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The Impact of Vertical Seedling Placement Non-Uniformity on Survival Performance and Agrocenosis Biopotential

The article addresses the problem of improving the precision of vegetable seedling transplantation as a key direction in the mechanization of vegetable production in Ukraine and the Republic of Moldova. It is substantiated that the systematic reduction of areas sown with vegetable crops is driven by water resource scarcity, degradation of irrigation networks, and an acute shortage of skilled labor, which necessitates a transition to full automation of the transplanting process.

It is demonstrated that deviations of the actual planting depth from the optimal value exceeding ±5–10 mm disrupt the physiological conditions of plant development: shallow planting causes temperature stress and dehydration, whereas excessively deep planting leads to root system asphyxia and root collar rot. A mathematical model of the dependence of seedling survival rate on depth deviation, based on a normal distribution, is proposed. It is established that the typical accuracy of mechanical (±10–15 mm) and hydraulic (±5–10 mm) stabilization systems is insufficient and reduces yield by 10–20%. The necessity of developing adaptive control systems ensuring an accuracy within ±1–2 mm is substantiated.
seedlings, planting depth, survival rate, mechanization, precision, adaptive control

Problem Statement. As agriculture constitutes a foundational pillar of the economies of Ukraine and the Republic of Moldova, optimizing crop cultivation technologies remains a critical imperative amid escalating global market competition. Concurrently, while vegetable production historically represents a primary agricultural sub-sector in both nations, recent decades have witnessed systemic stagnation. Driven by shifting market dynamics, shrinking trade channels, and associated socio-economic constraints, this decline has ultimately culminated in a substantial reduction of arable land dedicated to the region's staple vegetable crops [1, 2].

Analysis of Recent Research and Publications. In Moldova, the area for growing vegetables has decreased threefold [3]. Climate-induced challenges represent a pivotal factor driving down regional vegetable yields, rendering un-irrigated cultivation financially unviable. The systemic shortage of water resources, compounded by inadequate technological modernization of irrigation networks, has forced a dramatic contraction of sown areas. This domestic supply deficit has, in turn, heightened regional import dependence for staple vegetable commodities [1, 3, 4]. However, this led to an increase in the area under other agricultural crops such as wheat, corn and sunflower, the products of which are well exported, since as a result of improvements in the production technology of these crops and technical means, their yields have increased significantly [5, 6].

Total output yields are further constrained by systemic deficiencies inherent to current vegetable crop cultivation methodologies. These outdated agro-technological frameworks impede the comprehensive mechanization of labor-intensive operational phases, most notably precision seeding and automated seedling transplantation [1, 7, 8].

Within the scope of vegetable cultivation, seedling transplantation represents one of the most critical and labor-intensive operational phases. This technical challenge is currently exacerbated by an escalating deficit in the agricultural workforce specializing in vegetable production. Consequently, under these socio-economic constraints, the full-scale mechanization of transplanting operations emerges as a pivotal strategy to sustain production capacity and optimize labor efficiency [1, 7].

Current transplanting machinery fails to fully satisfy the precise agronomic specifications required for uniform seedling establishment. Notably, the operational components of imported transplanters are frequently incompatible with the specific physical and mechanical profiles of regional soils dedicated to vegetable cultivation. This structural misalignment accelerates the tribological wear of the working organs and induces catastrophic mechanical failures, leading to costly operational downtime during critical field campaigns [9].

Studying the fundamental problems of seedling planting technology is an important task in improving the design of seedling planting machines. The main problems with mechanization of the planting process are the low operating speed of seedling planting machines and the poor quality of seedling planting [10]. The stability of planting depth is one of the most critical agronomic parameters, directly affecting the seedling survival rate, uniformity of development, and yield of agricultural crops grown from seedlings.

Traditional transplanting machines using mechanical contour following systems demonstrate insufficient accuracy, especially when operating at high speeds and on heterogeneous soils [5, 11]. Deviations from the specified optimal depth exceeding ± 5-10 mm can lead to significant yield losses and a decrease in the economic efficiency of production [12].

Let's take a look at the causes and problems associated with different planting depths and their impact on crop yield.

Indeed, shallow or surface planting – in which the root collar (the transition zone between the root and the stem) or the upper part of the root system remains above soil level – is considered the most significant human-induced factor contributing to seedling mortality in the first few years after planting.

The most detrimental causes of plant mortality are desiccation (dehydration) and heat stress. The upper soil layers are subject to sharp temperature fluctuations and rapid drying. Studies show that shallowly planted seedlings die from moisture deficiency long before critical atmospheric drought sets in, since their root system cannot reach the soil's capillary moisture [13].

In cases of mechanical instability, plants lose their resistance to being rocked by the wind. This leads to the formation of air pockets around the root collar, which further dries out the roots and breaks off young root hairs [13].

