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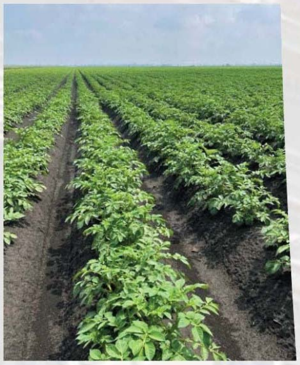

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DRIVERS OF REGENERATIVE AGRICULTURE: THE NEXT GENERATION OF SUSTAINABLE FOOD PRODUCTION

Adrian Csordas[*]

Guangzhou College of Commerce, Guangzhou, People's Republic of China

Abstract: Agriculture needs rapid and fundamental transformation to enhance its efficient and sustainable operation. Lately, Regenerative Agriculture (RA) has emerged as a comprehensive solution for the challenges of food production and climate change. Unlike the prohibition-based approach of organic farming, RA operates as an outcome-oriented, flexible framework focused on active ecosystem restoration. This study presents a systematic literature review based on the PRISMA guidelines to identify the key drivers of RA adoption and to provide clear recommendations for its effective introduction. The analysis highlights four categories of drivers that distinguish RA from other sustainable practices: economic (reducing input costs), ecological (restoring soil and climate resilience), social (peer networks and mentoring), and intrinsic (ecological mindset and autonomy). It is important to note that the findings primarily reflect Western farming contexts, which clarifies the generalisability of the results. To support the successful introduction of RA, policymakers and extension services should prioritise young, eco-friendly farmers operating on a smaller scale as the primary target group, while NGOs should directly organise farm visits and provide hands-on mentoring as necessary tools for successful adoption. Furthermore, for large-scale operations, the implementation of financial incentives linked to carbon markets and certification schemes is essential to encourage broader uptake. According to the findings, although change is fundamentally driven by individual mindsets, the deliberate implementation of these specific suggestions can significantly aid large-scale adoption and the development of more resilient agriculture.

Key words: agriculture, soil, sustainability, innovation, environment, review, regenerative, farmer.

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[*] Corresponding author: e-mail: csordas.adrian19@gmail.com

Introduction

Modern agriculture faces the dual challenge of ensuring food security for a growing global population while minimising environmental harm. Conventional methods relying on synthetic fertilisers and pesticides have increased yields (de la Cruz et al., 2023; Knapp et al., 2023), but have also contributed to soil degradation, water pollution, and greenhouse gas emissions (Tripathi et al., 2020; Abebe et al., 2022; Xu et al., 2023). Although organic farming provides a more environmentally friendly alternative (Canwat and Onakuse, 2022), its lower yields and limited scalability raise concerns about its overall sustainability (Thakur et al., 2022; de Ponti et al., 2012). In addition to organic farming, other sustainable paradigms have emerged, such as circular, green, and integrated agriculture. Circular agriculture focuses on closing nutrient loops and minimising waste, while green agriculture emphasises the reduction of negative externalities through technological efficiency (Jurgilevich et al., 2016; Koohafkan et al., 2012). Integrated agriculture seeks to achieve a balance by combining biological and chemical tools to optimise production (Atapattu et al., 2024). However, while these approaches primarily aim to reduce the "footprint" or maintain current resource use, regenerative agriculture (RA) is emerging as a holistic approach that not only avoids environmental harm but also seeks to restore ecosystems through practices such as reduced tillage, organic amendments, and biodiversity enhancement (Wiltshire and Beckage, 2022; Rehberger et al., 2023; Villat and Nicholas, 2024). Regarding productivity, quantitative LCA evidence shows that organic agriculture typically yields the lowest output per hectare, while RA produces intermediate yields – lower than conventional but often higher than organic (Cavallito et al., 2026). Unlike the mitigation-focused approach of green or integrated methods, RA's distinctive value lies in its proactive soil-building and carbon-sequestering capacity. These practices promote soil health, carbon sequestration, and resilience, with potential socio-economic benefits for smallholder farmers, who contribute over 30% of global food production (Ricciardi et al., 2018). Despite their critical role, small-scale producers often face constraints in resources and access (Ruml and Qaim, 2020; Quaicoe et al., 2024). Therefore, understanding the factors influencing their adoption of RA is essential to designing targeted interventions that enhance both environmental outcomes and farmer livelihoods.

Hence, this paper aims to explore the factors influencing farmers' transition to RA by analysing the findings of selected peer-reviewed scientific articles.

Material and Methods

Conducting a systematic literature review is a structured way to examine all the available high-quality studies related to a particular topic (Sarkis-Onofre et al., 2021). This method is based on the identification, evaluation, and analysis of scientific works that fulfill the requirements of the specified search criteria (Mishra and Mishra, 2023). This study was carried out following the mixed-methods systematic review guidelines of the Joanna Briggs Institute (Aromataris et al., 2024). This approach combines qualitative evidence with the synthesis of quantitative findings (Gough, 2015). The mixed methods systematic reviews (MMSRs) are mostly applied in healthcare-related studies because the integration of the various study types provides a more comprehensive basis for making informed decisions (Lizarondo et al., 2022). To find as many relevant studies as possible, three major academic databases: Scopus, Web of Science, and Science Direct, were searched (Page et al., 2021).

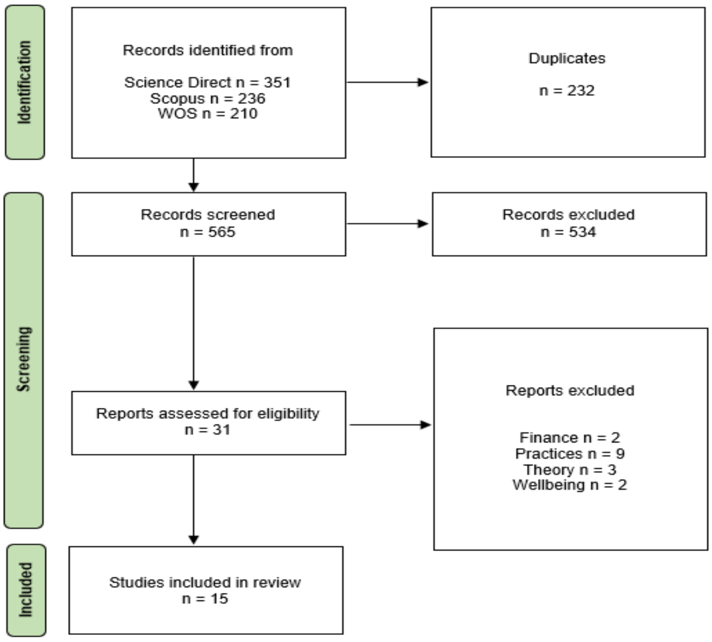

Figure 1. Stages of the applied PRISMA method.
Source: Author's elaboration.

This study specifically aimed to identify and synthesise the existing evidence on the factors driving farmers to adopt regenerative agriculture (RA). The brightest pool of studies was created by the keyword of "regenerative agriculture", which had to appear in the title, or in the abstract, or in the keywords. During the selection process, only studies published in English and released on or before 4 March 2024 were included. This initial search identified 797 articles. To manage this large number of articles, Rayyan (2024), a free online platform designed to conduct systematic reviews, was used. Only studies based on primary data were considered. To broaden the number of relevant publications, even the references of the selected studies were also scanned, but no additional works were included. However, the share of the selected articles did not provide such a bright pool of qualitative studies suitable for the proper application of the described method. Since the presented MMSRs could be considered as an extension of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses for Protocols (PRISMA) approach – both of the guidelines based on the same searching, and selection methods – the study follows these guidelines in presenting the results (Stern et al., 2020). The stages of the applied method are shown in Figure 1.

It is important to note that RA, due to its eco-friendly approach and major influence on the Sustainable Development Goals (SDGs), is widely researched. This broader interest resulted in the exclusion of many irrelevant studies. After the rigorous selection, only fifteen academic publications remained directly relevant to the defined topic of interest.

Results and Discussion

To provide a comprehensive overview of the existing knowledge, the published review articles were studied. The data collection method was exactly as described above. However, this time only “review” articles were considered. Two hundred and fourteen publications were found in the database, before detecting the duplicates, but none of them has studied the farmers’ drivers, or attitudes regarding the implementation of RA. The studies mostly focused on the comparisons of various agricultural systems/methods or on soil, as shown in Figure 2.

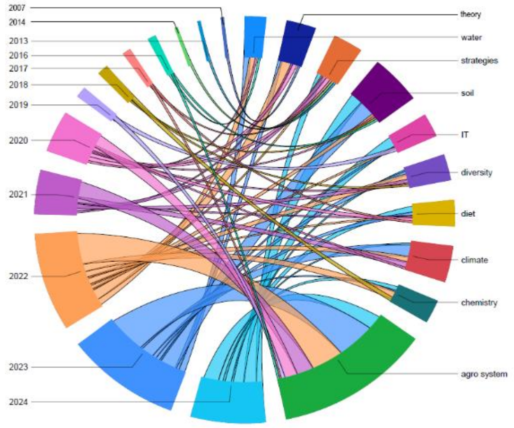

Figure 2. The directions and the publication years of the RA reviews.
Source: Author’s elaboration.

