to obtain historical and current data from official institutions, particularly from the CSA for 2025, which provides various figures on plantation areas and production. Furthermore, this study also utilised the 2025 report from the South Sumatra Provincial Plantation Office as a more specific sectoral data source, particularly regarding the dynamics of plantation commodities, the spatial distribution of production, and the development of the region's leading subsectors (CSA South Sumatra, 2025).

Data analysis techniques. Analysis of area and production using a descriptive percentage approach illustrates the relative contribution of a commodity, region, or unit of analysis to the overall production system. This approach is essential because it can more clearly demonstrate the spatial structure and distribution of production capacity. Percentages allow researchers to see the proportion of land area and production volume controlled by each commodity or region, thereby identifying growth centres, commodity dominance, and any spatial inequalities. Technically, this analysis compares the area or production of each entity to the total area or total output. The results are then translated into percentages for easy reading and analysis. The percentage formula is as follows:

$$Percentage\ (\%) = (Number\ of\ Shares)/(Total\ Shares)\ X\ 100\%. \quad (1)$$

The average GRDP growth of the plantation sector for each district/city during the 2020-2025 period using the following annual geometric growth average was calculated by the following formula:

$$Average\ growth\ rate\ (r) = \left(\frac{P_0}{P_t}\right)^{\frac{1}{t}} - 1, \quad (2)$$

where P_0 = GRDP of the plantation sector in the initial year (2020), P_t = GRDP of the plantation sector in the final year (2025) and t = number of years (2025-2020 = 5 years). To calculate the contribution of the plantation sector to the total GRDP of the district/city, the following formula was used:

$$Share = = GRDP\ of\ the\ plantation\ sector\ Total\ GRDP\ x\ 100\%. \quad (3)$$

The following analysis focused on the general formulation of the shift-share equation and its constituent components. In economic geography, this method is used to identify the sources of changes in a region's performance by separating regional, structural, and local factors. Therefore, understanding the general form of the equation provides an essential foundation for comprehensively interpreting the dynamics of interregional economic growth.

In principle, the basic shift-share equation consists of three main components: regional share, industry mix, and local shift. The regional share component shows how national economic growth influences a sector's performance in a given region. The industry mix component assesses whether a sector in that region is growing faster or slower than national sectoral growth. Meanwhile, the local shift component indicates competitive advantages or disadvantages between districts, as evidenced by differences in sectoral growth within that district compared to provincial performance.

By understanding the basic structure of this equation, shift-share analysis can provide a more accurate picture of the sources of district growth. Furthermore, the study can indicate whether regional factors, regional economic structure, or district competitiveness more influence economic change. This approach is crucial for developing more adaptive economic development strategies that focus on the district's unique potential. The shift share analysis formula is as follows:

$$D_{ij} = N_{ij} + M_{Ij} + C_{ij}, \quad (4)$$

where i represent economic sectors studied, j – regional variable studied (Regency), D_{ij} – change in sector i in region j (Regency), N_{ij} – national growth of sector i in region j (Regency), M_{ij} – industrial mix of sector i in region j (Regency), C_{ij} – competitive advantage of sector i in region j.

Despite the robustness of the quantitative descriptive and shift-share approaches in identifying growth patterns and structural changes in the plantation sector, this study had several limitations. First, the analysis relied exclusively on secondary data obtained from official government sources, making the findings dependent on the accuracy, consistency, and completeness of the published statistical records. Second, the shift-share method primarily measured changes in regional competitiveness and sectoral structure but did not explicitly capture the influence of external factors such as international commodity price fluctuations, climate variability, technological innovation, institutional quality, or policy interventions that may have affected plantation performance during the study period.

RESULTS AND DISCUSSION

South Sumatra Province exhibited considerable regional variation in plantation development during the 2021-2025 observation period, reflecting differences in biophysical conditions, land availability, and commodity specialisation across its 17 regencies and cities. The plantation sector was dominated by five major commodities oil palm, rubber, coffee, coconut, and cocoa which differed substantially in terms of cultivated area, production volume, and growth performance. Oil palm occupied the largest plantation area, followed by rubber and coffee, while coconut and cocoa covered relatively smaller areas. Production was spatially concentrated in several leading regencies, particularly Musi Banyuasin for oil palm and rubber, Banyuasin for coconut, South Ogan Komering Ulu and Empat Lawang for coffee, and Lahat for cocoa. The observed production patterns were generally associated with regional differences in land suitability, agroclimatic conditions, infrastructure availability, and commodity-based economic specialisation. Overall, the empirical results indicated contrasting development trends among plantation commodities. Growth analysis showed positive growth for coconut (0.025) and coffee (0.023), whereas oil palm (-0.019), rubber (-0.053), and cocoa (-0.021) experienced declining growth during the study period (Muchane *et al.*, 2020; Hayashi *et al.*, 2020; Wang *et al.*, 2021). Furthermore, the shift-share analysis revealed that oil palm, rubber, and cocoa maintained stronger regional competitiveness, while coconut and coffee remained concentrated in specific districts with relatively limited competitive performance. These findings provide an empirical overview of the plantation sector before presenting detailed results on production, plantation area, commodity growth, and structural dynamics (Merfeld & Brummund, 2022).

Extent and distribution of plantations in South Sumatra. During the 2019-2024 period, the development of primary commodity plantations in South Sumatra Province exhibited varying spatial and temporal dynamics across regions. For rubber, Musi Banyuasin Regency

consistently had the most significant area, peaking in 2020, followed by North Musi Rawas and Muara Enim Regencies, which also have substantial land coverage. In contrast, urban areas such as Pagar Alam, Prabumulih, and Lubuk Linggau showed relatively small and stable regions. For coconut, Musi Banyuasin again dominated, with the most significant area throughout the observation year. At the same time, other regencies, such as Ogan Komering Ulu, Ogan Komering Ilir, Musi Rawas, and Banyuasin, had much smaller and relatively stable areas. This indicates that coconut development in South Sumatra is centralised and has not experienced significant expansion during the study period.

Oil palm plantations exhibit extreme concentration in the Musi Banyuasin, Ogan Komering Ilir, Muara Enim, and Banyuasin regions, with a trend of increasing area in 2020, followed by relative stability until 2024. Meanwhile, urban areas continue to show minimal area. For coffee, production centres shifted, with Empat Lawang, Muara Enim, and South Ogan Komering Ulu dominating at the beginning of the observation period. However, during the 2020-2024 period, South Ogan Komering Ulu shows increasingly strong dominance. Coffee plantations in several cities remain small and stable, with a trend of decreasing area towards the end of the period. Cocoa is highly concentrated in Lahat, Musi Rawas, and Ogan Komering Ulu Regencies, with a peak area in 2020 followed by a decline. Overall, these results indicate that plantations in South Sumatra remain concentrated in certain regencies, with signs of slowing expansion and a decline in area for some commodities after 2020 (Barkah & Rojali, 2024).

The growth and contribution of the plantation sector to South Sumatra Province's GRDP demonstrate its highly strategic role in the regional economic structure. Plantation subsectors such as rubber, palm oil, coffee, cocoa, and coconut have been shown to contribute significantly to regional added value, primarily due to their export-oriented nature and high labour-absorption capacity. The consistent dominance of rubber and palm oil as regional economic drivers aligns with literature findings that indicate the plantation sector in Indonesia contributes significantly to resource-based regional growth. This aligns with the view that leading commodities have a multiplier effect on local economic activity and improve the welfare of surrounding communities (Syahza *et al.*, 2021). Furthermore, within the framework of economic geography, dominant commodities function as growth poles, attracting investment and strengthening a region's competitive position (Chetty & Hendren, 2018).

The contribution of plantation subsectors shows an uneven economic structure, with palm oil, rubber, and coffee as the three commodities that dominate South Sumatra's plantation GRDP. This aligns with shift-share analysis, which shows that subsectors with high production capacity and strong markets tend to have larger regional shares and greater proportional shifts than other subsectors, such as cocoa or coconut, whose contributions are relatively small and stagnant. This distribution of contributions reinforces the literature's view that productivity disparities between commodities are caused by differences in technology, business scale, and the effectiveness of regional governance (Reisman, 2022). Thus, the dominance of Musi Banyuasin in palm oil and rubber production, and South OKU and Empat Lawang in coffee, demonstrates agro-based growth centres that determine the overall structure of the provincial plantation economy.

Biophysical factors, including land suitability, soil characteristics, topography, and favourable microclimate, strongly influence variations in contributions and production growth across regions. As explained in the agronomic literature, successful plantation commodity production depends heavily on the suitability of ecological systems and specific biophysical conditions to plants' physiological needs (Muchane *et al.*, 2020). The high productivity of oil palm and rubber in Musi Banyuasin, as well as coffee production in South OKU and Empat Lawang, can be explained by biophysical factors such as rainfall levels, elevation, and soil fertility, which are highly suited to the characteristics of these crops. This confirms that physical geography remains a key determinant in the formation of plantation production centres in South Sumatra.

In addition to biophysical factors, the success of the plantation sector is strongly influenced by socioeconomic factors and environmental and ecological dynamics. Business scale, land ownership patterns, farmer access to markets, road infrastructure, and local government policies all play significant roles in determining production performance and long-term growth. Research shows that regions with strong institutional governance, access to technology, and good market integration can increase production efficiency and strengthen commodity competitiveness (Wang *et al.*, 2021). However, environmental pressures, such as land degradation, climate change, and ecological vulnerability, pose long-term challenges that can reduce productivity (Hayashi *et al.*, 2020). Therefore, the sustainability of the growth of the South Sumatra plantation sector is greatly influenced by how the three factors – biophysical, socioeconomic, and ecological – are managed in an integrated manner to maintain production stability and strengthen the plantation sector's contribution to the province's GRDP.

Plantation production in South Sumatra. Rubber production in South Sumatra Province during the 2019-2024 period exhibited quite fluctuating spatial dynamics across regencies. At the beginning of the period, Muara Enim Regency was recorded as the highest rubber producer, but from 2020 to 2024, production dominance shifted consistently to Musi Banyuasin Regency. This shift indicates differences in land carrying capacity,

planted area, and the effectiveness of plantation management across regions (Muchane *et al.*, 2020). In addition to Musi Banyuasin, Muara Enim, and Musi Rawas Regencies, the three also demonstrated relatively high and stable production capacity, categorising all three as major rubber production centres in South Sumatra. Conversely, other regencies/cities contributed less, with production tending to stagnate or decline, possibly related to limited land area, low productivity, and suboptimal management of smallholder plantations (Masitah *et al.*, 2023).

Coconut production in South Sumatra exhibits a highly concentrated spatial pattern. Throughout the 2019-2024 period, Banyuasin Regency consistently produced the highest coconut production, reaching approximately 4-5 million tons per year, while other regencies produced only a few thousand tons per year. This reflects the geographic characteristics of Banyuasin Regency, which is dominated by coastal areas and tidal swamps suitable for coconut cultivation. Meanwhile, palm oil production also exhibited a strong dominance pattern, with Musi Banyuasin Regency as the largest producer throughout the observation period, followed by Banyuasin Regency. Other regencies, such as Musi Rawas, Ogan Komering Ilir, and South Ogan Komering Ulu, contributed moderate amounts, while other regions produced relatively small quantities. In general, palm oil production in South Sumatra has been stable, with high concentrations in several key regencies.

Coffee and cocoa commodities exhibited different production characteristics. South Sumatra's coffee production during 2019-2024 was dominated by South Ogan Komering Ulu and Empat Lawang Regencies, with the highest and relatively stable production volumes, followed by Lahat, Muara Enim, and Ogan Komering Ulu Regencies. In contrast, urban areas such as Palembang, Pagar Alam, and Lubuk Linggau contribute virtually no coffee production. For cocoa, Lahat Regency has the highest production, although it has shown a downward trend over the past six years. Musi Rawas and Ogan Komering Ulu Regencies also produce significant amounts of cocoa, although this fluctuates. Overall, cocoa production in South Sumatra remains concentrated in specific regions and is in decline, indicating the need for strengthened cultivation, rejuvenation, and improved sustainable plantation management (Toffolini *et al.*, 2020).

Research results indicate that the plantation sector in South Sumatra Province makes a significant economic contribution to the region's GRDP. Based on previous research, the plantation sector accounts for approximately 45% of South Sumatra Province's GRDP (Feninda, 2023). This indicates that the rapid expansion of plantation areas, such as rubber, oil palm, coffee, cocoa, and coconut, is not merely an agrarian phenomenon but also a major driver of regional added value. This high contribution reinforces the understanding that the plantation sector is the backbone of South Sumatra's economy, particularly given its labour-intensive nature, upstream and downstream value chain linkages, and potential to export leading commodities.

Analysis of growth and share across subsectors reveals interesting dynamics. Based on land area data, oil palm appears to be very dominant in South Sumatra, particularly in regencies such as Musi Banyuasin, Muara Enim, and Banyuasin, which consistently had the most significant areas from 2021 to 2024. As a leading subsector, oil palm is highly likely to contribute a significant percentage of the province's plantation GRDP. This aligns with findings that palm oil area expansion has historically been positively correlated with regional economic growth (Barkah & Rojali, 2024). Meanwhile, for rubber, although Musi Banyuasin Regency has a large and fluctuating land area, its potential contribution to GRDP may be influenced by land productivity. Factors such as labour, investment, and rubber prices significantly determine the efficiency of rubber plantations, as research shows that productive land area, the quality of farmers' human resources, and rubber prices significantly influence rubber productivity (Barkah & Rojali, 2024). Coffee and cocoa, despite their smaller areas, still have the potential to be growth-promoting subsectors, given their relative stability in some regions and the added value of their exports.