Thus, shallow planting is the leading cause of forest crop mortality in North America, as the roots are unable to reach the critical moisture-retention depth during summer droughts.

When planting is excessively deep, the root collar and part of the stem become buried in the soil, which is considered a serious technical error. Modern research differentiates this effect depending on soil type and the biological characteristics of the species [13].

This can lead to root asphyxia. For example, in heavy clay soils and waterlogged soils, deep planting sharply restricts oxygen access to the roots. This inhibits root system respiration, halts ATP synthesis, and leads to the death of active root tips.

In addition, adventitious (accessory) roots may form. For some plant species, burying the stem stimulates the development of adventitious roots in the upper, well-aerated soil layer. However, this process requires significant energy expenditure by the plant, which slows the growth of aboveground biomass.

It should also be noted that in deciduous species, prolonged exposure of the bark of an unadapted stem to moist soil often leads to waterlogging, rot, and infection by fungal pathogens [14].

Thus, deep planting of conifers in well-drained or sandy soils can even increase survival during drought, as it protects the roots from overheating; however, in heavy soils, it causes high mortality due to oxygen deficiency [15].

Experiments have shown that precise adherence to the root collar level is critical for species sensitive to soil aeration, where even a planting depth of 3-5 cm significantly reduces the survival rate [16].

Thus, deviations from the optimal planting depth critically disrupt the basic physiological conditions for plant development. When planted too shallowly, moisture deficiency and temperature stress become limiting factors, whereas when planted too deeply, oxygen deprivation (hypoxia) and pathogenic root collar rot become limiting factors. Furthermore, deviations in planting depth directly reduce the viability (survival rate) of individual seedlings, weaken the plants' overall immunity, and make them vulnerable to adverse environmental factors. At the same time, uneven planting disrupts the synchrony of the plants' initial development. This triggers intense interplant competition for resources (light, moisture, nutrients) within the plant community, which ultimately leads to a decrease in the field's total productivity and yield. Thus, disturbances in the hydrothermal and oxygen regimes lead to the degradation of individual and community immunity and a decrease in the productivity of the agrocenosis.

Results and discussions. The aim of this research is to provide a theoretical rationale and systematic analysis regarding the impact of uneven seedling positioning depth on survival performance. To achieve this, the study employs a multi-method approach encompassing a critical review of scientific literature, mathematical simulation of the 'planting depth deviation-survival rate' dependency, and a comparative analysis of the precision characteristics inherent in existing depth-control systems.

The influence of the deviation of the actual planting depth (h_{real}) from the optimal (h_{opt}) on the survival rate (P) can be approximated by a mathematical model based on a normal distribution, where the maximum survival rate is achieved at $\Delta h = 0$ [17, 18].

$$\Delta h = h_{real} - h_{opt} = 0. \tag{1}$$

The model of plant survival depending on the deviation in seedling planting depth is as follows:

$$P(\Delta h) = P_{\max} \cdot e^{-\frac{1}{2}(\frac{\Delta h}{\sigma})} + P_{\min}, \tag{2}$$

where $P(\Delta h)$ – survival rate in case of deviation Δh, %; P_{max} – maximum survival rate (e.g. 98%); P_{min} – minimal survival rate (for example, 2%); Δh – deviation from optimal depth, mm; σ – standard deviation characterizing the sensitivity of the culture to changes in depth.

Analytical evaluation of the empirical data presented in Table 1 demonstrates that a standard precision threshold inherent to conventional mechanical depth-control systems (±10–15 mm) induces up to an 8% deficit in seedling survival. Under conditions of soil heterogeneity, where vertical placement deviations escalate to ±20 mm, the survival rate experiences a critical regression of 18% or greater. Consequently, this survival deficit diminishes the biopotential of the agrocenosis, resulting in lower net yields while concurrently driving up the operational expenditures required for subsequent crop management.

Table 1 – The impact of planting depth variability on the survival performance of seedlings

Deviation from optimal depth, Δh, mm	Seedling survival rate P, %	Decreased survival rate ΔP, %
±5	97,5	0,5
±10	95,0	3,0
±15	90,0	8,0
±20	80,0	18,0
±30	65,0	33,0

Modern transplanting machinery integrates various depth-stabilization systems operating on a parallelogram linkage to sustain the target planting depth [19]. These architectures are fundamentally categorized into:Mechanical systems, which are characterized by high structural inertia and a passive control principle. Their typical operational tolerance spans ±10–15 mm, a precision threshold insufficient for mitigating seedling mortality.

Hydraulic systems, which exhibit the following engineering limitations [19]:

a) Force-centric regulation:

The control loop modulates the downforce rather than explicitly tracking the absolute vertical position;

b) Precision constraints:

Positioning accuracy is inherently bounded by valve sensitivity parameters and hydraulic fluid compressibility;

c) Residual tolerance:

The typical positioning accuracy ranges within ±5–10 mm, which fails to entirely neutralize the adverse agronomic effects of planting depth non-uniformity.