Even within the reviews, diverse articles considered different practices and approaches as RA, since there is no unified definition. The review of Newton et al. (2020) aimed to define it from both process and outcome-based perspectives. However, given the great variety of approaches presented, the authors instead suggested the free application of RA. Notwithstanding the absence of a unified definition, the various forms of RA (Newton et al., 2020) and a framework to track the agricultural changes (driven by RA) have been identified (O’Donoghue et al., 2022). The use of the framework-based collected data can support further studies and innovations in the agricultural sector, fostering the refinement of our knowledge. The resulting outcomes could specify, for example, by territory or species, the most ideal circumstances for the application of RA. Considering that the latest meta-analysis-based evidence states that none of the studied RA practices simultaneously increase soil carbon and the yield (Jordon et al., 2022). In contrast, the work of Khangura et al. (2023) stresses the need for more specific data. Their review highlights the possibility of achieving both outcomes at the same time, but notes that the various climate zones, plants, livestock, and soil types have to be considered in these analyses. These reviews suggest that a holistic approach – applying multiple practices together – is considered as “expected” by the (lacking) definition, and that such practices can strengthen each other’s effects.

Academic papers

Considering that RA embodies various concepts, the studies cover a wide range of approaches, as presented in Table 1.

As systematised above, what truly distinguishes RA from other sustainable practices is not merely its ecological awareness, but also its systemic approach to risks and outcomes. While organic agriculture operates as a highly regulated, prohibition-based system focused on input substitution (replacing synthetic inputs with organic ones), RA is perceived by farmers as an open-ended, continuous process of ecological regeneration. Farmers often accept initial yield fluctuations because RA fundamentally changes the metric of success: it shifts the focus from maximising gross yields to maximising ecosystem resilience and net financial stability by reducing dependence on external inputs. Therefore, these diverse aspects present slightly different contexts, although their main findings were revealed. Van den Berg et al. (2018) analyse how political-economic pressures and environmental degradation prompted farmers to explore innovative, ecologically sound farming strategies. Soil erosion and declining yields due to conventional practices, combined with rising fertiliser costs, encouraged farmers to adopt RA practices, which enhanced soil fertility and reduced dependence on external inputs. Gosnell et al. (2019) find that the transition to RA was often triggered by personal or financial crises, which led farmers to question conventional methods.

Table 1. Theoretical frameworks and perspectives of the studied articles.

Article	Focus	Research Gap	Location	Data
van den Berg et al. (2018)	Agricultural innovation, sustainable farming practices, farmer cooperation	Lack of studies on the long-term impact of cooperative farming models on sustainability and economic outcomes.	Brazil	Interviews with farmers
Gosnell et al. (2019)	Shift from conventional to regenerative farming practices	Lack of understanding of the long-term economic viability of regenerative farming in different regions.	Australia (New South Wales)	Interviews with farmers
Rosenzweig et al. (2020)	Shifts in cropping systems and soil health management	Further exploration needed on the role of insurance and policy in the adoption of continuous cropping systems.	USA (Colorado, Nebraska)	Interviews with farmers
Gosnell et al. (2020)	Motivations behind the adoption of regenerative practices	More research on the economic impacts of regenerative farming practices and the role of financial incentives.	Australia, USA	Interviews with farmers
Gosnell (2022)	Influence of chemical fertilisers and soil microbe on farmers' shift to RA	Further research needed on the emotional and mental hurdles farmers face in transitioning to regenerative practices.	Australia, USA	Interviews with farmers and consultants
Kenny and Castilla-Rho (2022)	Exploring the difficulties and possibilities for adopting RA	Further exploration needed on how government policies and subsidies could support or hinder the transition to RA.	Australia	Interviews with farmers
Page and Witt (2022)	How Australian beef farmers perceive RA and their farming goals	Additional research on the perceived role of science and technology in regenerative practices is needed.	Australia	Interviews with farmers
Beacham et al. (2023)	Farmer perspectives on adopting RA	More research on the barriers caused by market regulations and uncertainty, such as certification and subsidies.	England (East, South-West)	Interviews with farmers
Jordon et al. (2023)	Reasons for non-adoption of RA among sheep and beef farmers in England	Further research on the role of older farmers and their resistance to RA could provide deeper insights.	England	Interviews with farmers
Keshavarz and Sharafi (2023)	Barriers to the restoration of degraded agroecosystems in developing countries	Research needed on how global and local policies interact to either support or hinder the adoption of RA in developing countries.	Iran	Interviews with experts

Table 1. Continuation.

Article	Focus	Research Gap	Location	Data
Wojtynia et al. (2023)	Adoption of regenerative farming practices	Limited research on how the global farming system impacts small-scale regenerative farming.	Netherlands	Interviews with farmers
Ntawuhiganayo et al. (2023)	Adoption of recycling and regenerative practices	Exploration of barriers to adoption beyond training and extension visits, such as policy or community-level factors.	East Africa (Rwanda, Kenya)	Survey
Miller-Klugesherz and Sanderson (2023)	Transition from conventional farming to RA	Longitudinal studies on the personal and social transformation of farmers during RA adoption.	USA	Interviews with farmers
Frankel-Goldwater et al. (2024)	Motivations for adopting RA	Lack of focus on specific policy support for RA adoption across different regions.	USA	Interviews with farmers
Phelan et al. (2024)	Engagement with soil carbon sequestration programmes	Research gap in assessing the long-term financial benefits of soil carbon sequestration for farmers.	UK	Survey with farmers and interviews

Source: Author’s elaboration.

The adoption of RA allowed them to align ecological processes with farm operations, promoting low-input systems that reduced costs and improved profitability. However, major obstacles included scepticism from peers, institutional resistance, and the psychological difficulty of abandoning entrenched paradigms. Rosenzweig et al. (2020) highlight that perceptions of profitability, risk management, and ecological resilience were central to farmers’ decisions to intensify cropping systems. Motivated by soil health campaigns and dissatisfaction with conventional advice, farmers pursued crop diversification to reduce input costs, yield volatility, and market risk. However, challenges such as labour demands, crop insurance limitations, and insufficient support for non-traditional practices posed significant barriers to adoption. Gosnell et al. (2020) explore the motivations behind farmers’ adoption of RA, emphasising that environmental resilience, cost reduction, and improved forage quality are among the key incentives. Regenerative practices such as holistic grazing enhance ground cover and reduce dependency on inputs, thereby lowering financial risk and increasing ecological stability. However, the transition is challenging; the initial phase is labour-intensive, requiring a shift in mindset and the acquisition of new monitoring and decision-making skills. Farmers often encounter emotional resistance, especially when conventional success metrics no longer apply. Gosnell (2022) delves further into the psychological and cultural dimensions of this transition. Farmers’ increasing dissatisfaction with chemical inputs, due to rising costs and declining efficacy, motivates a search for alternatives. However, fear of failure, social stigma, and entrenched norms – such as valuing tidiness and weed-free fields – pose significant psychological barriers. Adopting RA involves redefining one’s identity as a farmer and often entails overcoming community disapproval and institutional inertia. Despite these challenges, gaining knowledge and a sense of autonomy fosters empowerment and sustains the transition process. Kenny and Castilla-Rho (2022) reinforce this perspective by highlighting systemic obstacles to RA adoption. They argue that institutional support for conventional agriculture – reflected in policy, education, and consumer expectations – creates a self-reinforcing cycle that resists change. The perceived benefits of RA, though substantial, are not yet widely recognised or valued enough to outweigh the perceived risks, costs, and labour demands, particularly in the absence of targeted policy interventions or cultural shifts. Page and Witt (2022) reveal that farmers’ perceptions of RA vary across a spectrum of value systems, with some prioritising productivity, others favouring environmental goals, and a third group navigating both. While farmers motivated by ecological outcomes see RA as aligned with their values and lifestyle, those more focused on productivity remain sceptical, viewing technology and conventional science as more reliable tools. Across all groups, tension remains between the perceived long-term environmental benefits of RA and the short-term economic risks, particularly amid market volatility and limited data. Beacham et al. (2023) also find that, although RA is viewed as environmentally beneficial and potentially profitable, significant barriers to adoption persist. These include uncertainty about certification, shifting government policies, and scepticism regarding the authenticity of RA practices. Many farmers express a desire for regulatory clarity and market incentives to make regenerative labelling more meaningful and profitable. Additionally, social and generational dynamics influence the depth of farmers’ commitment – some follow RA trends without internalising its principles, which undermines transformational change. Jordon et al. (2023) emphasise the practical and structural impediments to adoption, especially among older farmers and those managing smaller or less diversified operations. High upfront costs for infrastructure and equipment, reluctance to adopt labour-intensive practices, and concerns about yield uncertainty limit RA uptake. The study identifies distinct farmer profiles, ranging from enthusiastic adopters to resistant traditionalists, each influenced by different motivations, risk perceptions, and financial priorities. Keshavarz and Sharafi (2023) focus on broader systemic and policy-level barriers in developing agricultural contexts. They identify economic insecurity, weak institutional support, outdated technologies, and fragmented land ownership as major hindrances to RA adoption. The lack of reliable markets, inadequate infrastructure, and limited access to credit or technical expertise compound these challenges. Cultural and psychological barriers, including risk aversion and low collective action, further inhibit progress. According to Wojtynia et al. (2023), farmers are primarily motivated by tangible outcomes such as improved soil health, aesthetic satisfaction, and collaboration with like-minded peers. They also expressed a strong desire to contribute positively to society. However, systemic barriers persist, asmost advisory services, subsidies, and educational programmes favour conventional farming. Farmers cited a lack of impartial advice and public support, noting that consumers demand sustainable farming without offering price premiums. Some have begun differentiating through direct-to-consumer sales, though changing mindsets and practices remains challenging. Media distrust and perceived public criticism further complicate the transition. According to Ntawuhiganayo et al. (2023), the farmers' motivations to adopt RA are influenced by both practical and ideological factors. Many farmers are driven by the potential for improved soil fertility, which they perceive as essential for long-term agricultural productivity. Additionally, formal training and support from extension agents significantly increase the likelihood of adoption, highlighting the importance of education in facilitating the transition. The opportunity for enhanced food security through sustainable practices also motivates farmers to shift towards RA. However, barriers remain, including financial constraints and the persistence of traditional farming norms, which hinder the adoption process. Proximity to protected areas was found to reduce the likelihood of adopting RA, possibly due to regulatory restrictions or a lack of clear benefits. Despite these challenges, training and community-level interventions are critical to overcoming adoption barriers and encouraging wider implementation of RA practices. Miller-Klugesherz and Sanderson (2023) analyse farmers transitioning from conventional agriculture to RA. Transitions were often triggered by financial or personal crises, with farmers undergoing significant identity transformations during the shift. The adoption of RA often led to social isolation, as farmers distanced themselves from conventional agricultural communities, including friends and family. Motivations included both financial necessity and environmental concerns, particularly regarding chemical use. While most adopted one or two RA practices within two years, implementing three or more took an average of eight years. The early phases were especially difficult due to income instability. Farmers reported a growing connection between ecological and personal well-being and expressed a desire to promote RA to challenge industrial agriculture norms. Frankel-Goldwater et al. (2024) found that environmental concerns and financial stability are central motivators. While some farmers had the resources to experiment with RA, others faced significant financial constraints. A recurring challenge was balancing environmental goals with economic sustainability. Many participants believed RA could address systemic issues in agriculture, particularly for small-scale farms. Some identified market potential in value-added “regenerative” products. The study identifies two distinct groups: one more privileged, driven by large-scale ecological goals; and another, more financially vulnerable group focused on survival and legacy preservation. Despite their differences, both groups strongly opposed conventional farming due to its reliance on synthetic inputs. Phelan et al. (2024) explore farmers’ perspectives on regenerative practices, focusing on soil carbon sequestration. Their main motivations for RA adoption included declining soil fertility, extreme weather, and climate change concerns. While farmers were generally open to new practices, most expected financial compensation. Few were willing to adopt innovations without payment, and a comparable share only sought compensation for existing practices. The study highlights both openness to RA and the importance of financial incentives for widespread adoption.