The underlying determinants of plantation area growth and land distribution in South Sumatra include several structural and economic variables. For palm oil, land expansion is often driven by global and domestic demand, as well as by incentive policies and relatively easy access to land, particularly in flat areas and near forests (Barkah & Rojali, 2024). Additionally, empirical studies show that palm oil industry productivity is influenced by worker wages, worker education level, and the size of the production area (Masitah *et al.*, 2023). For rubber, another study found that, in addition to rubber prices, aspects such as equipment investment, bank financing, and farmers' human resources significantly influence the growth and productivity of rubber plantations. On the social side, a case study in South Sumatra also influenced decisions about rubber plantation expansion and maintenance (Mulyo *et al.*, 2023).

The geographic-economic implications of the observed land-use patterns are highly relevant to regional development planning. The concentration of palm oil plantations in regencies such as Musi Banyuasin and Muara Enim indicates the presence of major plantation centres with the potential to become value-adding centres and integrated agribusiness clusters. However, fluctuations in rubber plantation area and decreases in several regions in recent years indicate sustainability risks, especially if not offset by investments in productivity and plantation maintenance. Within a growth-share framework, regions with large areas must focus on increasing productivity and down streaming to not

only grow in area but also increase their share of GRDP contributions. Local policies need to align incentives for plantation maintenance, technology adoption, and value chain development to optimise the economic potential of superior commodities and manage the risk of future land area reduction.

Plantation growth in South Sumatra province. The research results show that the plantation sector in South Sumatra Province makes a significant contribution to the regional economy, with key commodities including palm oil, rubber, and coffee. Based on data from 2019-2024, considerable variations in dynamics are observed between regencies/cities, both in terms of area and production of each commodity. The development of land area for several key plantation commodities in South Sumatra Province and Indonesia in 2021 and 2025, along with the results of growth analysis over the four years, are presented. Overall, variations in growth dynamics are observed between commodities, both regionally and nationally. The average annual growth rates of the major plantation commodities, calculated using the geometric growth rate formula, are presented in Table 1.

Table 1. *Results of the plantation growth analysis in South Sumatra province, 2021-2025*

No	Plantation sector	Growth analysis (%/year)
1	Palm Oil	-0.019
2	Coconut	0.025
3	Rubber	-0.053
4	Coffee	0.023
5	Cocoa	-0.021

Source: *Data analysis results 2026*

Based on Table 1, which presents the results of the Growth Analysis of the plantation subsectors in South Sumatra Province for the period 2021-2025, each commodity exhibits varying growth rates. Palm oil experienced a decline in land area from 4,267 thousand hectares in 2021 to 3,951.37 thousand hectares in 2025, with a growth rate of -0.019. This decline indicates a slowdown in land expansion and a possible shift in management focus toward production intensification.

Conversely, coconut showed a positive growth trend. Land area increased from 55.4 thousand hectares to 61.12 thousand hectares during the observation period, with a growth rate of 0.025. A positive trend was also observed for coffee, which increased its land area from 191.2 thousand hectares to 209.47 thousand hectares, with a growth rate of 0.023. The growth of these two commodities illustrates the promising potential for plantation economic development in South Sumatra.

Meanwhile, rubber and cocoa prices declined. Rubber land area decreased from 804.8 thousand hectares to 648.18 thousand hectares at the provincial level, and from 2,884.6 thousand hectares to 2,262.09 thousand hectares nationally, with a growth rate of -0.053. Cocoa also experienced a decrease in land area from 4.2 thousand hectares to 3.86 thousand hectares in South Sumatra, and from 713.4 thousand hectares to 632.7 thousand hectares nationwide, with a growth rate of 0.021.

Overall, the analysis results show that the palm oil, rubber, and cocoa sectors experienced negative growth with values of -0.019, -0.053, and -0.021, respectively, indicating a decline in performance between 2021 and 2025. Conversely, the coconut and coffee sectors showed positive growth of 0.025 and 0.023, respectively. These findings suggest that coconut and coffee commodities have positively impacted the growth dynamics of the plantation subsector in South Sumatra Province during the analysis period.

An analysis of the growth of the plantation subsector in South Sumatra Province reveals structural dynamics reflecting changes in production patterns and spatial allocation between 2021 and 2025. Findings regarding variations in growth between commodities indicate that changes in productivity and area are not solely determined by internal factors within the plantation subsector but are also influenced by global market dynamics, policy changes, and environmental pressures. From an economic geography perspective, changes in agrarian structure and investment direction in leading commodities are often linked to regional economic restructuring, shifts in downstream industry preferences, and land-use transformation (Barrett *et al.*, 2017).

The decline in oil palm plantation area in the province, with a growth rate of 0.019%, reflects a transition from extensification to more sustainable intensification. This phenomenon aligns with global trends in palm oil-producing countries tightening land expansion due to pressures for sustainability, environmental certification, and deforestation. Furthermore, changes in international market demand and commodity diversification by farmers can also reduce dependence on single commodities such as palm oil, as demonstrated in various studies on the dynamics of tropical commodities in Southeast Asia (Carlson *et al.*, 2018).

Conversely, coconut and coffee commodities exhibited favourable growth rates of 0.025 and 0.023, respectively. This growth indicates opportunities for regional economic development, particularly given the high added value of both commodities in the supply chain and stable global demand. Coffee growth, for

example, is heavily influenced by global consumption trends and the growing specialty coffee market, which incentivises improvements in cultivation quality (Carlson *et al.*, 2018). Similarly, increases in coconut plantation area are often associated with revitalisation programs for smallholder plantation commodities and the increasing role of coconut-based industries in the local economy (Firsta *et al.*, 2020).

The declining performance of rubber and cocoa commodities indicates a significant shift in the structure of the plantation economy. The negative growth rate of -0.053 for rubber is in line with declining international prices and increased competition from other, more efficient producing countries, such as Thailand and Vietnam. Previous studies have shown that global rubber price volatility is a significant factor in farmers' declining interest in maintaining production (Ali *et al.*, 2021). Meanwhile, the decline in cocoa plantations, which grew by -0.021%, can be attributed to declining productivity of mature plants and pest and disease attacks, a situation common in tropical cocoa-producing countries (Toffolini *et al.*, 2020).

Overall, the research findings indicate that the plantation subsector in South Sumatra is in a phase of growth differentiation between commodities. Palm oil, rubber, and cocoa contracted, while coconut and coffee grew. This condition indicates a structural change important for regional development strategies. In the context of economic geography, this phenomenon illustrates how a region's comparative and competitive advantages can change over time through interactions among market factors, policies, and agroecological capacity (Akbar *et al.*, 2020). Therefore, regional development strategies need to be directed at strengthening commodities with positive growth while simultaneously revitalising those in decline, so that the plantation subsector can maintain its contribution to the regional economy.

Analysis of the dynamics of structural change. Shift-share analysis is a quantitative approach used to understand the dynamics of changes in a region's economic structure over a specific period. This method allows researchers to identify how national factors, sectoral characteristics, and local competitive advantages influence a region's economic growth. In the context of regional analysis, shift-share provides a comprehensive picture of the extent to which economic changes at the local level follow, deviate from, or exceed growth patterns occurring at the broader regional level. In the 2021-2025 period, shift-share analysis plays a crucial role in tracking shifts in leading sectors within a district and within a province. The results of the shift-share analysis for South Sumatra Province are shown in Table 2.

***Table 2**. Results of shift share analysis of the plantation sector in South Sumatra province 2021-2025*

No	Plantation Sector	N_{ij}	M_{ij}	C_{ij}	D_{ij}
1	Palm Oil	-4431492.85	3644016571	2161960.89	3641747039
2	Coconut	-57535.67	-588014.5474	-249.3	-645799.5174
3	Rubber	-835825.04	520309445.7	374948.272	519848568.9
4	Coffee	-198570.76	-10659278.4	-6770.392	-10864619.55
5	Cocoa	-4361.91	352006.137	337.512	347981.739

***Source:** Data analysis results 2026*

The analysis shows that palm oil, rubber, and cocoa experienced relatively rapid growth in South Sumatra Province. These three commodities not only demonstrated increasing production dynamics but also made significant contributions to the regional economic structure. This consistent growth indicates a strong sectoral specialisation process, along with increasing land expansion and support for agribusiness infrastructure in various regencies/cities.

Conversely, coconut and coffee commodities did not demonstrate a regional competitive advantage. Their performance tended to stagnate and did not contribute significantly to the province's economic growth. This condition indicates a weak financial base for these two commodities across productivity, business scale, and added value. Limited production facilities and a lack of technical innovation further weakened these commodities' competitiveness.

Spatially, there was a positive shift in the prices of palm oil, rubber, and cocoa, as evidenced by their relatively even distribution across almost all regencies/cities. This broad distribution indicates that these three commodities have become a widespread economic base, supporting more equitable regional development. Conversely, a negative shift occurred for coconut and coffee. Coconut production is concentrated in Banyuasin Regency, while coffee production is limited to two regencies: South OKU and Empat Lawang. This uneven distribution indicates that these two commodities have not developed into leading provincial sectors and serve only as a local economic base in certain areas.

Research results show that shift-share analysis can more comprehensively reveal the dynamics of plantation sectoral growth in South Sumatra Province. Findings on the growth of palm oil, rubber, and cocoa indicate the effectiveness of regional economic structures in responding to changes in national and global demand. This aligns with the understanding that the plantation sector in tropical regions tends to grow positively when supported by market factors, technology,

and adaptive regional policies (Barbier, 2004). Thus, the growth patterns identified through the proportional shift and differential shift components confirm that South Sumatra Province possesses a continuously developing sectoral advantage.

The rapid growth of palm oil, rubber, and cocoa demonstrates that these sectors are highly competitive, both in terms of productivity and market structure. This positive performance can be attributed to increased agribusiness investment, strengthening supply chains, and land expansion in various regencies/cities, which is conceptually consistent with the theory of regional competitive advantage (Merfeld & Brummund, 2022). Furthermore, the growth dynamics of palm oil and rubber in Sumatra have long been influenced by global market integration, leading to more intensive and stable sectoral specialisation.

Conversely, coconut and coffee commodities exhibit uncompetitive performance, reflected in negative differential shift values. This achievement underscores that these two commodities cannot keep pace with sectoral growth at provincial and national levels. Cross-regional studies indicate that the stagnation of the coconut and coffee sectors is often associated with limited cultivation technologies, low productivity among smallholder farmers, and minimal diversification into high-value-added products (Mauladi *et al.*, 2022). In other words, the sector's inability to grow stems not only from internal production factors but also from an economic structure that does not support innovation.

From a spatial perspective, research findings confirm that palm oil, rubber, and cocoa are relatively evenly distributed across most districts/cities, strengthening their position as regionally based sectors. This wide distribution indicates the process of economic diffusion and regional integration, which are key characteristics of sectors that have achieved regional scale (Brooks *et al.*, 2020). A strong spatial distribution also indicates a region's high capacity to provide labour, land accessibility, and agribusiness infrastructure.

Conversely, the limited distribution of coconut and coffee commodities indicates that these two sectors have only a local economic base and have not yet developed into leading provincial sectors. The spatial concentration of coconut in Banyuasin and coffee in South OKU and Empat Lawang indicates that these commodities are trapped in a subsistence production structure without adequate market and technological support. The literature shows that sectors with narrow spatial distributions tend to struggle to compete in regional growth contexts due to limited economies of scale and weak market integration (Yeung & Coe, 2015). This situation reinforces the finding that coconut and coffee have not been able to expand or contribute significantly to the economic growth of South Sumatra Province.

The results of the study indicate that the growth of the plantation sector in South Sumatra Province is dualistic: leading sectors (palm oil, rubber, cocoa) exhibit inclusive growth dynamics, both spatially and sectorally, while non-leading sectors (coconut, coffee) remain localised and stagnant. These findings provide a strategic overview of the need for policy differentiation, both to maximise the potential of leading sectors and to improve the performance of marginal sectors to contribute more to regional development. These research findings can inform the formulation of evidence-based policies for sustainable plantation development at the provincial level.

CONCLUSIONS

The results of this study indicate that the plantation sector holds a highly strategic position in the economic structure of South Sumatra Province. Through growth and share analysis, it is clear that differences in contributions between commodities and between regions reflect the dynamics of new growth centres and determine the direction of regional plantation transformation. Overall, the four main aspects of production, area, growth, and structural dynamics form an important foundation for understanding the potential and challenges of the provincial plantation sector.

Plantation production in South Sumatra demonstrates the dominance of rubber, palm oil, and coffee as the region's main pillars of GRDP. These three commodities not only contribute significantly to the economy but also act as growth poles that drive local economic activity through a multiplier effect. They are key determinants of production centres such as Musi Banyuasin for rubber palm oil and South OKU and Empat Lawang for coffee.

The plantation area demonstrates the dominance of oil palm, which is widespread in regencies such as Musi Banyuasin, Banyuasin, and Muara Enim. The expansion of plantation areas, particularly oil palm and rubber, has been a driving force for regional economic growth due to its strong linkages with upstream and downstream activities, employment, and export potential. However, the dynamics of land area also indicate structural shifts: rubber fluctuates, while several other commodities remain stagnant. The contribution of land to GRDP is strongly influenced by the productivity and efficiency of its utilisation. Therefore, regions with large areas need to focus on increasing productivity and downstream processing to maintain their role as value-added centres and integrated agribusiness clusters. Subsector growth indicates that plantations in South Sumatra are in a phase of sharp differentiation between commodities. Palm oil, rubber, and cocoa tend to experience contraction. Conversely, coconut and coffee show positive growth, reflecting regional development opportunities, primarily due to stable market demand and high added value in the processing industry.