Table 2 – Comparative analysis of the accuracy of landing depth stabilization Systems

System type	Mechanism regulation	Typical accuracy of depth maintenance, mm
Mechanical	Passive copying	± 10 - 15
Hydraulic	Active force control	± 5 - 10

The operational tolerances inherent to contemporary depth-stabilization systems (Table 2) exhibit insufficient precision, consequently causing a substantial proportion of seedlings to be deployed with vertical deviations that exceed the critical threshold of 10 mm (Table 1). Enhancing the kinematic and dynamic accuracy of these stabilization frameworks represents a primary pathway toward optimizing seedling survival performance. Specifically, suppressing the standard deviation (σ) within the mathematical model (Formula 1) to a target range of 2-3 mm effectively prevents the seedling distribution from shifting into the critical deviation zones. This optimization is statistically predicted to yield a 10-20% increase in the overall survival rate.This creates an urgent need to develop and implement systems that can ensure the accuracy of maintaining the planting depth within ± 1-2 mm.

Conclusions. The current state of vegetable production in Ukraine and Moldova is characterized by a systematic reduction in cultivated areas, driven by a combination of agroclimatic factors (water scarcity, degradation of irrigation networks) and an acute shortage of specialized labor. This necessitates a transition to full-scale automation and mechanization of transplanting as the only strategy for preserving the industry.

The existing fleet of imported transplanters does not meet modern agrotechnical requirements due to their low operating speed and the structural incompatibility of their working parts with the physical, mechanical, and rheological properties of regional soils. This leads to increased tribological wear, breakdowns in the field, and poor planting quality.

Deviations from the optimal planting depth exceeding ±5–10 mm disrupt the physiological basis of plant development. Shallow planting limits seedling viability due to temperature stress, dehydration, and loss of mechanical stability in the soil. Excessive planting depth causes root system asphyxia (inhibition of ATP synthesis), pathogenic bark rot, or unproductive energy expenditure on the formation of adventitious roots.

Uneven coulter penetration depth disrupts the synchrony of the plants' initial ontogenesis. This triggers intense intraspecific competition for light, moisture, and nutrients within the plant community, leading to a decline in individual and coenotic immunity and reducing the field's overall yield by 10–20%.

Thus, traditional mechanical terrain-following systems do not provide the necessary depth stability under high-speed operating conditions and soil heterogeneity, which justifies the need to develop new, highly efficient systems for adaptive control of the suspension parameters of the working bodies.

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Вплив нерівномірності вертикального позиціонування розсади на показники виживаності та біопотенціал агроценозу

У статті здійснено теоретичне обґрунтування та системний аналіз впливу нерівномірності глибини позиціонування розсади на показники її виживаності, а також розглянуто проблему підвищення точності висаджування як ключового напряму механізації овочівництва в Україні та Республіці Молдова.

Установлено, що сучасний стан овочівництва обох країн характеризується систематичним скороченням посівних площ, зумовленим сукупністю агрокліматичних чинників (дефіцит водних ресурсів, деградація зрошувальних мереж) та гострою нестачею спеціалізованої робочої сили. Це посилює імпортозалежність регіону щодо основних овочевих культур і робить повномасштабну механізацію процесу пересаджування єдиною стратегією збереження галузі. Водночас наявний парк імпортних розсадосадних машин не відповідає сучасним агротехнічним вимогам через низьку робочу швидкість та конструктивну несумісність робочих органів із фізико-механічними й реологічними властивостями регіональних ґрунтів, що спричиняє трибологічне зношування, польові поломки та незадовільну якість висаджування.

Доведено, що стабільність глибини садіння є одним із найкритичніших агрономічних параметрів, який безпосередньо впливає на виживаність, рівномірність розвитку та врожайність рослин. Відхилення фактичної глибини від оптимальної понад ±5–10 мм порушують фізіологічну основу розвитку: мілке садіння обмежує життєздатність через температурний стрес, зневоднення й утрату механічної стійкості, тоді як надмірно глибоке спричиняє асфіксію кореневої системи (пригнічення синтезу АТФ), патогенне загнивання кори або непродуктивні витрати енергії на утворення додаткових коренів.

У роботі запропоновано математичну модель залежності «відхилення глибини — виживаність» на основі нормального розподілу та виконано порівняльний аналіз точності наявних систем стабілізації глибини. Установлено, що типова точність механічних (±10–15 мм) і гідравлічних (±5–10 мм) систем є недостатньою та знижує врожайність агроценозу на 10–20 %. Обґрунтовано необхідність розроблення нових високоефективних систем адаптивного керування параметрами підвіски робочих органів, здатних забезпечити точність висаджування в межах ±1–2 мм.

розсада, глибина висаджування, виживаність, механізація, точність, адаптивне керування, овочівництво

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