Systematisation of drivers vs. barriers and distinction from organic agriculture

To provide a comprehensive overview, the factors influencing the adoption of RA must be systematised in direct relation to the persistent structural barriers. Rather than operating in isolation, each positive driver directly counters or reshapes a specific hurdle, altering the farmer’s decision-making matrix. Furthermore, while both organic agriculture and conventional sustainable practices share the ecological dimension of reducing environmental harm, RA is distinguished by a distinct operational philosophy. Table 2 systematises these dynamics, highlighting the interplay between drivers and barriers, as well as the specific features that differentiate RA from organic farming.

As systematised above, what truly distinguishes RA from other sustainable practices is not merely its ecological awareness, but also its systemic approach to risks and outcomes. While organic agriculture operates as a highly regulated, prohibition-based system focused on input substitution (replacing synthetic inputs with organic ones), RA is perceived by farmers as an open-ended, continuous process of ecological regeneration. Farmers often accept initial yield fluctuations because RA fundamentally changes the metric of success: it shifts the focus from maximising gross yields to maximising ecosystem resilience and net financial buffering by reducing dependency on external inputs.

Table 2. Systematisation of RA adoption factors (drivers vs. barriers) and differentiation from organic agriculture.

Dimension	Drivers	Barriers	Compared to organic farming
Economic and input	Rising input costs	High upfront investment costs	Focuses on lowering input costs rather than paying for rigid, expensive organic certifications.
	Focus on net profitability	Early-phase income instability	
	Carbon market potentials	High market and yield volatility	
Ecological and env.	Active soil restoration	Fear of short-term yield decline	Organic limits negative inputs; RA actively rebuilds soil health and ecosystem functions.
	Enhanced water retention	Lack of baseline ecological data	
	Resilience to drought/floods		
Social and operat.	Peer-to-peer networks	Institutional bias	RA offers a context-specific framework without strict, legally codified prohibitions.
	Farm emonstrations/workshops	Lack of impartial advisory services	
	Support from extension agents		
Psychological	Ecological mindset shift	Social stigma and peer pressure	Driven by internal values and systemic cognitive shifts rather than compliance with external checklists.
	Desire for operational autonomy	Fear of transition failure	
	Securing farm legacy	Cultural norms of “tidy” fields	

Source: Author’s elaboration.

The reviewed literature predominantly explores the factors motivating farmers to transition to RA, with a strong emphasis on exploratory, interview-based studies. Most research is concentrated in Australia and the United States, which shapes the findings toward Western farming contexts, while limited attention is given to African or developing regions. Across studies, participants often cited environmental concerns and a desire to contribute to sustainability – whether local or global – as key motivations. Critical turning points frequently included personal or environmental crises, such as droughts, floods, or rising input costs, particularly for fertiliser and fuel. Many farmers reported declining fertiliser effectiveness and financial strain due to price surges, prompting a reassessment of conventional practices. In only a few cases was RA adopted solely to enhance soil fertility. A recurring distinction emerged between motivations and predisposing characteristics for RA adoption. A mindset aligned with ecological harmony was consistently linked to openness to transition. Although participant characteristics such as climate zone, plant/livestock focus, and age were rarely central in the studies, their influence was evident – particularly in cases where mixed crop-livestock systems supported RA goals. Age often played a role, with older farmers more resistant due to impending retirement, adherence to conventional norms, or reluctance to change. Farm size and ownership also impacted adoption decisions, with larger farms facing greater logistical and financial barriers. Interestingly, individuals entering farming from other professions – sometimes referred to as “career-changers” or “new entrants without an agricultural background” – often showed more willingness to adopt RA, lacking preconceptions from conventional agriculture. Successful transitions were frequently associated with small-scale, consumer-facing food production, reflecting increased public demand for traceable or affordable food. Hobby farmers also viewed RA as a viable model. External support structures were critical: few farmers cited national programmes as helpful, but where government or NGO-led initiatives were available, they were taken seriously. In contrast, agrochemical companies were often viewed as obstructive, influencing agricultural policies, education, and insurance systems. The value of trusted information sources– such as workshops, farm demonstrations, or peer networks – was widely acknowledged. Information access, particularly in less developed regions, was seen as both a key barrier and an opportunity. A summary of the identified factors is presented in Figure 3.

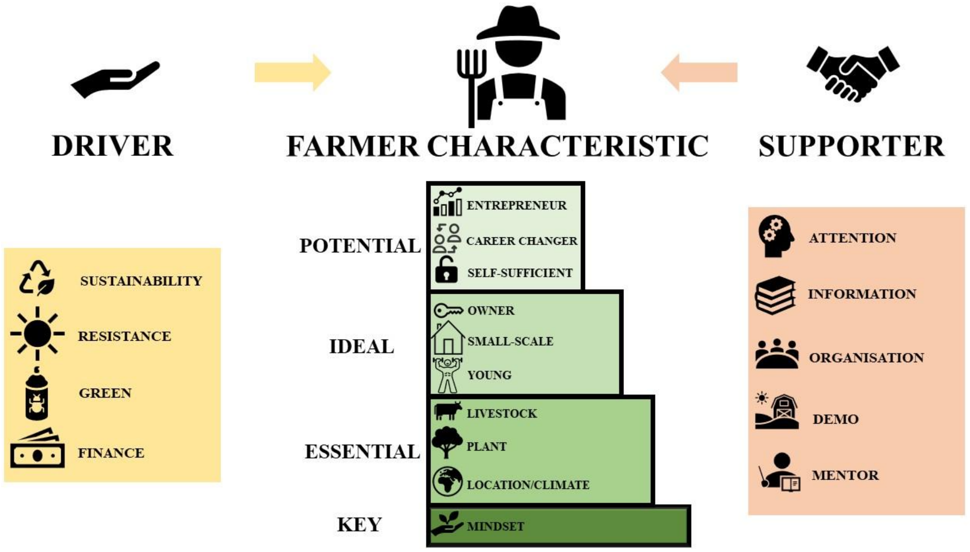

Figure 3. Factors influencing the farmers’ transition to RA.
Source: Author’s elaboration, 2025.