The identified structural dynamics indicate that palm oil, rubber, and cocoa have strong regional

competitiveness and serve as basic sectors spread across various districts. This positive performance aligns with market integration, agribusiness investment, and strengthened supply chain networks. Conversely, coconut and coffee commodities exhibited negative differential shift values, indicating an inability to keep pace with provincial and national sectoral growth. The limited distribution of coconut and coffee indicates that both commodities remain trapped in a subsistence production structure and have not yet developed into leading provincial sectors. This finding confirms the dual nature of the plantation sector in South Sumatra: some commodities have become drivers of inclusive regional growth, while others require revitalisation to contribute more significantly to regional development.

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CONFLICT OF INTEREST

The authors of this study declare no conflict of interest.

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Анотація. Плантаційний сектор є одним із ключових елементів економічної структури провінції Південна Суматра, оскільки забезпечує вагомий внесок у валовий регіональний внутрішній продукт. Тому необхідним є поглиблене дослідження динаміки його розвитку та структурних змін на регіональному рівні. Метою цього дослідження було визначення характеристик виробництва, площ насаджень, динаміки зростання основних культур і змін у структурі плантаційного сектору в округах і містах провінції Південна Суматра. Використовуючи вторинні дані Центрального статистичного управління Індонезії та Управління плантацій за 2021-2025 роки, у дослідженні застосовано кількісні описові методи, зокрема відсотковий аналіз, аналіз динаміки зростання та shift-share-аналіз для оцінювання конкурентних позицій кожної плантаційної культури. Результати аналізу показали, що пальмова олія, каучук і кава є домінуючими культурами як за обсягами виробництва, так і за просторовим поширенням, тоді як кокос і какао роблять значно менший внесок. Аналіз динаміки зростання за 2021-2025 роки засвідчив позитивні темпи розвитку кокоса (0,025) та кави (0,023), тоді як пальмова олія (-0,019), каучук (-0,053) і какао (-0,021) продемонстрували негативну динаміку. Shift-share-аналіз також показав, що пальмова олія (C_{ij} = 2 161 960,89), каучук (C_{ij} = 374 948,27) і какао (C_{ij} = 337,51) мають позитивні регіональні конкурентні переваги, тоді як кокос (C_{ij} = -249,30) і кава (C_{ij} = -6 770,39) характеризуються від'ємними показниками конкурентоспроможності та залишаються зосередженими в обмеженій кількості виробничих районів. Отримані результати свідчать про дуалістичну структуру плантаційного сектору Південної Суматри, у межах якої лише обмежена кількість культур виступає рушіями регіонального економічного зростання, тоді як інші залишаються стагнуючими та потребують відновлення й розвитку. Результати дослідження формують емпіричне підґрунтя для органів місцевого самоврядування щодо зміцнення позицій провідних культур, підвищення продуктивності плантацій та розроблення диференційованої політики розвитку окремих культур відповідно до їхнього потенціалу й конкурентоспроможності. Отримані висновки також створюють стратегічну основу для посилення розвитку провідних культур, підвищення продуктивності плантаційних площ і формування диференційованої політики з урахуванням потенціалу та особливостей розвитку кожного округу

Ключові слова: провідний потенціал; структурна трансформація; shift-share-аналіз; валовий регіональний внутрішній продукт; структура плантаційного сектору; продуктивність плантацій; розвиток сільськогосподарських культур

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Integrating environmental, economic, and welfare dimensions in sustainable dairy farming: Literature review

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Abstract. Sustainable cow milk production is critical for global food security, rural livelihoods, and human nutrition, yet it poses environmental, economic, and ethical challenges. Dairy systems contribute significantly to greenhouse gas emissions, water and land use, nutrient losses, and biodiversity impacts, while also shaping animal welfare and farm profitability. This review aimed to examine how environmental protection, economic viability, resource efficiency, and animal welfare were integrated in sustainable dairy production systems. A structured narrative review of recent scientific literature was conducted, and evidence on greenhouse gas emissions, land and water use, nutrient management, animal health, housing, farm profitability, precision livestock farming, genetic improvement, nutrition, circular economy strategies, and policy support was synthesised. The review established that sustainable dairy production required balanced action across environmental, economic, and social dimensions, since improvements in one area often produced trade-offs in another. Environmental impacts were investigated through strategies such as improved feed efficiency, methane-reducing diets, manure management, pasture-based systems, water stewardship, nutrient recycling, renewable energy use, and integrated crop and livestock farming. Animal welfare was analysed as a central component of sustainability, and appropriate housing, pasture access, preventive health care, reduced lameness and mastitis, longer productive lifespan, and welfare certification were identified as factors that supported both ethical responsibility and farm performance. Economic sustainability was summarised as a prerequisite for adoption of sustainable practices, because production efficiency, cost control, market incentives, policy support, and risk management determined whether farmers could maintain profitability while improving environmental and welfare outcomes. The results could be used by dairy farmers, advisers, researchers, policymakers, certification bodies, and industry stakeholders to design, evaluate, and promote more resilient, efficient, and ethically responsible dairy production systems

Keywords: agroecology; circular economy; feed efficiency; precision livestock farming; resource efficiency

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INTRODUCTION

Dairy production plays a central role in global agricultural systems, contributing significantly to human nutrition, rural livelihoods, and food security; however, its role is increasingly contested due to environmental and ethical concerns. Cow milk is widely valued as a nutrient-rich food, while dairy farming supports employment, income generation, and the social structure of many rural areas. At the same time, milk production raises important sustainability concerns because it depends on natural resources, generates environmental pressures, and involves ethical responsibilities related to animal welfare. For these reasons, improving the sustainability of cow milk production is an important priority for researchers, farmers, policymakers, and the dairy industry.

Accordingly, to B.O. Manono (2026), sustainability in livestock production is a key priority, addressing climate change, resource pressure and environmental harm, with dairy farming contributing significant methane and manure emissions. Nevertheless, the magnitude of these impacts varies substantially between production systems, limiting the generalisability of mitigation strategies. M. Cheng *et al*. (2022) added that livestock supply chains also contribute substantially to global greenhouse gas (GHG) emissions through methane (CH_4), nitrous oxide, (N_2O) and carbon dioxide (CO_2) released during animal digestion, manure handling, feed production, and land use change.

M. Herrero *et al*. (2023) argued that sustainable cow's milk production must address economic and social factors, as livestock supports livelihoods, employment and food security, especially within rural economies worldwide. Ensuring farm profitability and resilience is therefore a fundamental component of sustainability in dairy systems, as economically viable farms are better able to maintain production while adapting to environmental and market pressures. The integration of environmental performance, economic viability, and social considerations, including animal welfare, reflects the broader concept of sustainability, which is commonly described through the three interconnected pillars of environmental, economic, and social responsibility in agricultural systems. In practice, however, these pillars often conflict, requiring trade-offs rather than simultaneous optimisation.

A.N. Hristov *et al*. (2022) indicated that researchers and practitioners are exploring strategies to enhance dairy sustainability, including improving feed efficiency and optimising diets to reduce CH_4 emissions while maintaining milk productivity. In addition, E. Mixtajova *et al*. (2026) indicated that further mitigation approaches focus on improved manure management, genetic selection, and integrated herd management strategies to reduce GHG emissions and enhance production efficiency. Adoption of precision livestock farming (PLF) technologies, including sensors and automation, can optimise management practices, improving efficiency while reducing environmental impacts within dairy systems. H.H.E. Van Zanten *et al*. (2023) concluded that circular agriculture and resource-efficient livestock systems promote feeding by-products and non-edible biomass, improving efficiency, reducing environmental impacts, and supporting resilient, productive food systems. While these approaches can reduce emissions intensity, their effectiveness depends strongly on local conditions and baseline system efficiency. Recent systematic reviews such as C. Pavanello *et al*. (2024) highlighted that research draws on a wide array of indicators and assessment frameworks to capture environmental, economic and social performance, with no single set of metrics universally adopted, such as multiple environmental, economic and social indicators identified in EU dairy systems literature. The purpose of this review was therefore to provide an integrated synthesis of the main factors shaping sustainable cow milk production and to identify management and research priorities that may support more resilient, efficient, and welfare-oriented dairy systems.

This article was developed as a narrative literature review. Scientific sources published between 2020 and 2026 were selected according to their relevance to sustainable cow milk production, with priority given to recent peer-reviewed studies addressing environmental impacts, resource efficiency, animal welfare, economic viability, technological innovation, and policy or market instruments. The literature was identified through targeted searches using combinations of terms related to dairy sustainability, greenhouse gas emissions, feed efficiency, manure management, water use, animal welfare, farm profitability, PLF, genetic improvement, circular economy, and agroecological dairy systems. The selected sources were analysed qualitatively and systematised according to the main sustainability dimensions addressed in the review: environmental performance, animal welfare, economic viability, and innovation strategies. Evidence was compared across production systems and management approaches in order to identify common challenges, practical mitigation options, synergies, and trade-offs.

Concept of sustainability in dairy production

Sustainability in dairy production means providing nutritious food and economic benefits while minimising environmental impacts and supporting animal and community welfare, guided by the three pillars of environmental, economic, and social performance. For example, systematic reviews identify sets of sustainability indicators expressed under the environmental, economic and social pillars, highlighting how these dimensions overlap and interact within dairy farming assessments and how farm-level sustainability encompasses animal welfare, work-life balance, income and ecosystem services in addition to resource use and

emissions. In milk production, environmental, economic, and social pillars are interconnected; efficiency gains may reduce impacts but also affect profitability and social outcomes, requiring sustainability strategies to balance multiple objectives simultaneously. This interdependence complicates sustainability assessments, as improvements in one dimension may lead to unintended consequences in another. Table 1 summarises this concept, showing the 3 key dimensions, their indicators, challenges, and strategies.

***Table 1**. Conceptual framework of dairy production sustainability*

Pillar	Impacts	Sustainability strategies
Environmental	Environmental impacts include greenhouse gas emissions such as methane and nitrous oxide, water and land use, nutrient losses, biodiversity decline, nutrient pollution, water scarcity, and land-use pressure.	Improved feed efficiency, dietary interventions, manure management, PLF, efficient irrigation.
Economic	Economic impacts include profitability, production efficiency, input costs and farm resilience, with key challenges arising from price volatility, rising feed and energy costs, and financial barriers to innovation.	Cost optimisation, efficiency improvements, diversification, policy support, market incentives.
Social / animal welfare	Animal welfare and health impacts include animal health, behaviour, longevity, housing conditions and societal acceptance, with key challenges including lameness, mastitis, inadequate housing and ethical concerns.	Improved housing, pasture access, preventive health care, welfare certification schemes.

***Source:** compiled by the author*

Research on sustainable dairy systems has expanded, driven by climate change, resource pressures, and environmental impacts, with publications increasingly addressing GHG emissions and broader sustainability challenges. P.F.P. Ferraz *et al.* (2024) found that in dairy production, greenhouse gas emissions, primarily CH_4 from enteric fermentation and manure, as well as N_2O from manure and fertilisers, constitute a substantial share of total emissions and are therefore key indicators in life-cycle and whole-farm sustainability assessments. Dairy systems provide important ecosystem services as well as food and economic benefits, such as converting fibrous feed into highquality protein, supporting rural livelihoods and contributing to food security, which are increasingly recognised in sustainability frameworks that seek to balance environmental burdens with socioeconomic gains. For this reason, contemporary sustainability frameworks increasingly aim to balance the environmental burdens of dairy production with its socio-economic gains. Consequently, contemporary sustainability assessments of dairy production use integrated frameworks that combine environmental indicators (e.g. GHG emissions, nutrient flows), economic performance (e.g. resource efficiency, profitability) and social and animal welfare outcomes to reflect the multifaceted nature of sustainability in milk production systems (Fiorillo & Amico, 2024).

Life cycle assessment (LCA) is widely used to evaluate dairy environmental impacts, systematically quantifying emissions and resource use across the entire milk production chain, from feed cultivation to on-farm operations and processing stages. A systematic review L.S. Carvalho *et al.* (2022) showed LCA is a key tool in milk production sustainability research, assessing inputs, outputs, and impacts like global warming, eutrophication, acidification, and resource use to guide environmental interventions. Study consistently showed feed production, enteric CH_4, and manure management as major contributors to milk's environmental footprint; cradle-to-farm-gate assessments highlight CH_4 and N_2O from these sources per kilogram of milk. These findings reveal the importance of improving feed efficiency, optimising manure management practices and enhancing overall farm management as ways to reduce environmental burdens in dairy systems and improve sustainability outcomes.

Technological and management innovations, particularly PLF, are explored to enhance dairy sustainability. Sensor-based and digital tools monitor health, behaviour, feed intake, and milk production, improving efficiency, welfare, and productivity. S. Das *et al.* (2023) showed advanced technologies, computer vision, machine learning, and sensors, monitor behaviour, detect disease, and optimise feeding, supporting more sustainable, efficient, and welfare-friendly dairy production systems. Additionally, research showed that ICT-based monitoring systems can improve reproductive health management and labour efficiency, further supporting sustainable farm performance.

Genetic improvement programmes enhance dairy sustainability by selecting for feed efficiency, disease resistance, longevity, and reduced CH_4 emissions, enabling cumulative genetic progress that lowers environmental impacts while maintaining productivity and profitability in commercial herds. C. Richardson *et al.* (2025) showed that CH_4 emission traits in dairy cattle are heritable and can therefore be targeted through genetic selection. Their findings indicate that incorporating CH_4-related and feed-efficiency traits into breeding goals can contribute to a gradual reduction in greenhouse gas emissions across generations. L.M. Alderkamp *et al.* (2025) emphasised that integrated and agroecological farming approaches can enhance dairy sustainability by combining crop and livestock production, recycling nutrients, reducing dependence on external inputs, and improving resource efficiency, soil fertility, and system resilience. Compared with specialised systems, such approaches may also contribute to lower greenhouse gas emissions. By embedding

eco-logical principles alongside modern management practices, these systems support long-term sustainability in dairy farming, balancing productivity with environmental and socio-economic benefits.