In Kenya, for example, lack of knowledge related to RA was identified as the main constraint (Otara et al., 2023). Participatory approaches, such as monitoring and evaluation processes, not only enhanced learning but also deepened understanding of the benefits of RA (Luján Soto et al., 2021). In developed countries, RA has the potential to complement or extend organic farming practices (Gordon et al., 2023). This complementarity operates through a functional synthesis: while certified organic farming provides a rigorous, legally regulated framework for eliminating synthetic chemicals, it often relies heavily on intensive mechanical tillage for weed control, which can inadvertently degrade soil structure. RA extends these practices by introducing intensive soil-building techniques – such as continuous living cover, complex crop rotations, and non-inversion or zero-tillage (no-till) systems – directly into organic protocols. By combining the chemical prohibitions of organic farming with the functional, process-driven soil restoration practices of RA, farmers can achieve greater ecological synergy, actively rebuilding soil organic matter, and enhancing microbiological biodiversity while remaining chemical-free. In less mechanised regions, openness to RA may be higher due to closer ties to nature (Daum & Birner, 2020). Community-based knowledge sharing has been proposed as a pathway for RA adoption in such contexts (Ogunyiola et al., 2022). Broader uptake – particularly among large-scale operations – may depend on financial incentives and integration into mechanisms such as carbon markets and certification schemes (Stephens, 2021; Reed et al., 2022; Gordon et al., 2024). Future research should therefore move beyond identifying barriers and systematically investigate the positive adoption factors, particularly how economic, ecological, social, and intrinsic drivers interact across diverse farming systems and regions.

Conclusion

Agriculture plays a critical role in achieving the Sustainable Development Goals (SDGs). Through its effective operation, multiple SDGs – particularly climate action, soil protection, and responsible production – could be advanced and addressed simultaneously. Lately, widely adopted agricultural approaches have been reconsidered, developed, and discussed, but the precise socioeconomic, behavioural, and intrinsic factors driving farmer adoption toward RA are sporadically studied. Traditional agricultural paradigms often treat sustainability as a set of rigid, top-down regulations. This study directly addresses this gap by mapping the internal and external decision-making matrix of the farmer. The main factors for RA implementation are economic (reducing dependency on costly synthetic inputs and improving net profitability), ecological (restoring soil health, water retention, and climate resilience), social (access to peer networks, farm demonstrations, and mentoring), and intrinsic (an ecological mindset, desire for operational autonomy, and securing a farm legacy). The study revealed a structured systematisation of drivers versus barriers across four dimensions, and identified the farmer groups most receptive to transitioning to RA, namely career changers, small-scale consumer-facing producers, hobby farmers, and younger farmers with an ecological mindset. Currently, no comprehensive, behaviour-focused framework exists that synthesises how intrinsic mindsets interact with economic and social barriers during the RA transition. Because such integrated synthesis materials were not previously available, this study was developed to fill this scientific gap. However, further research is needed to fully realise the benefits of these findings, as this study has clear boundaries and limitations. The analysed primary literature is heavily skewed toward Western farming contexts – predominantly centred in Australia and the United States – which shapes the findings and clarifies expectations regarding the generalisability of the results to less mechanised or smallholder regions. Furthermore, the selection process was strictly confined to peer-reviewed articles published in the English language across three major academic databases (Scopus, Web of Science, and ScienceDirect) that were released before the temporal boundary of 4 March 2024. Consequently, highly recent institutional changes or local socio-economic developments after this date have not been captured. Policymakers play a crucial role in creating an enabling environment for this method. By shifting away from conventional subsidy biases, providing targeted funding, and implementing supportive regulations – such as integrating regenerative land covers into verified carbon markets and standardised certification schemes – they could facilitate the widespread adoption of RA. In practical terms, extension services and NGOs should prioritise young, eco-friendly farmers operating on a small scale as the primary target group, directly organising farm visits and providing hands-on mentoring to mitigate the fear of transition failure. For large-scale farms, financial incentives linked to carbon markets and certification schemes are essential to encourage broader uptake. Finally, regarding future research directions, it is essential to focus on addressing the practical challenges identified in this real-world setting. Future empirical studies should explicitly aim to confirm or refute the adoption dynamics identified in this review. Longitudinal research is strongly recommended to monitor long-term farm profitability, while expanding these studies to diverse, non-Western agricultural commodities and regions is critical to establish the universal reliability and scalability of the regenerative paradigm.

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POKRETAČI REGENERATIVNE POLJOPRIVREDE: NOVA GENERACIJA ODRŽIVE PROIZVODNJE HRANE

Adrian Csordas[*]

Guangzhou College of Commerce, Guangzhou, People's Republic of China

Rezime

Poljoprivredi je potrebna brza i temeljna transformacija kako bi se poboljšalo njeno efikasno i održivo poslovanje. Poslednjih godina, regenerativna poljoprivreda (RP; engl. *regenerative agriculture – RA*) pojavljuje se kao sveobuhvatno rešenje za izazove proizvodnje hrane i klimatskih promena. Za razliku od pristupa organske poljoprivrede zasnovane na zabranama, RP funkcioniše kao fleksibilan okvir orijentisan na ishode, usredsređen na aktivnu obnovu ekosistema. Ova studija predstavlja sistematski pregled literature zasnovan na PRISMA smernicama kako bi se identifikovali ključni pokretači usvajanja RP i pružile jasne preporuke za njeno efikasno uvođenje. Analiza ističe četiri kategorije pokretača koji razlikuju RP od drugih održivih praksi: ekonomske (smanjenje troškova inputa), ekološke (obnova zemljišta i klimatska održivost), društvene (vršnjačke mreže i mentorstvo) i intrinzične (ekološki način razmišljanja i autonomija). Važno je napomenuti da nalazi pre svega odražavaju kontekste zapadne poljoprivredne proizvodnje, što razjašnjava generalizaciju rezultata. Kako bi se podržalo uspešno uvođenje RP, kreatori politika i savetodavne službe trebalo bi da daju prioritet mladim, ekološki osvešćenim poljoprivrednicima koji posluju na manjim posedima kao primarnoj ciljnoj grupi, dok bi nevladine organizacije (NVO) trebalo da organizuju posete poljoprivrednim gazdinstvima i obezbede praktično mentorstvo kao neophodne alate za uspešno usvajanje ovih praksi. Za velike poljoprivredne sisteme, primena finansijskih podsticaja povezanih sa tržištima ugljenika i šemama sertifikacije je od suštinskog značaja za podsticanje šireg usvajanja. Rezultati istraživanja ukazuju da, iako su promene prvenstveno uslovljene individualnim stavovima i načinom razmišljanja, planska primena predloženih mera može značajno doprineti njihovoj široj primeni i razvoju otpornijeg poljoprivrednog sektora.

Ključne reči: poljoprivreda, zemljište, održivost, inovacije, životna sredina, pregled, regenerativno, poljoprivrednik.

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[*] Autor za kontakt: e-mail: csordas.adrian19@gmail.com

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Review paper

IMPACT OF CIRCULAR AGRICULTURE IN BANGLADESH: WASTE-TO-VALUE STRATEGIES FOR BIOGAS PRODUCTION AND CROP RESIDUE MANAGEMENT

Md. Masud M. Rana[1] and Md. Younus M. Ali[2*]

[1]Department of Agricultural Extension Education,
Bangladesh Agricultural University, Mymensingh, Bangladesh
[2]Department of Animal Breeding and Genetics,
Bangladesh Agricultural University, Mymensingh, Bangladesh

Abstract: Circular agriculture (CA), derived from circular economy (CE) principles, promotes resource-efficient, closed-loop systems where organic waste is converted into renewable energy, fertilisers, and soil amendments. In Bangladesh, poor management of livestock manure, crop residues, and urban organic waste contributes to greenhouse gas emissions, soil degradation, and environmental pollution, underscoring the need for sustainable waste-to-value strategies. This review evaluates the potential of circular agriculture in Bangladesh, focusing on crop residue management and biogas production as key pathways for resource recovery and renewable energy generation. A structured literature review of 102 peer-reviewed articles and policy documents was conducted to assess current practises, technological opportunities, and policy frameworks. Waste-to-value approaches, including composting, vermicomposting, biofertilisers, biochar, and anaerobic digestion, enable conversion of agricultural residues into nutrient-rich soil amendments and renewable energy, improving soil fertility, enhancing crop productivity, and reducing reliance on chemical fertilisers. Bangladesh generates over 106 million tonnes of biomass annually, with the potential to produce more than 5 billion m^3 of biogas. However, most biogas systems remain small-scale due to technological, financial, and awareness constraints. Expanding circular agriculture through integrated management of livestock manure, crop residues, and organic waste could reduce emissions, improve soil health, and strengthen rural energy security. Enhancing capacity building, technology transfer, green financing, and public–private collaboration is essential to scale up circular agriculture and support sustainable agricultural and energy systems in Bangladesh.

Key words: waste-to-value, crop residue management, biogas production, sustainable agriculture.

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[*] Corresponding author: e-mail: younus_abg@bau.edu.bd

Introduction

The circular economy (CE) is a sustainability-focused framework that emphasises minimising waste and optimising resource use, in contrast to the traditional linear “take–use–dispose” production model. In agriculture, the application of CE principles can transform conventional production systems into regenerative, closed-loop cycles that reduce external inputs, enhance biodiversity, and strengthen the resilience of food systems (Katunar, 2025). Integrating CE in agriculture is also recognised as an important pathway toward achieving several Sustainable Development Goals (SDGs), particularly those related to climate action, food security, and environmental conservation. Circular agriculture (CA) represents a resource management approach derived from CE principles that focuses on reusing agricultural waste as valuable inputs, thereby creating closed-loop production systems that minimise resource extraction and environmental impact (Azizuddin et al., 2021). Unlike the linear economic model, which follows a one-way flow of input–production–consumption–disposal (Aznar-Sánchez et al., 2020), CA seeks to optimise resource efficiency while supporting environmental, economic, and social sustainability. The fundamental concepts of CA are grounded in the principles of reduce, reuse, and recycle (Manickam and Duraisamy, 2019). Several key principles guide the implementation of circular agriculture. First, resource efficiency and system optimisation aim to reduce unnecessary consumption and minimise waste generation (Zabaniotou et al., 2015). Second, closed-loop processes convert agricultural byproducts into useful resources, such as transforming crop residues and livestock manure into organic fertilisers or renewable energy, thereby reducing dependence on external inputs and lowering greenhouse gas emissions (Stillitano et al., 2021; Ellen MacArthur Foundation, 2019). Third, regenerative technologies support nutrient cycling, restore soil health, and enhance ecosystem resilience (Morseletto, 2020). In addition, circular economy principles promote broader societal benefits, including environmental protection, economic development, job creation, and poverty alleviation (Constant et al., 2013; Ghisellini et al., 2016). These principles include designing systems without waste or pollution to avoid environmental degradation (Aznar-Sánchez et al., 2019), maximising the reuse of products and materials throughout the agro-food supply chain (Ellen MacArthur Foundation, 2019), and regenerating natural systems through the use of renewable resources that enhance soil fertility, conserve biodiversity, and maintain ecosystem functions (Velasco-Muñoz et al., 2021). Figure 1 illustrates a schematic representation of the circular economy, demonstrating how these interconnected principles can contribute to the development of sustainable agricultural systems. By adopting CA models, agriculture can function as a key driver of economic growth while simultaneously supporting biodiversity conservation, environmental sustainability, food security, and improved rural livelihoods (Bos and Broeze, 2020; Kristensen et al., 2016). In Bangladesh, the livestock sector plays a crucial role in ensuring food security and sustaining rural livelihoods. It contributes approximately 1.85% to the national GDP and supports millions of farming households across the country (BBS, 2022; DLS, 2023). The sector also generates a significant amount of organic waste, with an estimated 12.3 million tonnes of cattle manure produced annually (Rahman et al., 2017).

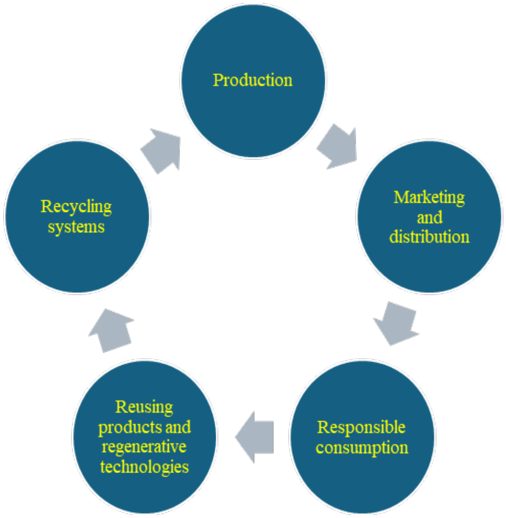

Figure 1. Schematic diagram of the circular economy.
Source: Adapted and organised by the authors from the literature.

However, conventional waste disposal practices, such as open dumping or burning, lead to the release of greenhouse gases and cause substantial environmental pollution (Gupta et al., 2016; Mudway et al., 2005; Cathy, 2023; Wang et al., 2022). Similarly, crop residues are often burned in agricultural fields, contributing to air pollution, nutrient loss, and soil degradation. These challenges highlight the urgent need for integrated waste-to-value strategies capable of converting livestock manure and crop residues into renewable energy sources, such as biogas, as well as organic fertilisers. Despite the abundance of biomass resources, the adoption of composting and large-scale biogas production systems in Bangladesh remains limited due to infrastructural, financial, technological, and policy constraints. Therefore, promoting circular agricultural practices is essential to improve waste management, reduce environmental impacts, and enhance sustainable agricultural productivity. This review focuses on waste-to-value strategies within Bangladesh's agricultural sector, with particular emphasis on biogas production from livestock manure and sustainable crop residue management. It aims to examine current practices, explore technological opportunities, and evaluate policy frameworks that can facilitate the transition toward circular agriculture, ultimately contributing to sustainable development and food security.

Material and Methods

This review explores the potential of circular agriculture to promote sustainable agricultural development and economic growth while identifying factors that contribute to institutional capacity-building. The study followed a structured literature review approach as proposed by Colicchia and Strozzi (2012) and Ammar et al. (2022). This method enhances scientific rigour, minimises bias, and facilitates the identification of emerging knowledge (Tricco et al., 2018; Mallett et al., 2012). Both quantitative and qualitative studies were reviewed using a mixed-method analysis approach (Van der Knaap et al., 2008; Mallett et al., 2012). Scholarly articles published in peer-reviewed journals were considered. Documents published in exclusively English were included to ensure global accessibility and consistency (López-Fernández et al., 2016). Duplicate and unreliable grey literature was excluded. The literature search covered the period 2000–2025, allowing the review to capture both early developments and recent advancements in circular agriculture and agricultural waste management. Searches were conducted in ScienceDirect, Web of Science, Scopus, Google Scholar, ResearchGate, FAO Library, JSTOR, and PubMed Central (Baier-Fuentes et al., 2019) using keywords such as circular economy, green economy, agricultural waste management, crop residue recycling, waste-to-value, renewable energy, and circular agriculture policy frameworks. A total of 325 studies were initially identified; after screening titles and abstracts and removing duplicates, 162 papers were shortlisted. Finally, 102 studies meeting the inclusion criteria were selected for full review. The selected literature was subjected to thematic analysis, with the studies systematically reviewed and categorised into key themes related to circular agriculture. These themes included waste-to-value strategies, technological innovations, policy frameworks, and environmental and socioeconomic impacts. Thematic coding enabled the identification of recurring patterns, knowledge gaps, and emerging opportunities for advancing circular agriculture in Bangladesh. A limitation of this review is that it included only English-language, peer-reviewed studies with variable methodologies, which may not fully capture all local or unpublished evidence relevant to circular agriculture in Bangladesh.

Results and Discussion

Agricultural Waste Landscape in Bangladesh

Bangladesh, an agriculture-based country, generates a vast array of agricultural waste, which can be broadly categorised into crop residues, animal waste, and food/agro-industrial byproducts. Common types of crop residues include rice straw, jute sticks, maize stalks, sugarcane leaves, wheat straw, groundnut straw, and pulse straw, whereas animal waste primarily comprises manure and poultry litter (Miah et al., 2022). Table 1 presents the different types of agricultural waste in Bangladesh, along with their sources, utilisation patterns, and associated environmental concerns.

Table 1. Agricultural waste types, sources, utilisation patterns, and environmental concerns in Bangladesh.

Waste type/residue	Source crop/activity	Typical uses	Environmental concern if unused
Rice straw	Paddy fields (rice cultivation)	Animal feed, animal bedding, housing material, fuel, compost, biogas	Air pollution from burning
Rice husk	Rice mills	Poultry bedding, cattle feed, fuel	Adds to solid waste burden
Wheat straw	Wheat fields	Fuel, housing material	Air pollution from burning
Jute sticks/stalks	Jute fibre processing	Fencing, fuel, biochar, housing material	Landfill clogging, decay
Groundnut straw	Groundnut cultivation	Fuel, animal feed	Decomposes, attracts pests if dumped
Vegetable plants/peels	Agro-processing units, vegetable farms, households	Compost, biogas, fuel, animal feed	Attracts pests, decomposes in dumps
Pulse straw	Pulse crops	Fuel, animal feed	Decay, contributes to solid waste
Sugarcane leaves	Sugarcane farms	Fuel, animal feed	Decomposition-related emissions
Sugarcane bagasse	Sugarcane mills	Fuel	Waste burden if not reused
Maize leaf and straw	Maize cultivation	Fuel, animal feed	Attracts pests and waste burden
Maize husk	Maize processing	Fuel	Adds to solid waste burden
Poultry litter	Broiler/layer poultry farms	Organic fertiliser, biogas	Water contamination, odour
Cow dung	Dairy farms, cattle sheds	Biogas, compost	Methane emissions

Source: Authors' systematisation based on published literature.

In addition, vegetable peels, kitchen waste, and rice husk are also generated in significant quantities from agro-processing and household activities (Baker et al., 2017). On average, farm households produce approximately 822 kg of agricultural waste monthly, depending on the type of farming activity and seasonal variation. These wastes are mainly used in rural areas for cooking fuel (57.06%), animal feed (68.04%), cow dung ball preparation (61.86%), composting, and reuse in subsequent cultivation cycles (Islam et al., 2022). Figure 2 illustrates the daily waste generation in Bangladesh, while Figure 3 shows the composition of agricultural residues.