Sustainability in dairy production is conceptualised through three interconnected pillars – environmental, economic, and social/animal welfare – whose interactions mean that improvements in one dimension can create trade-offs or unintended consequences in another. Assessing this multidimensional concept relies on integrated analytical tools, particularly life cycle assessment, alongside emerging technological and genetic innovations such as precision livestock farming and methane-focused breeding programmes. Ultimately, sustainable dairy systems must balance resource efficiency and productivity with broader socio-economic and ecological goals, including rural livelihoods, food security, and long-term farm resilience.

Environmental sustainability of cow milk production

Environmental sustainability is a key component of sustainable dairy farming, as milk production systems can exert considerable pressure on natural resources and ecosystems. Dairy production is associated with GHG emissions, land and water use, nutrient losses, and potential impacts on biodiversity. As global demand for dairy products increases, improving the environmental performance of cow milk production systems has become an important priority for researchers, policymakers, and farmers. Addressing these challenges requires the adoption of management practices and technological innovations that reduce environmental impacts while maintaining productive and economically viable farming systems.

Greenhouse gas emissions represent one of the most widely discussed environmental impacts of dairy farming because dairy cattle produce CH_4 through enteric fermentation, a natural digestive process in the rumen. Methane is a potent GHG with a much higher global warming potential than CO_2 over shorter time periods, roughly 27-30 times greater than CO_2 over a 100-year horizon as used in climate assessments, making its reduction important for climate mitigation efforts (Lei *et al.*, 2024). Enteric CH_4 emissions account for a substantial proportion of the total climate impact associated with dairy production, with enteric fermentation being the largest direct source of CH_4 emissions from dairy systems and often representing over half of the direct GHG emissions from dairy cattle when assessed on a CO_2-equivalent basis.

In addition to enteric fermentation, GHGs are also produced through manure management and the use of nitrogen fertilisers in feed crop production. Manure stored and handled on farms emits both CH_4 and N_2O during storage and decomposition, with emissions varying by storage practice and duration (Al Zahra *et al.*, 2024). At the same time, fertiliser use in feed crop cultivation contributes to N_2O release from soils through microbial nitrification and denitrification processes, making fertiliser-related N_2O an important part of dairy feed crop emissions and the overall carbon footprint of milk production. These on-farm and off-farm sources of CH_4 and N_2O collectively contribute substantially to the GHG profile associated with dairy farming, alongside enteric emissions (Al Zahra *et al.*, 2020). Technologies such as anaerobic digestion, improved manure storage and nutrient recycling have been proposed to mitigate these emissions, although adoption remains constrained by economic and technical barriers, particularly on smaller-scale farms (Vergote *et al.*, 2020).

Several strategies have been explored to mitigate GHG emissions in dairy systems. S. Roques *et al.* (2024) reported that improving feed quality and digestibility, particularly by increasing forage digestibility, can enhance rumen fermentation efficiency and reduce CH_4 emissions per unit of milk produced by influencing volatile fatty acid profiles and rumen passage rates. The same authors also noted that dietary interventions with feed additives, such as 3-nitrooxypropanol (3-NOP), have consistently demonstrated CH_4-reducing effects in dairy cattle. In the longer term, S. Roques *et al.* identified genetic selection for improved feed efficiency and lower CH_4 intensity traits as a promising mitigation approach, since genetic variation exists in CH_4 emission-related phenotypes and selection can progressively reduce emissions across generations. A.N. Hristov *et al.* (2022) further showed that dietary supplementation with lipids and tannin-containing feeds can alter rumen fermentation and suppress methanogenesis.

Land use is another important factor influencing the environmental sustainability of dairy production because dairy farming requires substantial land both for grazing and for the cultivation of feed crops such as maize, grass silage and other forage plants. The expansion of feed crop production and pasture often leads to conversion of natural ecosystems to agricultural land, resulting in habitat loss, forest degradation and reductions in biodiversity, particularly where agricultural land expansion occurs in highly biodiverse regions (Salari *et al.*, 2025). Agricultural land use, including pasture and cropland for livestock feed, is a dominant driver of terrestrial biodiversity loss globally, as the conversion of forests and other natural habitats to agriculture significantly disrupts species' habitats and contributes to declines in species richness and ecosystem integrity. At the same time, pasture systems typically require more land per unit of milk than intensive systems, creating a trade-off between productivity and land occupation.

Intensive dairy systems often rely on imported feed such as soybean meal, a common high-protein ingredient in cattle rations that is predominantly sourced from major exporters like Brazil and Argentina. This reliance on imported soy shifts a substantial portion of the environmental impact of dairy production to regions where

soy cultivation has been linked with land-use change and deforestation, raising concerns about biodiversity loss and carbon emissions associated with agricultural expansion. Soybean production for livestock feed drives agricultural land expansion in South America, contributing to habitat conversion and ecosystem pressures far from the consuming region, illustrating the global environmental consequences of intensive livestock systems that depend on international feed supply chains.

Pasture-based dairy systems, when managed sustainably, may offer certain environmental benefits because well-maintained grasslands can support soil carbon storage, enhance biodiversity and contribute to ecosystem services such as nutrient cycling and habitat provision. Meta-analyse of grazing effects by J. Su *et al.* (2023) showed that moderate grazing can increase plant diversity and soil organic carbon content relative to ungrazed or poorly managed systems, indicating potential benefits for biodiversity and carbon sequestration. However, grazing impacts are context-dependent; higher grazing intensity and poor pasture management tend to degrade natural capital, reducing soil health, plant diversity and other supporting ecosystem services, underscoring the importance of appropriate pasture management to balance productivity with ecological protection (O'Grady *et al.*, 2024).

Water use is a key environmental concern in dairy production. While cattle need water for drinking and farm operations, most consumption is indirect, coming from irrigation of feed crops. C.D. Higham *et al.* (2024) showed that green and blue water used for forage and pasture growth represent the largest share of milk's water footprint, varying by region and climate, and dominating total freshwater use per unit of milk. Direct water use on the farm (for animal water consumption, cleaning and other service demands) represents a small fraction of the overall footprint compared with the water required for growing feed crops, making indirect water use via irrigation a major driver of dairy water demand and a central focus in efforts to improve sustainability.

In regions experiencing water scarcity, excessive agricultural water use can exert significant pressure on local freshwater resources, making improved water-use efficiency in dairy farming a key sustainability objective. Dairy water footprints are dominated by indirect consumption for irrigation of pastures and feed crops, and higher water demand in arid regions is linked to increased blue water use and associated scarcity impacts (Higham *et al.*, 2024). Practices such as efficient irrigation systems, water recycling on farms and improved water management technologies have been identified as effective ways to reduce the water footprint and enhance water-use efficiency in dairy production systems (Monteiro *et al.*, 2023).

Nutrient management is closely related to both water quality and soil health because dairy manure contains valuable nutrients such as nitrogen (N) and phosphorus (P) that can support crop growth when applied appropriately. E. Young *et al.* (2022) reported that excess or poorly managed manure application can substantially increase nitrogen and phosphorus loading in runoff, thereby contributing to water quality deterioration and the eutrophication of aquatic ecosystems. T.J. Van der Weerden *et al.* (2023) further noted that manure storage and land application are significant sources of ammonia (NH_3) and N_2O emissions. In particular, NH_3 volatilisation from manure contributes to air pollution and nitrogen deposition, whereas N_2O emissions from manure-amended soils represent an important source of greenhouse gas emissions. Effective nutrient management in dairy systems includes balanced fertilisation, improved feed formulation to reduce nutrient excretion, and integration of crop and livestock production to enhance recycling of manure nutrients. In addition, anaerobic digestion of dairy manure can capture CH_4 for energy production while producing a nutrient-rich digestate that can be used as a biofertiliser, potentially substituting synthetic fertilisers and supporting soil health and nutrient cycling when applied appropriately (Martín-Sanz-Garrido *et al.*, 2025).

Improving environmental sustainability in dairy milk production requires integrated approaches addressing GHG emissions, land use, water consumption, and nutrient management. Strategies such as enhanced feed efficiency, manure management, pasture-based systems, efficient irrigation, and anaerobic digestion can reduce environmental impacts while maintaining productivity. By combining improved farm management with technological innovation and sustainable resource use, dairy systems can lower their environmental footprint while continuing to supply safe and nutritious milk globally.

Animal welfare in sustainable dairy production

Animal welfare is increasingly recognised as a fundamental component of sustainable dairy production systems. Modern sustainability frameworks extend beyond environmental and economic performance to include ethical responsibilities, particularly the treatment of animals (Arvidsson Segerkvist *et al.*, 2020). Ensuring that dairy cattle are raised under conditions that support health, comfort, and the expression of natural behaviours is now considered essential for both productivity and system sustainability (AHAW *et al.*, 2023). Growing public awareness of animal welfare has significantly influenced consumer expectations, market demands, and policy development. Consumers increasingly prefer products derived from systems perceived as humane, prompting the adoption of welfare standards and transparent assessment methods (Linstädt *et al.*, 2024). Consequently, animal welfare is now widely embedded in sustainability indicators and agricultural policies, reinforcing its role as a key pillar of responsible and sustainable dairy farming (Pavanello *et al.*, 2024). Systematic review by M. Verdon *et al.* (2025)

of dairy cow welfare research show a growing number of studies addressing welfare domains such as health, environment and behaviour, reflecting increasing scientific and public interest.

In dairy production systems, animal welfare is influenced by multiple interrelated factors, including housing conditions, nutrition, health management, and the opportunity for animals to express natural behaviours. Adequate housing design, appropriate feeding strategies, and effective disease prevention are essential to maintaining both welfare and productivity in dairy cattle (AHAW *et al.*, 2023; Linstädt *et al.*, 2024). Sustainable dairy systems, therefore, aim to provide environments that minimise stress, reduce the incidence of disease, and support normal behavioural expression. Poor welfare conditions can result in significant ethical and economic consequences. Compromised welfare is associated with decreased milk yield, higher veterinary costs, and reduced longevity of animals within the herd, ultimately undermining farm sustainability. Consequently, improving animal welfare is not only a moral obligation but also a practical strategy to enhance efficiency, resilience, and long-term sustainability in dairy production systems.

Housing design plays a crucial role in determining the welfare of dairy cattle. Well-designed systems provide adequate space, comfortable resting areas, proper ventilation, and reliable access to clean water and feed, all of which are essential for maintaining health and productivity (AHAW *et al.*, 2023). Particular emphasis is placed on lying comfort, as dairy cows spend a substantial proportion of their time resting. The provision of well-bedded lying areas, using materials such as straw or sand, has been shown to improve cow comfort, reduce the risk of injuries and lameness, and support natural resting behaviour (Linstädt *et al.*, 2024). Adequate rest is closely linked to improved physiological functioning, including enhanced milk yield and better overall welfare outcomes. Conversely, poorly designed housing can restrict movement, increase stress, and predispose animals to disease, thereby negatively affecting both welfare and farm performance (Arvidsson Segerkvist *et al.*, 2020). Ensuring appropriate housing conditions is therefore a key component of sustainable dairy production systems.

Modern dairy housing systems often incorporate free-stall barns, which allow cows to move freely within designated areas and express more natural behaviours compared with more restrictive systems. These housing designs are intended to reduce stress, improve comfort, and support overall welfare (AHAW *et al.*, 2023). By enabling voluntary movement between feeding, resting, and social areas, free-stall systems contribute to better behavioural and physiological outcomes in dairy cattle. Proper flooring, adequate space, and effective ventilation are essential in dairy systems. They reduce lameness, competition, and stress, while maintaining temperature, humidity, and air quality to prevent heat stress. Together, these factors help to ensure hygiene, reduce disease risk, and enhance both animal welfare and productivity within sustainable dairy systems.

Access to pasture is widely associated with improved animal welfare in dairy systems. Grazing enables cows to express natural behaviours such as foraging, walking, and social interaction, which are important indicators of positive welfare. In addition, outdoor access has been linked to a lower incidence of certain health issues, particularly lameness, which is often associated with prolonged exposure to hard indoor flooring. Pasture-based systems need careful management to ensure welfare, providing adequate nutrition, protection from extreme weather, and proper grazing practices, including controlled stocking density and rotation, to prevent overgrazing and maintain pasture quality.

Maintaining good health is fundamental to ensuring high levels of animal welfare in dairy production systems. Dairy cattle are susceptible to several prevalent health disorders, including mastitis, lameness, metabolic issues and reproductive problems, each of which can cause pain and discomfort and impair well-being if not effectively managed (AHAW *et al.*, 2023). Mastitis is one of the most frequent and costly diseases in dairy herds, reducing milk yield and quality while increasing veterinary and replacement costs, and remains a leading cause of culling when recurrent or severe. Lameness, often stemming from hoof lesions or suboptimal flooring and housing conditions, is a major welfare concern due to its association with pain, reduced mobility and impaired natural behaviours (Thomsen *et al.*, 2023). Together, these health challenges not only compromise animal welfare but also lead to significant economic losses for farmers, underscoring the importance of proactive health management and welfare-focused practices in sustainable dairy systems. P.T. Thomsen *et al.* (2023) estimated mean lameness prevalence at around 23% in dairy herds.

Preventive health management is a critical component of sustainable dairy farming. Regular veterinary monitoring, vaccination programmes, and early detection of disease symptoms help maintain herd health and reduce reliance on therapeutic interventions (AHAW *et al.*, 2023). Maintaining good hygiene during milking, managing bedding effectively, and providing balanced nutrition are also essential measures to prevent common health problems such as mastitis, metabolic disorders, and lameness (Thomsen *et al.*, 2023). By prioritising preventive strategies, farmers can improve animal welfare, reduce economic losses from disease, and enhance productivity. Integrating these practices into routine farm management supports both ethical responsibilities and the long-term sustainability of dairy production systems.