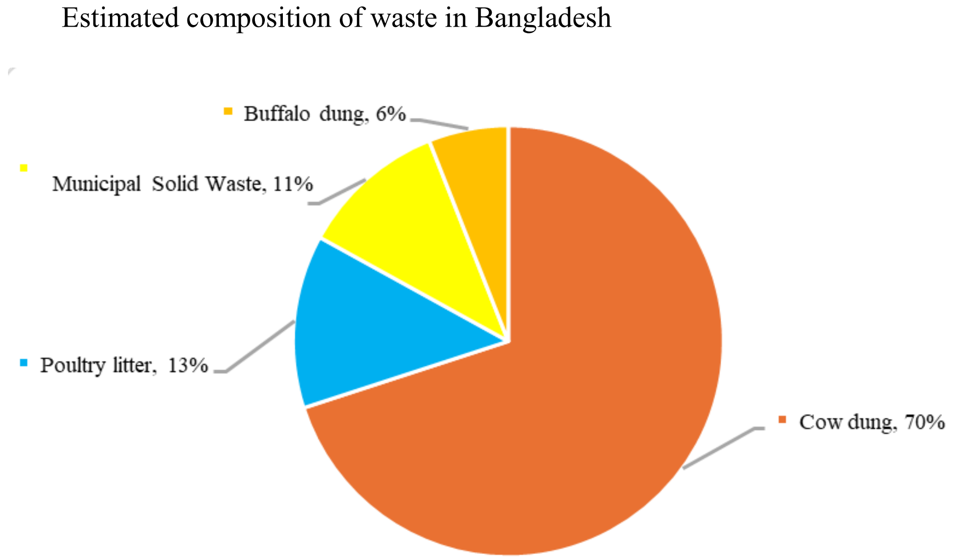

Figure 2. Waste generation per day in Bangladesh.
Source: Adapted from Karmaker et al., 2020.

However, owing to the lack of appropriate collection systems and technologies, approximately 29–100% of crop residues are left to rot or are burned in the field, while most manure and poultry litter are either dumped in pits or used in traditional, unregulated ways (Alam and Ahmade, 2013). This inefficient and often unscientific utilisation not only leads to resource underuse but also causes severe environmental issues. Poor agricultural waste management contributes significantly to greenhouse gas (GHG) emissions, including methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2), which arise from open burning and unmanaged decomposition processes (Zalidis et al., 2002; Josimovic et al., 2015; Steinmetz et al., 2016; Pardo et al., 2017; Dai et al., 2018; IPCC, 2022). The long-term improper application of poultry manure further results in elevated atmospheric ammonia and accumulation of microelements, increasing the bioavailability and toxicity of metals in the environment (Zhang, 2012; Vrzel et al., 2016; Fan et al., 2020; Rahman et al., 2022).

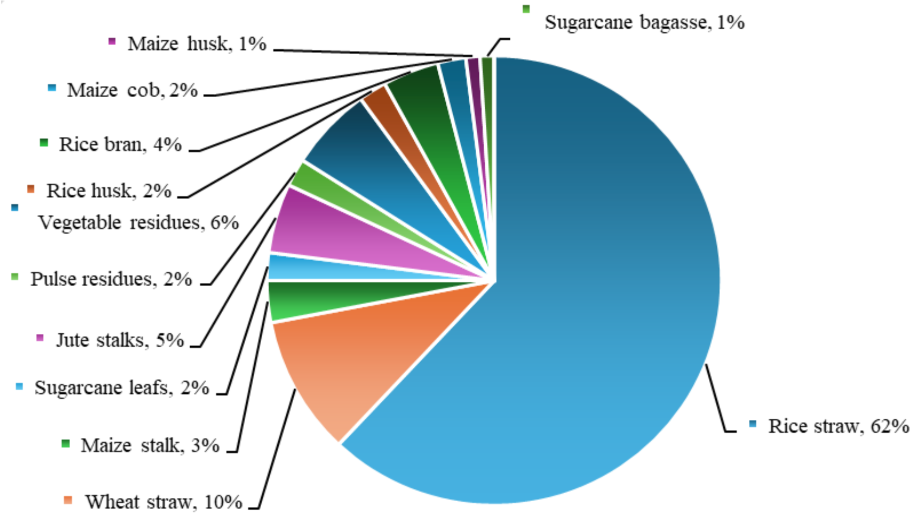

Figure 3. Composition of agricultural residues in Bangladesh.
Source: Adapted from Halder, 2014.

In terms of soil health, persistent residue burning depletes soil organic matter, reduces microbial diversity, disrupts nutrient cycles, and ultimately decreases soil fertility and crop productivity (Atinkut et al., 2020). Furthermore, leachate from inadequately stored manure and decomposed waste leads to contamination of surface and groundwater sources, causing eutrophication, fish mortality, and health risks for local communities, especially in areas with poultry farms located near water bodies, which become particularly hazardous during the monsoon season (DCC, 2004; Oyedotun et al., 2021). Table 2 summarises the waste generation trend in Bangladesh over the years, highlighting its rapid escalation.

Table 2. Waste generation scenario in Bangladesh.

Year	Waste generation (tonnes/day)
1991	9,873.5
2001	11,695
2015	27,492
2025	47,064 (projected)

Source: Adapted from SREDA, 2020.

This escalating trend in waste generation from 9,873 tonnes/day in 1991 to a projected 47,064 tonnes/day by 2025 highlights the urgent need for sustainable waste management solutions. Addressing these interconnected issues through effective waste-to-value strategies and circular bioeconomy models is crucial for ensuring environmental sustainability and agricultural resilience in Bangladesh.

Waste-to-Value Strategies in Circular Agriculture

Agricultural residues, including crop waste, livestock manure, and urban organic waste, present both challenges and opportunities for sustainable agriculture (Ioannou et al., 2015; Shinde et al., 2022; Koul et al., 2022). Globally, millions of tonnes of crop residues are generated annually, and in Bangladesh alone, urban areas produce approximately 4.86 million tonnes of organic waste each year, 75–85% of which is biodegradable (Aminul, 2005; Sujauddin et al., 2008; Guerrero et al., 2013). Proper management of these wastes through circular agricultural approaches such as composting, vermicomposting, bio-fertilising, and biochar production can increase soil fertility, reduce environmental pollution, and improve crop productivity. In Bangladesh, several practical waste-to-value strategies can be implemented to strengthen circular agricultural systems. The most promising approaches are as follows:

(1) Composting is a controlled biological process in which organic substrates are decomposed by microorganisms, producing nutrient-rich compost suitable for agricultural use (Haug, 1980). In Bangladesh, composting urban and agricultural waste offers a natural alternative to chemical fertilisers, improving soil structure, aeration, and fertility. High-quality compost requires optimal feedstock selection and a balanced carbon-to-nitrogen (C:N) ratio, typically 10:1–20:1, which combines carbon-rich "brown" materials with nitrogen-rich "green" materials (Huang et al., 2004; Gajalakshmi and Abbasi, 2008; Hubbe et al., 2010; Bernal et al., 2009). Composting proceeds through three microbially driven phases mesophilic, thermophilic, and maturation resulting in stabilised, pathogen-free compost suitable for storage and application (Büyüksönmez et al., 2000; Sundberg et al., 2004; Novinsak et al., 2008; Zeng et al., 2011). Despite its potential, large-scale composting in Bangladesh remains limited due to technical, institutional, and training constraints, with only a few facilities treating substantial waste volumes (Zurbrügg et al., 2005; Cofie et al., 2014).

(2) Vermicomposting is a biologically efficient and eco-friendly method of converting organic waste, particularly livestock manure and crop residues, into nutrient-enriched fertiliser via earthworms and associated microorganisms (Kumar et al., 2014; Ibrahim et al., 2024). Earthworms modulate microbial communities, secrete nutrient-rich mucus, condition substrates, and regulate pH, thereby increasing nitrogen (N), phosphorus (P), and potassium (K) contents in the final

product (Kumar et al., 2017). This process bypasses the thermophilic stage, producing homogenised, stable, and high-quality compost in 45–60 days while conserving water, energy, and land (Whiston and Seal, 1988; Syers et al., 1979; Eastman, 1999; Azis et al., 2022; ESF, 2006; Sakthivel, 2012).

(3) Biofertilisers complement composting and vermicomposting by increasing soil fertility and nutrient availability through beneficial microorganisms (Vessey, 2003). They improve root development, nutrient uptake, and plant growth while reducing dependency on chemical fertilizers and pesticides by up to 60% and increasing crop yields by 20–35% (Basak et al., 2015; Singh et al., 2021; Dai et al., 2004). In Bangladesh, biofertiliser adoption is gradually increasing, supported by initiatives from BINA, RDA, and NGOs such as PROYASH, although barriers including limited awareness, training, and access remain (Hasan et al., 2025). The combination of compost, vermicompost, and biofertilisers can have synergistic effects, improving soil health, nutrient cycling, and crop productivity.

(4) Biochar production via the pyrolysis of crop residues, urban organic waste, or livestock manure offers an additional waste-to-value strategy (Singh and Sidhu, 2014). Pyrolysis converts biomass into a stable, carbon-rich product that enhances soil fertility, water-holding capacity, and microbial activity while sequestering carbon for long periods and mitigating greenhouse gas emissions (Whitbread et al., 2003; Warnock et al., 2007; Nematian et al., 2021). Biochar can also act as a nutrient reservoir, improving fertiliser-use efficiency and crop performance, with reported yield increases of up to 30% in rice, chilli, cabbage, and kohlrabi (Ali et al., 2015; Ali et al., 2019; Karim et al., 2020; Karim et al., 2025; Sutradhar et al., 2021). Co-application with compost or reduced nitrogen fertiliser further reduces ammonia emissions and increases nutrient availability (Ferdous et al., 2023). Historically, biochar has been used in Amazonian Terra Preta soils and in modern applications through low-cost stoves and pyrolysis units, offering the dual benefits of energy production and soil amendment (Cui, 2015; Lehmann, 2009; Barrow, 2012; BBI, 2015; Magnusson, 2015). Collectively, these strategies-composting, vermicomposting, biofertilisers, biochar production, biogas generation, and integrated waste recycling enable circular agriculture by converting organic waste into valuable inputs that improve soil health, reduce environmental impacts, increase crop productivity, and support sustainable farming practices. In Bangladesh, scaling these approaches through awareness programmes, farmer training, technological adoption, and research on long-term impacts can significantly strengthen sustainable agricultural systems while addressing waste management challenges (FAO, 2010; Scholz et al., 2014; Duer, 2004).

Crop Residue Management in the Circular Economy

There are several ways to utilise crop residues produced at different stages of agricultural operations, as practisced by developed nations (Bhuvaneshwari et al., 2019). The most common applications include incorporation into soil, use as livestock feed, mulching materials, production of bioenergy, and even rural construction materials (Tenelli et al., 2021; Duan et al., 2021; Win et al., 2021). During tillage operations, crop residues, straw, or stubble are mixed with the topsoil to promote faster degradation and reduce surface residues, thereby facilitating intercultural operations (Lohan et al., 2018). Crop residue management can also help mitigate climate change impacts, particularly for crops grown after the wet season, by improving water use efficiency (Liu et al., 2017). In wheat cultivation, for example, the use of rice straw combined with fertiliser application has been shown to improve soil pH, microbial population, and enzymatic activity (Chowdhary et al., 2020), whereas residue reuse has been associated with an average yield increase of approximately 5% (Lu, 2020). The surface retention of straw, trash, leaves, and other plant parts as mulch conserves soil moisture, enhances organic carbon recycling and nutrient availability, ultimately improving input use efficiency, minimising soil erosion, and increasing productivity (Wu et al., 2021). In developing countries, a significant portion of crop residues is still used as feed for domestic animals, with leguminous residues providing higher crude protein and nutrient contents than rice straw does; the palatability of different residues depends on their lignocellulose and nutrient composition (Devi et al., 2017; Win et al., 2021). Additionally, the use of cereal straw as a roof material is a common rural practice, and the production of building materials such as straw–clay bricks and walls has been a traditional method for generations (Zhao et al., 2014). In Bangladesh, crop residues are traditionally managed through burning, mulching, or use as fodder and fuel, although burning notably causes air pollution and results in the loss of valuable organic matter. Sustainable alternatives such as incorporating residues into the soil, composting, and converting them into bioenergy are being promoted for their benefits in improving soil fertility, enhancing carbon sequestration, and reducing greenhouse gas emissions. Technological interventions, including residue collectors, shredders, and microbial inoculants, help streamline residue processing and accelerate nutrient cycling. These circular practices can reduce dependence on chemical fertilisers, lower emissions, and increase productivity. However, yet adoption remains limited by challenges such as a lack of technological access, insufficient awareness, and financial constraints which could be addressed through education, policy support, and infrastructure development.

Biogas Production from Agricultural Residues in Bangladesh

Agriculture employs approximately 80% of Bangladesh’s population, generating significant quantities of crop residues and organic waste materials (Tasnim et al., 2017). With nearly 87% of households dependent on biomass energy, these agricultural residues constitute crucial resources for renewable energy generation (Rahman et al., 2018). Bangladesh is also experiencing severe energy shortages but possesses considerable potential for the development of renewable energy, particularly biomass, solar, hydro, and wind power. Efforts by government bodies and NGOs have promoted technologies such as biogas systems, improved cooking stoves, and biomass briquettes, positioning renewable energy as a practical approach for rural development (Islam et al., 2008). Animal manure, particularly from dairy farms, produces an estimated 156 million tonnes annually (Huque et al., 2017), along with crop residues, which serve as primary substrates for anaerobic digestion (AD) processes to produce biogas (Khan and Martin, 2016). Despite the substantial biogas potential arising from Bangladesh's large poultry population, approximately 200 million birds, and extensive dairy farming, biogas utilisation in poultry farms remains minimal (Das et al., 2016). The predominant biogas technology employed is the brick-built fixed-dome digester, which is implemented primarily on the household scale. Survey data indicates that most digesters utilise single-manure feedstock, whereas poultry litter-based digestion yields comparatively lower biogas production efficiency (SREDA, 2021). By the end of 2020, an estimated 140,500 biogas plants were operating across Bangladesh, predominantly at the household scale; commercial-scale biogas facilities remain underdeveloped due to infrastructural and technical limitations (IDCOL, 2014; IDCOL, 2018). The Infrastructure Development Company Limited (IDCOL), established in 1997, financed over 56,500 small-scale biogas plants by 2020, facilitating renewable energy deployment through both domestic and international partnerships (Sovacool and Drupady, 2011). Since 1996, Grameen Shakti has also played a pivotal role in expanding renewable energy access through the installation of solar systems, cookstoves, and biogas plants, positively impacting millions. However, challenges related to staffing, cost, political factors, and awareness persist (IDCOL, 2018). In Bangladesh, Infrastructure Development Company Limited (IDCOL) and Grameen Shakti are working together to develop several biogas plants with plans to establish approximately 80,000 small biogas plants. The government of Bangladesh also aims to establish a 1 MW biomass-based plant and 5 MW biogas-based plants in different regions (Power Cell, 2019). Financial assessments indicate that small-scale biogas plants are economically feasible, offering positive returns and adequate energy for typical household consumption (Hossain et al., 2020; Bedana et al., 2022). Data suggest that approximately 106 million tonnes of biomass can produce more than 5 billion cubic meteres of biogas annually, with 6 m^3 biogas plants identified as the most viable for rural applications (Sarker et al., 2020). Livestock-associated greenhouse gas emissions have increased, yet the utilisation of urban livestock waste for biogas could reduce emissions by 37.5% by 2050. On a national scale, livestock waste can generate 27.9 billion m^3 of biogas, 50 TWh of electricity, and 29.2 million tonnes of organic fertiliser annually, aligning with climate goals and sustainable energy objectives. In 2016 alone, Bangladesh's 229 million tonnes of livestock waste had the capacity to produce nearly 17 billion m^3 of biogas, potentially reducing CO_2 emissions by several million tonnes (Siddiki et al., 2021). According to the Bangladesh Biogas Development Foundation, cattle manure alone can generate approximately 77.4 million cubic meteres of biogas annually, equivalent to approximately 170,000 MWh of energy and displacing several million tonnes of fossil fuel consumption (ILMM, 2015). Common animal manures yield high biogas outputs, with methane concentrations ranging from 60% to 74% (Rahman et al., 2018). The optimal conditions for anaerobic digestion occur between 35 and 40°C, with cow dung delivering the highest yields of biogas and methane (Nandi et al., 2020). In refugee camps, biogas has successfully replaced significant quantities of LPG, achieving an 85% reduction in emissions (Chowdhury et al., 2022). Household biogas plants have been shown to reduce emissions by more than 80%, decrease CO_2 output significantly, replace conventional fuels, and produce nutrient-rich fertiliser, highlighting their environmental, economic, and social benefits (Rahman et al., 2019).

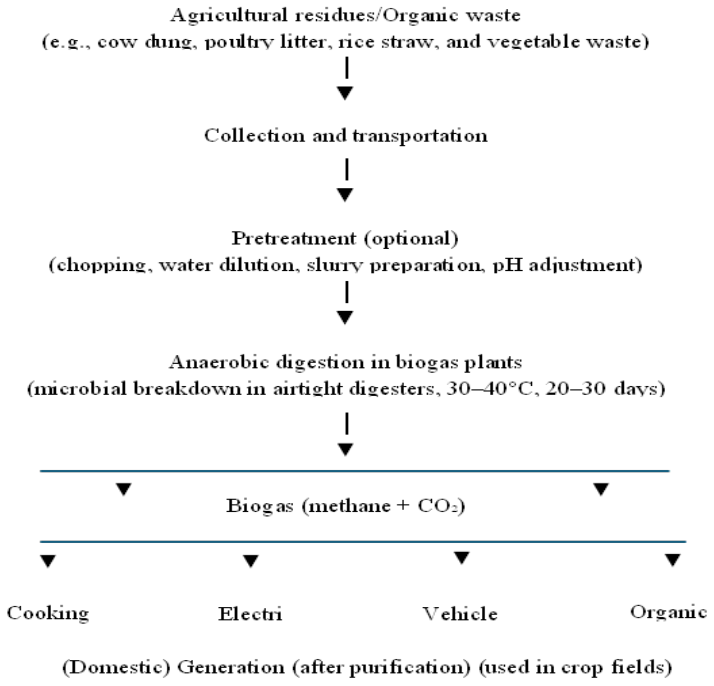

Figure 4. Biogas production process from agricultural residues in Bangladesh, showing key steps from waste collection to biogas and organic fertiliser utilisation. Source: Developed by the authors based on information synthesised from multiple studies on biogas production and agricultural waste management.