Lameness is one of the most prevalent welfare issues in dairy cattle and is often linked to poor flooring

conditions, inadequate hoof care, or prolonged standing times (Garvey, 2022). Clinical lameness not only causes pain and reduced mobility but also negatively affects feeding behaviour and milk production, making its prevention essential for both welfare and productivity. M.B. Sadiq *et al*. (2021) showed that implementing regular hoof trimming as part of a comprehensive hoof health programme can significantly reduce the incidence of lameness and the prevalence of hoof lesions in dairy herds. Improvements to flooring surfaces and the provision of comfortable resting areas further reduce mechanical stress on the hooves and joints, thereby helping to minimise lameness risks. P.T. Thomsen *et al*. (2023) also emphasised that peri-partum metabolic disorders, such as ketosis and displaced abomasum, can alter cow behaviour and activity, which underscores the importance of systematic health monitoring and proper nutrition.

R. Han *et al*. (2022) identified longevity as an increasingly important indicator of both animal welfare and sustainability in dairy systems. They noted that dairy cows with longer productive lifespans contribute to improved system efficiency because fewer replacement animals are required, reducing the resources and environmental impacts associated with raising heifers. Prolonged productive life may also reflect better health and management practices that support animal welfare. G.M. Dallago *et al*. (2021) further reported that short cow longevity is often associated with increased involuntary culling due to health and reproductive problems, which can compromise welfare and increase production costs. Reducing herd turnover lowers the need for rearing replacement heifers, thereby decreasing feed, water and energy requirements and the associated greenhouse gas emissions per unit of milk produced. Longer productive lifespans can therefore enhance environmental performance as well as economic outcomes.

Several factors influence the longevity of dairy cows, including genetics, nutrition, health management, and housing conditions. Genetic selection that balances production with functional traits such as disease resilience, fertility and structural soundness can contribute to longer productive lifespans, although the genetic basis of longevity is complex and involves multiple correlated traits. Genetic analyses indicate that health traits such as resistance to locomotory and metabolic diseases are genetically associated with longevity, providing targets for breeding programmes aimed at enhancing durability and resilience (Hu *et al.*, 2024). In addition, good herd management practices that prioritise animal health and welfare, such as preventive health care, balanced nutrition and comfortable housing, can extend productive life and reduce involuntary culling due to disease or injury (Dallago *et al.*, 2021; Han *et al.*, 2022). By improving both genetic potential and management conditions, dairy systems can support longer cow longevity, enhancing sustainability and reducing resource use.

Ethical considerations surrounding livestock production have become increasingly prominent in discussions of sustainable agriculture. Many consumers express concern about how animals are raised and are willing to pay premiums for products from higher-welfare systems, reflecting a growing ethical dimension in food choice behaviour (Mata *et al.*, 2026). Public expectations around animal welfare have also driven interest in welfare certification schemes, which aim to provide transparent information about on-farm practices and allow consumers to identify products from farms meeting defined welfare standards (Chang & Chen, 2022).

Welfare labelling and voluntary certification schemes, such as Certified Humane and assured by an animal welfare charity such as The Royal Society for the Prevention of Cruelty to Animals, the RSCPA Assured scheme in the UK, provide market incentives for improved animal care (Tuyttens *et al.*, 2025). Effective welfare schemes rely on clear standards, strict audits, and informed consumers, driving on-farm improvements and encouraging adoption of welfare-focused practices through market influence and policy support. High welfare standards in dairy farming offer ethical and economic benefits, granting access to premium markets, boosting consumer trust, and promoting healthier, more productive animals, thereby improving efficiency and sustainability (Tuyttens *et al.*, 2025).

Animal welfare is a fundamental aspect of sustainable dairy production. High welfare standards also have economic and market benefits. Farms demonstrating strong welfare practices can access premium markets, build consumer trust, and reduce costs associated with disease and high herd turnover Certification schemes and welfare labelling provide incentives for producers to adopt these practices, encouraging transparency and aligning production with societal expectations. Integrating animal welfare into dairy systems is therefore essential for both ethical responsibility and the long-term sustainability of milk production.

Economic sustainability and farm viability

Economic sustainability is fundamental to dairy production, as profitability ensures long-term farm viability while supporting environmental stewardship and animal welfare. Efficient resource management, cost control, and productivity optimisation are essential to maintain competitiveness. Dairy farms must also respond to challenges such as market volatility, fluctuating milk prices, and rising input costs, which threaten financial stability (Savickienė & Galnaitytė, 2024). V. Fiorillo & B.M. Amico (2024) showed that economically resilient farms are more capable of adopting and sustaining environmentally beneficial practices, aligning financial and ecological goals.

Dairy farming operates within highly dynamic and competitive markets, where milk prices fluctuate in response to global and regional supply–demand

dynamics. According to OECD/FAO (2022) and OECD/FAO (2024) agricultural market projections, global dairy commodity prices are expected to remain volatile over the medium term, with demand growth increasingly concentrated in emerging economies while production costs continue to rise in established dairy-exporting regions; the 2024-2033 outlook also points to slower expected growth in global milk production compared with the 2022-2031 projections, reflecting tightening margins and resource constraints. Farmers also face variable costs for feed, energy, labour, and veterinary services, all of which influence profitability and long-term viability (Savickienė & Galnaitytė, 2024). Such volatility increases financial risk and uncertainty. Consequently, improving technical efficiency, optimising input use, and adopting cost-reduction strategies are essential for maintaining economic sustainability and resilience in dairy systems. Production costs and profitability vary widely between farms, which significantly influences farm-level economic.

One of the main drivers of economic sustainability is production efficiency, often measured by milk yield per cow or per unit of feed. Higher productivity enables fixed costs, such as housing and machinery, to be distributed across greater outputs, thereby improving profitability (Pavanello *et al.*, 2024). However, this must be balanced with broader sustainability objectives, as excessive intensification can increase environmental pressures, compromise animal welfare, and heighten long-term risks. R. Savickienė & A. Galnaitytė (2024) highlighted that optimising, rather than maximising, production is essential for sustaining both economic performance and overall system resilience. G. Salcedo *et al.* (2025) provided empirical support for this view in temperate Atlantic dairy systems, showing that farms pursuing sustainable intensification, through moderate increases in stocking density combined with improved nutritional management, achieved higher milk output without proportional increases in environmental burden. However, their findings also indicated that further intensification beyond this point resulted in diminishing economic and environmental returns.

Cost management plays a vital role in maintaining dairy farm viability, with feed representing a substantial proportion of total production expenses. Improving feed efficiency and optimising nutrition are therefore critical for controlling costs and sustaining profitability (Pavanello *et al.*, 2024). Approaches such as precision feeding, the use of agricultural by-products, and improved ration formulation can reduce feed costs while maintaining milk yield. In addition, enhancing energy and water use efficiency further lowers operational expenses, contributing to overall economic sustainability and reinforcing the resilience of dairy farming systems (Savickienė & Galnaitytė, 2024). Beyond cost control, milk quality parameters such as protein and fat content and somatic cell counts directly affect farm-gate prices under most milk-pricing systems, making quality management an integral component of dairy farm profitability alongside efficiency gains.

Market structures, incentives, and policy frameworks strongly influence economic sustainability. Certification schemes and eco-labelling for sustainable or high-welfare dairy products can allow farmers to access premium markets and secure higher returns, as consumers frequently show willingness to pay higher prices for sustainability-labelled attributes (e.g., organic, welfare, origin) in dairy and plant-based milk alternatives (Madududu *et al.*, 2024). Y. Zhan *et al.* (2025) also found that recognition of eco-labels, such as carbon or environmental labels, increases consumer willingness to pay premiums, reinforcing market incentives for sustainable dairy practices. Sustainability certification standards, covering environmental, welfare and social criteria, are increasingly used to differentiate dairy products, although their scope and uptake vary widely.

Government policies and subsidies play a key role in supporting sustainable dairy production by lowering financial barriers and encouraging the adoption of environmentally friendly practices. Subsidies, regulatory programmes, and financial and technical assistance are among the main mechanisms used by governments to incentivise sustainable agricultural initiatives, including manure management, renewable energy uptake, and pasture-based systems. Public extension services and training enhance farmer capacity to implement improved practices, while targeted financial assistance and low-interest loans can bolster long-term economic resilience and farm viability.

Economic sustainability in dairy farming requires resilience to external risks such as market volatility, climate variability, and disease outbreaks. Diversifying income through integrated crop-livestock systems, production of value-added dairy products, or participation in cooperatives can buffer farms against fluctuating milk prices. Additionally, insurance schemes and risk management tools protect against catastrophic events, enhancing the financial stability and long-term viability of dairy operations. Investments in herd health, housing infrastructure, and technology enhance productivity and animal welfare while reducing economic vulnerability. Maintaining healthy cows with longer productive lifespans lowers replacement costs, and improved housing or automated systems reduce labour requirements and operational risks. Such strategic investments strengthen farm efficiency and resilience, supporting long-term economic sustainability in dairy production.

Achieving economic sustainability in dairy farming goes beyond simply maximising profits. Sustainable systems require balancing economic, environmental, and social objectives. Practices such as improved manure management or pasture-based systems may incur higher upfront costs but can reduce long-term risks, enhance farm resilience, and enable access to

value-added markets. Likewise, investments in animal welfare support healthier, more productive cows, improving economic performance while meeting societal expectations for ethical farming (Fiorillo & Amico, 2024). C. Pavanello *et al.* (2024) highlights that economically resilient farms are better able to implement sustainable technologies, respond to market and climatic shocks, and align production with consumer and societal expectations.

Economic sustainability ensures that dairy farms remain viable over the long term, supporting rural livelihoods and the continued supply of milk as a critical food resource. Beyond the individual farm, a financially resilient dairy sector sustains rural employment, intergenerational farm succession, and the broader agri-food economy of dairy-producing regions. By integrating cost-effective management, production efficiency, risk mitigation, and market-oriented strategies, farms can maintain profitability while adopting environmentally and socially responsible practices. As global demand for dairy products continues to grow, the ability of farms to remain economically viable will become increasingly important for ensuring a stable and sustainable milk supply. Economically resilient farms are better able to implement sustainable technologies, respond to market and climatic shocks, and align production with consumer and societal expectations. Ultimately, economic viability cannot be treated in isolation: it is the foundation that enables farms to sustain the environmental and welfare-related improvements discussed throughout this review.

Innovations and strategies for sustainable dairy systems

Advancing the sustainability of cow milk production requires adopting innovative management practices, technologies, and system-level strategies that concurrently address environmental, economic, and animal welfare objectives. Digital and PLF technologies, such as sensors, automated milking, and data systems, enhance monitoring, productivity, and decision-making, promoting efficiency and sustainability on dairy farms (de Oliveira *et al.*, 2024). In addition, selective breeding and genomic tools can improve genetic potential for balanced production, fertility, and longevity, supporting resource efficiency and lowering emissions per unit of milk (Bell, 2024). PLF involves using technology to monitor, analyse, and manage individual animals or groups in real time. Tools such as sensors, automated milking systems, wearable devices, and data analytics allow farmers to track milk yield, feed intake, body condition, activity, and health status. By providing detailed, cow-level information, PLF supports early detection of health issues, optimisation of feeding strategies, and more efficient herd management, ultimately improving productivity, animal welfare, and economic sustainability in dairy systems.

Implementing PLF technologies can reduce feed waste, improve milk production efficiency, and enhance animal welfare by detecting discomfort or disease early. Additionally, PLF supports environmental sustainability by enabling precise nutrient management, which lowers N and P excretion and decreases GHG emissions associated with overfeeding. N. Liu *et al.* (2023) demonstrated that integrating PLF into dairy operations improves productivity while simultaneously promoting economic, environmental, and animal welfare objectives. Genetic selection is a long-term strategy to improve sustainability in dairy systems by incorporating traits beyond milk yield, such as feed efficiency, disease resistance, fertility, and longevity, into breeding goals. Breeding programmes that target lower enteric CH_4, along with efficiency, can cumulatively reduce emissions and resource use, enhancing both environmental and economic sustainability of dairy production (Richardson *et al.*, 2025).

Innovations in dairy nutrition play a central role in sustainable milk production by optimising rumen efficiency and mitigating enteric methane emissions. Diet manipulation and specific feed additives, such as fats, tannins, and methane-inhibiting compounds like 3-NOP, have been shown to reduce methane output while maintaining productivity (Hristov, 2024). Increasing forage digestibility and incorporating high-quality forages or by-products from other agricultural sectors can also lower CH_4 intensity per unit of milk and support circular resource use.

Precision feeding strategies, which customise nutrient supply for individual cows or specific production stages, enhance feed efficiency and reduce nutrient excretion into the environment. Optimising diet composition through precision feeding improves rumen function, animal health, welfare, and milk quality, thereby supporting both economic performance and ethical standards in dairy farming. A.N. Hristov (2024) demonstrated that these targeted nutritional approaches contribute significantly to the sustainability of dairy systems by aligning productivity, environmental stewardship, and animal welfare goals. System-level innovations, such as integrated crop-livestock systems and agroecological approaches, enhance sustainability by combining ecological principles with productive farming. Integrating crop and livestock production enables the recycling of nutrients and organic matter, reduces dependence on external inputs, and promotes soil health. Dairy manure can be used as a fertiliser for feed crops, creating a closed nutrient loop that benefits both crop and livestock production and contributes to agricultural sustainability.

Agroecological strategies emphasise biodiversity, diversified forage species, and pasture-based systems that provide ecosystem services such as carbon sequestration, soil conservation, and habitat support. For example, silvopastoral systems that combine trees, pastures and livestock enhance nutrient cycling, soil fertility, biodiversity and carbon storage compared with

simpler systems, thereby reducing reliance on intensive, input-heavy practices while supporting ecosystem functions and sustainability (de Macêdo Carvalho *et al.*, 2024). Renewable energy technologies such as anaerobic digestion, solar panels, and biogas production contribute to sustainable dairy systems by reducing dependence on fossil fuels and lowering GHG emissions. Anaerobic digestion of dairy manure produces biogas that can be used for heat and electricity, cutting CH_4 emissions from manure management and supplying renewable energy on-farm, thereby offering both environmental and economic advantages.

Circular economy principles in dairy systems encourage use of agricultural by-products as feed, efficient water recycling, and reduced waste generation. Creating closed-loop systems that maximise resource efficiency, from recovering nutrients in effluent to valorising dairy co-products like whey, can reduce environmental impact while maintaining productivity and animal welfare. Such circular approaches are increasingly recognised as essential for sustainable dairy supply chains (Terpou *et al.*, 2025).

Despite the demonstrated benefits, the widespread adoption of innovative strategies faces several challenges, including high initial investment costs, technical complexity, and the need for farmer training. Evidence shows that increased costs and lack of supportive networks or advisory services are significant barriers limiting the uptake of sustainable practices on farms. Policy support, extension services, and market incentives are therefore critical to facilitate adoption and improve sustainable agricultural outcomes. Innovations and strategic approaches in dairy farming provide multiple pathways to enhance sustainability. PLF technologies, genetic improvement, nutritional optimisation, integrated farming systems, and renewable energy applications collectively contribute to creating resilient, resource-efficient, and ethically responsible dairy systems.

Strategies, trade-offs, and future perspectives

Sustainable cow milk production is often presented as a matter of improving efficiency or adopting new technologies, yet the evidence suggests a more complex reality. In practice, dairy systems operate under competing pressures: increasing production to meet demand, reducing environmental impacts, and responding to societal expectations around animal welfare. These goals do not fully align, and much of the challenge lies in managing the tensions between them rather than resolving them. Table 2 summarises the effects of main strategies in dairy production across the key environmental, economic, and animal welfare sustainability dimensions, highlighting potential synergies and trade-offs.

***Table 2**. Effects of main strategies in dairy production across the three key sustainability dimensions, highlighting potential synergies and trade-offs*

Strategy	Environmental Impact	Economic Impact	Animal Welfare Impact
Improved feed efficiency	Reduces CH_4 emissions and resource use per unit of milk	Lowers feed costs, improves productivity	Generally neutral to positive
PLF	Reduces nutrient losses and optimises resource use	Improves efficiency and labour productivity	Enhances health monitoring and early disease detection
Genetic selection (efficiency, longevity)	Long-term reduction in emissions intensity	Increases productivity and lifetime performance	Improves longevity and resilience
Manure management	Reduces CH_4 and N_2O emissions, enables nutrient recycling	Provides renewable energy and additional income streams	Neutral
Pasture-based systems	Can enhance biodiversity and ecosystem services, but may increase land use	Variable profitability depending on system	Improves behavioural welfare and natural expression
Use of agricultural by-products	Reduces demand for feed crops and resource use	Lowers feed costs and improves efficiency	Neutral

***Source:** compiled by the author*

Improving efficiency is frequently highlighted as a key pathway to sustainability. Strategies such as optimising feed use, improving genetics, and increasing milk yield per cow can reduce emissions per unit of output. While this is an important contribution, it does not necessarily translate into lower overall environmental impact. In systems where production continues to expand, efficiency gains may be offset by higher total output. This suggests that efficiency should be viewed as a necessary but insufficient condition for sustainability, rather than a complete solution. The contrast between intensive and pasture-based systems illustrates the difficulty of defining a single "optimal" model. Intensive systems tend to achieve higher productivity and lower emissions per unit of milk, but they often depend on external inputs and may raise concerns regarding animal welfare and indirect environmental effects. Pasture-based systems, in contrast, are commonly associated with improved welfare and ecosystem services, yet they generally require more land and may show lower production efficiency. These differences highlight that sustainability outcomes are highly context-dependent and that system performance cannot be assessed using a single metric.

Animal welfare further complicates this picture. It is increasingly recognised as a core component of

sustainability, but it does not always improve in parallel with environmental or economic performance. In some cases, management practices that enhance productivity can place additional pressure on animals, while higher-welfare systems may involve trade-offs in efficiency or cost. This indicates that welfare should be treated as an independent objective within sustainability frameworks, requiring specific attention rather than being assumed as a secondary benefit of other improvements. Economic viability remains a decisive factor in determining whether sustainable practices are adopted. Many of the strategies identified in the literature, including precision technologies, improved housing, and renewable energy systems, require substantial investment (AHAW *et al.*, 2023; Kaur *et al.*, 2023; Greene *et al.*, 2024). For farmers operating under variable milk prices and rising input costs, the adoption of such measures is not always feasible. This gap between technical potential and practical implementation is a recurring issue, suggesting that economic conditions and policy support are central to any meaningful transition toward sustainability.

Technological innovation is often presented as a major driver of progress in dairy systems. PLF, genetic improvement, and advanced feeding strategies offer clear advantages in monitoring, efficiency, and management. However, their impact should not be overstated. Technology can improve the performance of existing systems, but it does not eliminate the underlying trade-offs between productivity, environmental impact, and welfare. In some cases, it may even reinforce existing production models rather than encouraging more fundamental changes. Rather than focusing on identifying a single best approach, a more realistic objective is to improve the balance between environmental, economic, and welfare outcomes within existing systems. This involves recognising trade-offs, prioritising context-appropriate strategies, and integrating multiple approaches in a coordinated way. Progress is therefore likely to depend less on individual innovations and more on how effectively they are combined and adapted in practice.

Sustainable cow milk production is a complex and multi-dimensional horizon, requiring the integration of environmental, economic, and social considerations. Despite advances in management practices, technology, and policy frameworks, several challenges continue to affect the adoption and effectiveness of sustainable dairy systems. Additionally, recognising research limitations is critical for guiding future studies and evidence-based decision-making. A central challenge in dairy systems is balancing high productivity with environmental and social sustainability. Intensive production can increase milk yield per cow and reduce per-unit costs, but often results in higher greenhouse gas emissions, nutrient surpluses, and potential welfare concerns. Conversely, low-input or pasture-based systems may enhance biodiversity, animal welfare, and ecosystem services but can reduce productivity per hectare and require more land. Effective strategies must consider local conditions, resource availability, and farm-scale contexts to manage these trade-offs.

Climate variability and extreme weather events pose both direct and indirect threats to sustainable dairy production. Heat stress, drought, and altered rainfall patterns can affect forage availability, water resources, and animal health, reducing milk yield and herd resilience. Additionally, dairy farming contributes to climate change through CH_4 and NO_2 emissions, creating a feedback loop that necessitates both mitigation and adaptation strategies. Economic viability remains a major barrier to implementing sustainable practices. High initial costs for precision technologies, renewable energy, or improved housing can limit adoption, particularly for small-scale farms. Market volatility, fluctuating milk prices, and limited access to premium markets for sustainably produced milk reduce incentives for change. Financial support mechanisms, subsidies, and access to markets are essential to encourage investment in sustainable solutions. Fragmented or inconsistent policy frameworks can hinder the adoption of sustainable practices. Integrated policies that simultaneously address environmental impact, animal welfare, and economic viability are rare, making it difficult for farmers to align their management with sustainability goals. Clear, consistent, and incentivised regulatory frameworks are essential to accelerate the transition to sustainable dairy systems.

CONCLUSIONS

This study showed that sustainable cow milk production is a multidimensional issue that depends on the balanced integration of environmental, economic, and animal welfare objectives. It was found that dairy systems contribute important benefits to food security, rural livelihoods, and the supply of high-quality animal protein, but the analysis also showed that these benefits are accompanied by relevant sustainability pressures. In particular, cow milk production was associated with environmental impacts such as greenhouse gas emissions, especially methane and nitrous oxide, as well as water use, land use, nutrient losses, biodiversity decline, nutrient pollution, water scarcity, and land-use pressure. These findings confirm that environmental sustainability remains one of the central challenges for the dairy sector.

The analysis also showed that economic sustainability is essential for the adoption of improved production practices. Profitability, production efficiency, input costs, and farm resilience were identified as key dimensions influencing the capacity of dairy farms to implement more sustainable strategies. It was found that price volatility, rising feed and energy costs, and financial barriers to innovation can limit the transition towards more efficient and environmentally responsible

systems. Therefore, economic viability should not be treated as separate from sustainability, but as a necessary condition for farmers to invest in new technologies, improved management, and long-term adaptation.

Animal welfare was also identified as a central component of sustainable dairy farming. The study showed that animal health, behaviour, longevity, housing conditions, and societal acceptance are closely linked to both productivity and ethical responsibility. It was found that problems such as lameness, mastitis, inadequate housing, and broader ethical concerns remain major barriers to achieving sustainable milk production. These results indicate that improving animal welfare can support better health, longer productive life, improved efficiency, and stronger consumer trust.

Altogether, the findings show that no single solution is sufficient to ensure sustainable cow milk production. Instead, sustainability depends on combining technological, nutritional, genetic, managerial, economic, and welfare-based strategies within context-specific production systems. Precision livestock farming, automated monitoring, data analytics, selective breeding and genetic improvement, optimised nutrition, methane-reducing diets, circular feeding systems, renewable energy, nutrient recycling, agroecological approaches, and crop-livestock integration were all identified as relevant tools. However, the study showed that their effectiveness depends on practical implementation, farm resources, market conditions, policy support, and consumer expectations.

Future research should focus on integrating these tools into coherent, multi-dimensional frameworks that address environmental, economic, and social objectives simultaneously, rather than treating them as isolated interventions. Further studies should also examine how market and consumer influence, including demand for sustainable and high-welfare dairy products, labelling, certification schemes, and premium pricing, can support adoption at farm level. Collaborative research involving farmers, researchers, policymakers, and industry stakeholders will be essential to develop context-specific solutions that balance productivity, environmental stewardship, animal welfare, and social responsibility.

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Інтеграція екологічних, економічних та соціальних аспектів у сталий розвиток молочного тваринництва: огляд літератури

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Анотація. Стале виробництво коров'ячого молока має вирішальне значення для глобальної продовольчої безпеки, засобів до існування сільського населення та харчування людей, проте воно пов'язане з екологічними, економічними та етичними викликами. Системи молочного тваринництва суттєво впливають на викиди парникових газів, використання води та землі, втрати поживних речовин та біорізноманіття, а також визначають добробут тварин і прибутковість господарств. Мета цього огляду полягала в тому, щоб дослідити, як захист навколишнього середовища, економічна доцільність, ефективне використання ресурсів та добробут тварин інтегровані в сталі системи молочного тваринництва. Було проведено структурований описовий огляд новітньої наукової літератури та узагальнено дані щодо викидів парникових газів, використання землі та води, управління поживними речовинами, здоров'я тварин, умов утримання, прибутковості господарств, точного тваринництва, генетичного вдосконалення, харчування, стратегій циркулярної економіки та політичної підтримки. Огляд показав, що стале молочне виробництво вимагає збалансованих дій у екологічному, економічному та соціальному вимірах, оскільки покращення в одній сфері часто призводить до компромісів в іншій. Вплив на навколишнє середовище досліджувався через такі стратегії, як підвищення ефективності годівлі, раціони, що зменшують викиди метану, управління гноєм, пасовищні системи, раціональне використання води, рециркуляція поживних речовин, використання відновлюваних джерел енергії та інтегроване рослинництво й тваринництво. Питання добробуту тварин було проаналізовано як центральний компонент сталого розвитку, а належні умови утримання, доступ до пасовищ, профілактична ветеринарна допомога, зменшення випадків кульгавості та маститу, подовження продуктивного віку тварин та сертифікація добробуту були визначені як фактори, що сприяють як етичній відповідальності, так і підвищенню ефективності господарств. Економічну стійкість було визначено як необхідну передумову для впровадження стійких практик, оскільки ефективність виробництва, контроль витрат, ринкові стимули, політична підтримка та управління ризиками визначають, чи зможуть фермери зберегти прибутковість, одночасно покращуючи екологічні показники та показники добробуту тварин. Ці результати можуть бути використані молочними фермерами, консультантами, дослідниками, політиками, органами сертифікації та зацікавленими сторонами галузі для розробки, оцінки та просування більш стійких, ефективних та етично відповідальних систем виробництва молочної продукції

Ключові слова: агроекологія; циркулярна економіка; ефективність використання кормів; точне тваринництво; ефективне використання ресурсів

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Background concentrations and remediation strategies for heavy metals in soil ecosystems

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Abstract. The relevance of the present study is related to the growing anthropogenic pressure on Ukraine's land resources. This pressure has been further intensified by the consequences of Russia's full-scale war against Ukraine, which has continued since 2022. The destruction of industrial infrastructure and the extensive use of ammunition became the reasons of the uncontrolled accumulation of toxic elements in the soil profile. The purpose of the study was to systematise and summarise scientific data on the natural content of barium, zirconium, strontium, lead, arsenic, zinc, copper, and nickel in the Earth's crust and soil ecosystems. The study also examined existing strategies for the remediation of contaminated soils. To achieve this aim, a critical analysis and systematisation of scientific literature were carried out within the framework of the research. The study summarised data on regional background concentrations of heavy metals and identified critical determinants, which influence the mobility and bioavailability in the soil-plant system. These factors include pH level, organic matter content and the adsorption capacity of soil. The analysis also revealed gaps in Ukrainian legislation concerning the regulation of several studied metals in agricultural products and animal feed. This points out the need to improve the existing regulatory framework. Given the international experience, several effective hyperaccumulator plants for soil clean-up were defined. These plants encompassed industrial hemp for the phytoextraction of lead and nickel, sunflower and *Cortaderia nitida* for zinc, Indian mustard for barium and nickel, as well as specific aquatic plants such as cattail and papyrus. The findings showed that the use of local wild-growing species adapted to particular ecological niches may provide a basis for highly effective and biologically safe strategies for the reclamation of degraded land. The practical value of the study lies in its justification of phytoremediation as one of the most cost-effective and environmentally neutral methods for restoring damaged areas

Keywords: geochemical background; bioavailability; food security; hyperaccumulators; phytostabilisation; phytoextraction; fertility restoration

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INTRODUCTION

The accumulation of large amounts of pollutants in soils, including heavy metals, became unavoidable (Datsko *et al.*, 2024). It is because of increasing anthropogenic pressure, especially amid Russia's invasion of Ukraine and intensive industrialisation The problem is particularly acute in regions affected by hostilities. Destruction of industrial facilities, the use of military equipment and the deployment of ammunition lead to the large-scale release of toxic elements into the environment. Once accumulated in the soil profile, these elements alter its physicochemical properties, suppress soil microflora and enter food chains. It is necessary to define the natural geochemical background of metals clearly for an accurate assessment of technogenic pollution and the selection of appropriate clean-up strategies (Lopushniak *et al.*, 2022).

Ukrainian and international researchers widely study the monitoring of soil ecosystem degradation and the determination of background elemental concentrations. O. Tonkha *et al.* (2025) carried out a comprehensive assessment of soil contamination levels in southern Ukrainian regions directly affected by hostilities, focusing on southern low-humus chernozems. The study recorded substantial deviations from environmental standards. In particular, the concentration coefficient for copper ranged from 8.2 to 81.19. In affected areas containing fragments of molten metal, the individual ecological risk for cadmium rose to 1,228, while the total risk index reached 1,805. V. Zatserkovnyi *et al.* (2025) proposed a different approach to solving agrochemical problems through automation. The authors developed an information technology for precision agriculture aimed at improving the monitoring of agricultural land conditions.

International experience in determining the natural content of elements shows considerable variation in regional approaches. According to M.R. Alfaro *et al.* (2015), an assessment of the geochemical background in Cuba found that natural nickel and chromium levels in local soils were substantially higher than global averages. This was linked to the specific composition of parent rocks. The reference soil quality values developed by the authors reached 170 mg/kg for nickel and 153 mg/kg for chromium, indicating pronounced natural geochemical enrichment. Meanwhile, the analysis of fractional composition showed low bioavailability of copper, nickel, chromium, antimony, and arsenic. This reduces the risk of the intensive transfer into plant products. Y. Sun *et al.* (2019), in turn, conducted a systematic review of the evolution of soil quality standards in China and compared these standards with regulatory approaches in the United Kingdom. The authors underlined the importance of background differentiation. The researchers noted that China's first environmental soil quality standards, approved in 1995, applied uniform limit values for eight heavy metals across the entire country. Such an approach did not reflect geographical heterogeneity, soil type diversity or integrated environmental factors. As a result, individual provinces, including Hunan, later had to develop the pragmatic remediation targets. A major step in the evolution of the regulatory framework came in 2018, when updated standards replaced the previous system. The new framework introduced a two-level assessment model based on environmental screening values and risk intervention values. These modern limits rely on human health risk assessment procedures, vary depending on pH and clearly distinguish between land-use categories, including agricultural land and construction land.

Despite the large amount of experimental data on pollution levels, current scientific literature still lacks an integrated systematisation of methods for differentiating the natural geochemical background and assessing the bioavailability of elements. This gap is especially noticeable for territories exposed to combined military and industrial pressure. The purpose of the present article was to summarise global scientific approaches to establishing reference values for heavy metal content in the Earth's crust and soils. The study also aimed to provide a critical analysis of existing remediation strategies for agroecosystems. Analysis, critical synthesis and systematisation of scientific sources and current regulatory documents underlay the methodology of the present review. The work was performed in several consecutive stages. At the first stage, a targeted search for relevant materials was conducted in leading international and national scientometric databases, including Scopus, Web of Science and Google Scholar. The search used combinations of keywords such as "geochemical background concentrations", "natural metal content in soil", "heavy metal bioavailability", "soil remediation" and "soil and military actions" in Ukrainian and English. Clear source selection criteria were applied to create an objective sample. The analysis comprised only peer-reviewed studies published mainly in 2020-2025. Non-peer-reviewed publications, articles outside the research topic and outdated monitoring data were excluded. The collected information was structured by several thematic areas at the stage of critical analysis and synthesis. These areas encompassed sources of toxicant input, methods for assessing total metal content, biological availability within the "soil-plant" chain, and the ecological and economic effectiveness of physicochemical and biological remediation methods. A separate analytical component of the study was the systematic examination of the provisions of Order of the Ministry of Health of Ukraine No. 368 (2013). The final comparative analysis, which compared international data with national regulatory instruments, made it possible to summarise existing approaches, identify research gaps in the study of poorly investigated element migration and justify optimal strategies for land remediation.

Natural content and comparative geochemical analysis of heavy metals in soil ecosystems

Evaluating changes in the elemental composition of soils under anthropogenic pollution requires a clear distinction between natural elemental fractions and technogenic inputs. P. Madejón (2013) showed that the natural content of barium in the Earth's crust varied considerably, ranging from 425 to 668 mg/kg. In spite of playing no major role in the physiological development of plants, the distribution and accumulation of the above element deserve detailed attention. Barium enters plant organisms mainly from natural sources. This can be explained with the fact that chemical analysis of fertilisers confirmed the absence of high concentrations of this metal in industrial fertilisers.

D.T. Lamb *et al*. (2013) and L.K. Wang *et al*. (2018) described the mechanism of bioaccumulation in detail. In line with findings provided by aforementioned authors, barium was actively absorbed by the root system and then transported to assimilatory organs. However, its translocation was less efficient than the translocation of potassium. Plant residues decomposed. This process formed a specific geochemical cycle after this. This cycle enriched the upper soil horizons. L.K. Choudhary & A. Kumar (2024) reported that the biological effect of barium had a dual, dose-dependent character. It sometimes took part in certain metabolic reactions at very low concentrations. It acted as a dangerous toxicant at elevated levels, especially above 500 mg/kg. It disrupted nutrient uptake, slowed the development of roots and above-ground organs, and induced intense oxidative stress in plant cells. L.K. Choudhary & A. Kumar (2025) confirmed this assumption to the full extent in later research. The effects of barium were clearly differentiated using wheat as an example. The authors proved that low barium doses, up to 10 μg/g, had a promoting effect. Such doses stimulated chlorophyll accumulation and biomass growth. Critical concentrations, from 100 to 1000 μg/g, produced acute toxicity. The above-mentioned concentrations caused a sharp reduction in root length, a decrease in leaf surface area and a fall in overall seed productivity by more than 40%.

Unlike barium, zirconium is relatively more widespread in the lithosphere. Nevertheless, its biological role for phytocoenoses remains minimal. Pursuant to S. Ghosh *et al*. (1992), the average zirconium content in the lithosphere is around 300 mg/kg. Its concentration in soils ranges from 32 to 850 mg/kg. T.A. Hayes and M.E. Kassner (2006), M. Shahid *et al*. (2013), found that zirconium shows low mobility in the natural environment. This is due to its intense adsorption on solid surfaces of the soil absorption complex. The consequence is that the element accumulates mainly in the underground biomass of plants. The scientific debate on zirconium phytotoxicity remained open. A. Hbika *et al*. (2025) recorded a negative effect of zirconium on certain metabolic processes, but these results were isolated and required further verification. However, the almost complete immobility of zirconium and its resistance to weathering represent its main value in modern geochemical studies. M. Chen *et al*. (2024) demonstrated that zirconium serves as an ideal natural marker, or reference element because of its stability. Comparing the concentrations of mobile toxicants with the content of immobile zirconium enables researchers to calculate soil enrichment factors accurately. This is crucial for environmental monitoring, since it makes it possible to distinguish the natural lithogenic background of soil from artificial anthropogenic pollution, including pollution of military origin. I. Martínez-del-Pozo *et al*. (2026) supported further the unique status of zirconium as a reference element. The authors showed that zirconium demonstrated the highest measurement stability and accuracy among all trace elements during large-scale assessment of geochemical background using portable X-ray fluorescence analysers. This metal is strongly related to parent rock and does not depend on external factors, its spatial distribution acts as a reliable indicator. In field conditions, this marker helps define the natural boundaries of soil layers quickly and separate these layers from areas of artificial technogenic or military contamination.

A comparative analysis of alkaline earth metal distribution indicates the high migration capacity of strontium. In conformity with M.J. Chowdhury & R. Blust (2011), strontium accounts for around 0.037% of the Earth's crust. Its vertical migration rate increased substantially under conditions of higher moisture. The authors pointed out that humic substances in the upper horizons influenced the behaviour of this metal in two ways. On the one hand, these substances stimulated the formation of mobile organomineral complexes. Conversely, the substances bound strontium and prevented its leaching from the soil profile under certain conditions. Artificial application of calcium fertilisers or soil liming is an effective way to reduce strontium toxicity in agroecosystems due to this similarity. Saturating the soil solution with calcium blocks passive strontium uptake by the root system through ion antagonism (Gupta *et al*., 2017). Modern plant physiology also revealed the ability of strontium to act as an effective protective barrier against other, more dangerous toxicants. J. Liu *et al*. (2023) underscored that the presence of strontium in the environment can substantially reduce the uptake of highly toxic cadmium by the root system. Due to antagonism between these elements, strontium helps plants maintain stable chlorophyll levels, activates intracellular antioxidant defence and reduces biomass growth inhibition in areas contaminated by several elements.

Lead and arsenic pose the highest level of environmental danger and agronomic significance among the analysed elements. Military and industrial emissions exert influence over the background concentrations of these elements. E. Steinnes (2013) and S.M. Mousavi *et*

al. (2022) found that lead exists in soil systems as fractions with different degrees of mobility. The authors stressed that water-soluble anions, including nitrates and acetates, created the greatest threat to agroecosystem stability. These compounds increased lead mobility and raised the risk of its migration into groundwater. H. Cui *et al*. (2024) made a significant contribution to understanding lead dynamics in surface horizons. The authors studied metal mobilisation under conditions of intense atmospheric deposition. The researchers identified a critical scientific contradiction, which implies that new atmospheric inputs of lead are much more dangerous for the environment because 42.0-89.5% of the total lead in atmospheric deposits occurs in bioavailable and mobile forms. The same study experimentally showed that continuous atmospheric input of fresh lead can completely neutralise or substantially weaken the fixing effect of widely used chemical amendments such as lime. Newly deposited metal fractions rapidly increase mobile pools of the element in the upper 0-5 cm layer of the soil profile. Within the framework of the molecular level, the critical danger of lead entering plant tissues lies in the development of severe oxidative stress. N. Kumar & A.K. Jha (2024) noted that lead accumulation in cells induces excessive formation of reactive oxygen species. These compounds destroy the lipid layer of cell membranes and damage chloroplast structure. Lead causes irreversible disruption of the photosynthetic apparatus of crops by blocking intracellular antioxidant enzymes. This appears visually as inhibited biomass growth and reduced overall agroecosystem productivity. Arsenic contamination is similarly complex because of its isomorphic similarity to phosphorus. E. Moreno-Jiménez *et al*. (2012) and M. Aide *et al*. (2016) showed that typical natural arsenic content in soils ranged from 5 to 7.5 mg/kg. In ammunition disposal zones, however, arsenic oxides quickly transformed into toxic salts, namely arsenates and arsenites. This inhibited plant cellular respiration through competitive replacement of phosphate ions. The particular danger of arsenic for agroecosystems lies in its specific mechanism of entry into plant tissues. D. Sinha *et al*. (2023) described this process in detail. In the form of arsenate, this metalloid chemically imitates phosphate ions, so the root system passively absorbs it through nutrient channels. Inside the cell, arsenic replaces phosphorus in ATP molecules. This blocks energy metabolism, damages chloroplast cellular structure and slows photosynthesis. Most of the metalloid is usually deposited in the roots. However, more mobile pools can move into above-ground biomass through aquaporin proteins. This causes deep toxic stress and marked inhibition of crop development.

Copper and zinc have similar geochemical characteristics. Both elements are essential trace elements, yet copper and zinc become toxic when background levels are exceeded. Pursuant to K. Oorts (2013), copper concentration in the lithosphere was around 60 mg/kg, while its accumulation in the arable layer occurred extremely slowly. Precise monitoring of copper concentrations is essential because the boundary between copper as a micronutrient and copper as a dangerous toxicant is very narrow. Copper bioavailability depends strongly on environmental acidity because the ionic form, Cu^{2+}, dominates in acidic soils. In response to such contamination, plants change the composition of root exudates and release phenolic compounds to bind the metal directly in the rhizosphere. Meanwhile, excess copper acts as an antagonist of mineral nutrition and strongly blocks plant uptake of phosphorus, calcium, and manganese (Trentin *et al.*, 2022). F.J.R. Cruz *et al*. (2022) noted that the physiological norm of copper content for higher plants ranges from 2 to 20 mg/kg of dry matter. Exceeding this threshold triggers a cascade of biochemical disturbances. These disturbances damage iron-copper clusters in cells, block redox reactions and inhibit biomass growth. J. Mertens and E. Smolders (2013), together with C. Noulas *et al*. (2018), showed that the background content of zinc usually ranged from 10 to 100 mg/kg and depended strongly on the genesis of the parent rock. Excess zinc presents a serious threat because it is more mobile and bioavailable in the soil solution than many other heavy metals. H. Kaur *et al*. (2024) noted that critical zinc concentrations cause phytotoxicity through destruction of chloroplast ultrastructure and induction of oxidative stress. This leads to chlorosis and leaf necrosis. Excessive uptake of the element also triggers secondary iron and magnesium deficiency because zinc competes strongly with these nutrients for common transport channels on cell membranes.

Nickel occupies a separate place among the analysed elements. A.V. Barker and D.J. Pilbeam (2006) pointed out that its average content in European soils ranged from 3 to 48 mg/kg. The authors showed that exceeding the critical nickel threshold of 100 mg/kg of dry matter caused profound disturbances in stomatal conductance, slowed seed germination and led to generalised chlorosis. J. Kováčik & M. Vydra (2024) summarised data showing that excess nickel provokes deep oxidative stress. It causes prolonged hydrogen peroxide accumulation, destruction of protein molecules and a decline in photosynthetic pigment content. Nevertheless, plant physiological response differs strongly between species. Dicotyledonous crops show much higher tolerance to nickel excess than monocotyledonous crops. Such crops respond to stress by intensively accumulating protective amino acids, particularly proline, as a mechanism of cellular adaptation.

To provide a comprehensive understanding of the risks posed by heavy metal accumulation in agroecosystems, the study summarised the circulation scheme (Fig. 1). Primary metal input caused by hostilities or industrial emissions undergoes transformation in the soil

profile. The mobility of elements is controlled by the physicochemical parameters of the environment. The next stage involves the transfer of bioavailable fractions through the root system into plant tissues, followed by the translocation to assimilatory organs. The greatest risk arises when these elements reach the final links of the food chain. In addition to it, the migration of chemical elements into plant tissues can negatively affect crop development and produce pronounced phytotoxic effects.

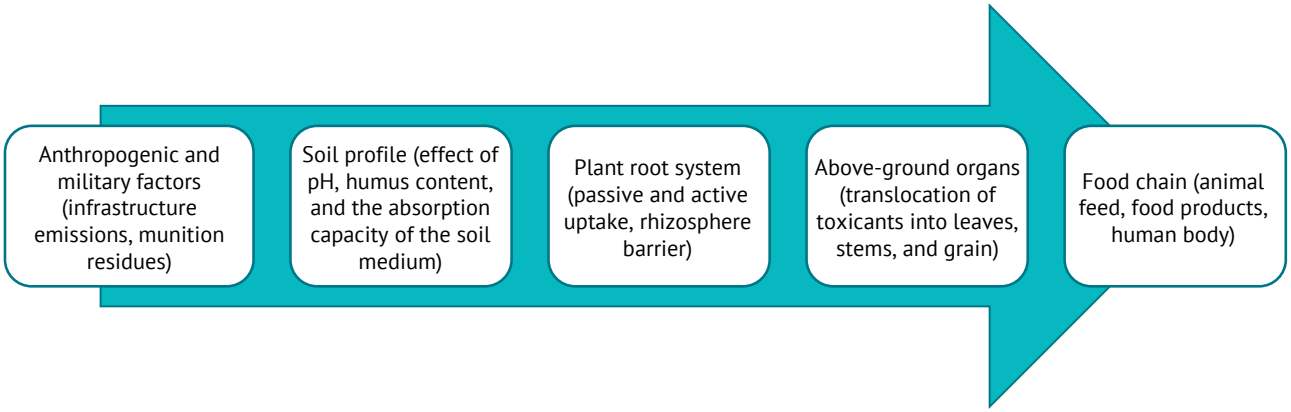

***Figure 1**. Scheme of heavy metal migration and transformation in the soil–plant–food chain system*
***Source:** developed by the autho*

The scheme above shows why the content of chemical elements in agricultural land requires careful control. Even components usually regarded as essential trace elements can cause damage when crops accumulate these components in excessive amounts. In such cases, these elements may harm the environment and enter the trophic chain.

Comparative analysis of phytoremediation strategies and regulatory control of heavy metal content

The practical implementation of soil clean-up measures directly relies on the specific features of national hygienic regulation. This system actually shows a certain imbalance. An analysis of the provisions of Order of the Ministry of Health of Ukraine No. 368 (2013) showed that the content of barium, zirconium, strontium, zinc, copper, and nickel in agricultural products is not currently regulated. This creates considerable environmental risks and calls for the development of preventive biological methods for land remediation. By contrast, strict legal limits exist for lead and arsenic. Pursuant to the same regulatory act, the maximum permissible lead content must not exceed 0.2 mg/kg in cereals and 0.10 mg/kg in vegetable crops. Arsenic content is also strictly limited in rice fields, with values ranging from 0.10 to 0.25 mg/kg depending on the intended use of the product.

The efficiency of metal removal through phytoremediation varies greatly. It depends on the biological characteristics of the plants used as remediators and on the selected strategy, whether phytostabilisation or phytoextraction. A comparison of findings from different authors makes it possible to define several key patterns in metal uptake. P.R.C.D.C. Ribeiro *et al.* (2018) compared in experiments the potential of *Typha domingensis* and *Cyperus papyrus* during the clean-up of model ecosystems contaminated with barium. The results revealed a clear difference in remediation mechanisms. Cattail concentrated most of the barium in its roots and followed a phytostabilisation strategy. Papyrus, in contrast, ensured intensive translocation of the metal into above-ground organs. Indian mustard (*Brassica juncea*) showed a similar phytoextraction potential for barium and nickel. According to V.M. Yatsenko *et al.* (2024), barium uptake by mustard during the flowering stage was statistically significant. N. Syam (2022) confirmed that the use of compost additives increased nickel accumulation in mustard plants to 425-455 mg/kg of dry weight by stimulating biomass growth.

Wild-growing and industrial crops proved effective for the remediation of land contaminated with strontium and lead. S. Ali *et al.* (2022) reported that cucumber showed features of a hyperaccumulator of the stable strontium isotope. In the context of lead remediation, G. Testa *et al.* (2023) substantiated the high resistance of industrial hemp varieties, including *Futura 75* and *Kc Dora*. E. Acuña *et al.* (2021) demonstrated that the shrub *Atriplex halimus* was suitable mainly for lead phytostabilisation. Even when citric and fulvic acids increased metal mobility, lead remained locked in the root system and did not move sufficiently into the above-ground biomass.

The remediation of soils contaminated with arsenic, zinc, and copper also depends on soil and climatic conditions, as well as on the ecological specificity of the plants used. T. Mehmood *et al.* (2021) showed that maize (*Zea mays* L.) effectively absorbed arsenic. The researchers also identified a critical pattern:

accumulation was much higher in sandy loam substrates than in heavy clay soils, where the metal was fixed by iron oxides. This conclusion corresponds with the findings of C. Picchi *et al*. (2022). The authors recorded a stable decline in hemp and mustard biomass under stress caused by arsenic contamination. During the remediation of zinc anomalies, E. Soares *et al*. (2021) confirmed the reliability of sunflower (*Helianthus annuus*), which immobilised zinc in the roots. Nevertheless, K.I. Paredes-Páliz *et al*. (2024) showed that the grass *Cortaderia nitida* actively transported zinc into the leaves. This made it more suitable for complete phytoextraction. J. Widmer and L. Norgrove (2023) recommended *Plantago lanceolata* L. and *Ricinus communis* L. for copper removal. These plants exceeded the accumulation threshold of 1,000 mg/kg. T. Luo *et al*. (2024) recorded similarly high results for rapeseed (*Brassica napus* L.). For a clearer comparison of the geochemical parameters and biological properties of the analysed elements, a summary comparative table is presented below.

Table 1. *Geochemical parameters, legal limits and promising remediator plants for heavy metal soil clean-up*

Chemical element	Background content in the Earth's crust, mg/kg	MPC in products according to Order of the Ministry of Health of Ukraine No. 368 (2013), mg/kg	Recommended remediator plants (type of remediation)
Barium (Ba)	425-668	Not regulated	*Cyperus papyrus* (extraction), *Brassica juncea* (extraction)
Zirconium (Zr)	~ 300	Not regulated	Limited data / accumulation in roots (stabilisation)
Strontium (Sr)	~ 370	Not regulated	*Carduus nutans* (extraction), *Cucumis sativus* (extraction)
Lead (Pb)	~ 14	0.10 (vegetables) – 0.20 (cereals)	*Cannabis sativa* (extraction), *Atriplex halimus* (stabilisation)
Arsenic (As)	1.5-5.0	0.10-0.25 (for rice)	*Zea mays* L. (extraction with addition of compost)
Zinc (Zn)	~ 70	Not regulated	*Cortaderia nitida* (extraction), *Helianthus annuus* (stabilisation)
Copper (Cu)	~ 60	Not regulated	*Brassica napus* L. (extraction), *Ricinus communis* L. (stabilisation)
Nickel (Ni)	~ 80	Not regulated	*Brassica juncea* (extraction with addition of compost)

Source: *developed by the author*

The above data show considerable heterogeneity in the geochemical parameters and regulatory approaches applied to the studied chemical elements. One issue deserves particular attention. Most metals, including Ba, Zr, Sr, Zn, Cu and Ni, are not currently regulated in plant products under Order of the Ministry of Health of Ukraine No. 368 (2013). This is the case despite the high background content in the Earth's crust or the potential ecotoxicity. Strict legal regulation applies only to lead and arsenic. The maximum levels of these elements are clearly differentiated by crop type, for instance from 0.10 mg/kg for vegetables to 0.25 mg/kg for rice. Differentiated biological methods were proposed for the clean-up of contaminated areas. These methods ranged from phytoextraction using hyperaccumulator plants to phytostabilisation with organic amendments or compost.

CONCLUSIONS

To summarise the review, increasing anthropogenic and military pressure on Ukraine's agroecosystems creates an urgent need for effective strategies to restore contaminated land. The study defined several gaps in the Ukrainian regulatory framework. In particular, it pointed to the need to develop comprehensive standards and maximum permissible concentrations for the elements analysed in this review in agricultural products and animal feed. The absence of clear regulation can create direct risks for food security and the national economy. The regional background concentrations of heavy metals in soils, identified through the literature analysis, indicate that the migration behaviour and toxicity of elements depend strongly on the "age" of contamination and the acidity of the environment.

The analysis showed that phytoremediation is the most promising, environmentally safe and economically justified method of land reclamation. Nevertheless, its effectiveness differs regarding the nature of the toxicant. For mobile and highly bioavailable elements, such as zinc and nickel, as well as for arsenic, which enters cells through phosphate transporters, active phytoextraction turns out to be the most effective strategy. This approach implies the removal of metalloids through the accumulation in above-ground biomass. Phytostabilisation is more appropriate for lead and copper. These elements bind strongly to soil organic matter. This strategy relies on the chemical immobilisation of elements in the rhizosphere through the activation of root exudates and the release of phenolic compounds. The analysis also showed that elemental antagonism

plays a pivotal role in reducing phytotoxicity. In particular, the presence of strontium can act as a protective barrier. It blocks root uptake of the more dangerous cadmium and stimulates cellular antioxidant defence. Further research should focus on a deeper study of the molecular mechanisms of oxidative stress in plants under conditions of combined military contamination. Special scientific value lies in the development of integrated technologies that combine the phytoremediation potential of industrial hemp, sunflower, and macrophytes with the application of environmentally safe amendments, which encompass biochar and limestone materials. Such approaches may optimise soil detoxification under changing climatic conditions.

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CONFLICT OF INTEREST

None.

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Фонові концентрації та стратегії ремедіації важких металів у ґрунтових екосистемах

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Анотація. Актуальність роботи зумовлена значним посиленням антропогенного тиску на земельні ресурси України, що доповнюється наслідками масштабних воєнних дій в рамках дій росії проти України, що тривають з 2022 року: руйнуванням промислової інфраструктури та інтенсивним застосуванням боєприпасів, що спричиняє неконтрольоване накопичення токсичних елементів у ґрунтовому профілі. Метою роботи була систематизація та узагальнення наукових даних щодо природного вмісту барію, цирконію, стронцію, свинцю, миш'яку, цинку, міді та нікелю в земній корі та ґрунтових екосистемах, а також аналіз існуючих стратегій ремедіації забруднених ґрунтів. Для досягнення мети було використано метод критичного аналізу та систематизації наукової літератури. У ході дослідження було систематизовано дані про регіональні фонові концентрації важких металів та ідентифіковано ключові чинники, що визначають їхню рухливість і біодоступність у системі «ґрунт-рослина», зокрема рівень pH, вміст органічної речовини та адсорбційну здатність ґрунту. Також було зафіксовано прогалини в українському законодавстві щодо нормування вмісту ряду досліджуваних металів у сільськогосподарській продукції та кормах, що вказує на потребу оптимізації нормативно-правової бази. На основі аналізу світового досвіду виділено ефективні рослини-гіперакумулятори для очищення ґрунтів: технічні коноплі (для фітоекстракції свинцю й нікелю), соняшник та *Cortaderia nitida* (для цинку), гірчиця сарептська (для барію та нікелю), а також специфічні водні рослини, як-от рогіз та папірус. Доведено, що використання місцевих дикорослих видів, адаптованих до конкретних екологічних ніш, може стати основою для високоефективних та біологічно безпечних стратегій рекультивації деградованих земель. Практичне значення роботи полягає в обґрунтуванні фіторемедіації як найбільш рентабельного та екологічно нейтрального методу відновлення територій

Ключові слова: геохімічний фон; біодоступність; продовольча безпека; гіперакумулятори; фітостабілізація; фітоестракція; відновлення родючості

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