Biogas production not only provides a sustainable energy source, but also produces nutrient-rich bio-slurry, a valuable organic fertiliser that enhances soil fertility and reduces reliance on synthetic chemical fertilisers, thereby improving crop yields and farmer livelihoods (Parawira, 2009; Ch'ng et al., 2014). Nevertheless, improper management and disposal of bio-slurry can lead to adverse environmental and health impacts (Khanam et al., 2019). The overall process of biogas generation from agricultural residues, including collection, pretreatment, anaerobic digestion, and subsequent utilisation of both biogas and bio-slurry, is illustrated in Figure 4. Untreated poultry litter is a major source of greenhouse gas emissions, which can be reduced by 65% through anaerobic digestion, with additional reductions achieved by applying digested slurry as bio-fertiliser (Mainali et al., 2017). However, the expansion of biogas technology faces challenges, including limited user awareness, high capital and operational costs, technical malfunctions, and inadequate maintenance and training services (Muñoz, 2019; Huque et al., 2017). Although advanced monitoring and control systems can increase biogas production by up to 75%, their cost remains prohibitive for most rural farmers (Islam et al., 2014). Despite the considerable biogas potential within rural households and poultry operations, uptake remains limited (Sarker et al., 2020).

While poultry waste composting and biogas production provide environmental benefits, improving knowledge and investment remains critical (Rahman et al., 2022). The full benefits of biogas technology necessitate improved farm management, optimised feedstock handling, and effective waste management strategies to integrate diverse agricultural residues, such as manure, bedding materials, hatchery waste, kitchen scraps, and processing byproducts (John and Teto, 2013; Nasrin et al., 2021; Nasiruddin et al., 2020; Muduli et al., 2019). Bangladesh's abundant biomass resources—comprising crop residues, animal manure, and solid waste are increasingly being tapped through supportive initiatives (Huda et al., 2014). However, current policies largely emphasize household-scale biogas systems, highlighting the need to support commercial-scale ventures (Islam et al., 2021). For example, slaughterhouses in Dhaka alone can generate approximately 2.15 million m^3 of biogas annually, which can be used for heating, electricity, or biomethane (Salehin et al., 2021). Community biogas plants utilising dairy manure can produce 31 million m^3 of biogas annually, generate 200.6 GWh of electricity, reduce greenhouse gas emissions substantially, and increase the nation's renewable energy share by 1.25% (Aktar et al., 2024). Similarly, livestock waste from Chattogram holds significant promise for bioenergy (Das et al., 2023). Thermal conversion via the pyrolysis of rice straw and plastic waste has shown promise as an effective waste-to-energy method. However, farmers need training to improve their waste recycling capacity (Islam et al., 2021; Kabir et al., 2023). While agricultural waste is plentiful at the household level, limited knowledge of scientific composting restricts its utilisation. Enhancing composting practices could lower fertiliser costs and advance sustainable agriculture (Miah et al., 2022). Geospatial analyses have identified 558 optimal sites for large-scale biogas plants, which can collectively produce 7,683 GWh of electricity and reduce greenhouse gas emissions by 6,636 Gg CO_2 annually (Mahal and Yabar, 2025). Agricultural residues alone could supply 9.7 billion m^3 of biogas, potentially fulfilling almost 88% of the country's energy requirements (Rahman et al., 2018). Moreover, integrating agriculture, forestry, and livestock systems offers opportunities to advance sustainable development goals, although resource constraints and gender disparities must be addressed (Datta et al., 2024). Although considerable potential exists, challenges such as insufficient research and development, fragmented coordination, low public awareness, and a lack of tariffs feedback, hinder broader biogas adoption. Nevertheless, the country's extensive waste-to-energy capacity and climate adaptation priorities create clear opportunities for growth (Hasan et al., 2022).

Circular Agriculture in Bangladesh: Policy, Institutions, and Future Prospects

Bangladesh has made significant strides in establishing policies and institutional frameworks to promote circular agriculture, emphasising waste-to-value strategies such as biogas production and crop residue management for sustainable growth. Key national policies, including the National Agricultural Policy (2012), Industrial Policy (2016), and Renewable Energy Policy (2008), along with strategic plans such as the Eighth Five-Year Plan and Bangladesh Delta Plan 2100, advocate efficient resource use, renewable energy adoption, and circular bio-economy initiatives such as composting and jute innovation (IEA, 2025; Reuters, 2025; MoEFCC, 2023). Regulatory bodies such as the Sustainable and Renewable Energy Development Authority (SREDA), together with waste management rules (D'Costa et al., 2022), operationalise the 3R (reduce, reuse, recycle) approach and extended producer responsibility (EPR) mechanisms. These efforts are supported by the Ministry of Environment, Forest and Climate Change and international partners (FICCI, 2024; IIBD, 2024; UNDP, 2025). NGOs, including Grameen Shakti, RDA, BRAC, RSF, BBF, GIZ, ISDE, and BEES, provide technical support, microfinance, and farmer training for digester installation, composting, and residue management (Sarker et al., 2020; Uddin et al., 2019; BEES, 2024). Community-led initiatives, such as the engagement of religious leaders by ATEC, have successfully addressed social barriers to adoption (The Business Standard, 2024). To accelerate adoption, Bangladesh can draw on international best practices, such as India's training models promoting composting and bio-decomposers (Krishi Jagran, 2024). Embedding circular agriculture into formal education and extension programmes can further enhance awareness.

Currently, awareness of 3R principles and conservation agriculture remains limited (Kabir et al., 2023), highlighting the need for strengthened extension services, capacity building, and public engagement.

Conclusion

Circular agriculture in Bangladesh transforms livestock manure, crop residues, and organic waste into valuable resources through biogas production, composting, vermicomposting, biofertilisers, and biochar, enhancing soil fertility, crop productivity, and renewable energy generation. These waste-to-value strategies reduce environmental pollution, mitigate greenhouse gas emissions, and support rural livelihoods while promoting efficient resource utilisation. Scaling up adoption requires strengthened policies, institutional capacity, extension services, and active community engagement to support sustainable agricultural development. Although Bangladesh has established a supportive policy and institutional framework, key challenges remain, including limited infrastructure, inadequate social outreach, financial constraints, and low field-level adoption. Addressing these barriers through targeted incentives, technology integration, improved extension services, and inclusive stakeholder collaboration is essential for advancing circular agriculture and achieving sustainable growth. Better utilisation of Bangladesh's abundant biomass resources, particularly crop residues and livestock manure, can significantly strengthen renewable energy production and sustainable soil management. Expanding decentralised biogas systems, promoting crop residue valorisation, and enhancing organic waste recycling can contribute to rural energy security and environmental protection. Increasing farmer training, awareness programmes, and access to appropriate technologies will further support wider adoption. Future research should focus on evaluating the long-term impacts of compost, biochar, and biogas slurry on soil health and crop productivity across different agro-ecological conditions in Bangladesh. Additional studies are needed to optimise biomass conversion technologies and assess their environmental and socioeconomic feasibility to support large-scale implementation of circular agriculture.

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UTICAJ CIRKULARNE POLJOPRIVREDE U BANGLADEŠU: STRATEGIJE STVARANJA VREDNOSTI IZ OTPADA U PROIZVODNJI BIOGASA I UPRAVLJANJU BILJNIM OSTACIMA

Md. Masud M. Rana[1] i Md. Younus M. Ali[2*]

[1]Department of Agricultural Extension Education,
Bangladesh Agricultural University, Mymensingh, Bangladesh
[2]Department of Animal Breeding and Genetics,
Bangladesh Agricultural University, Mymensingh, Bangladesh

Rezime

Cirkularna poljoprivreda (CP), proistekla iz principa cirkularne ekonomije (CE), promoviše resursno efikasne i sisteme zatvorene petlje u poljoprivredi u kojima se organski otpad pretvara u obnovljivu energiju, đubriva i sredstva za poboljšanje zemljišta. U Bangladešu, neadekvatno upravljanje stajnjakom, biljnim ostacima i organskim otpadom doprinosi emisijama gasova, degradaciji zemljišta i zagađenju životne sredine, što ukazuje na potrebu za strategijama stvaranja vrednosti iz otpada. Ovaj rad procenjuje uticaj cirkularne poljoprivrede u Bangladešu, sa posebnim naglaskom na upravljanje biljnim ostacima i proizvodnju biogasa kao ključnim putevima za oporavak resursa i proizvodnju obnovljive energije. Pregled literature sproveden je na osnovu 102 naučna rada i zvaničnih dokumenata kako bi se procenle postojeće prakse, tehnološke mogućnosti i okviri javnih politika. Strategije stvaranja vrednosti iz otpada, uključujući kompostiranje, proizvodnju biođubriva, proizvodnju bioćumura i anaerobnu digestiju omogućavaju pretvaranje poljoprivrednih ostataka u sredstva za poboljšanje zemljišta bogata hranljivim materijama i obnovljivu energiju, čime se unapređuje plodnost zemljišta, povećava produktivnost useva i smanjuje zavisnost od mineralnih đubriva. Bangladeš proizvodi više od 106 miliona tona biomase godišnje, sa potencijalom za proizvodnju preko pet milijardi m³ biogasa. Međutim, većina sistema za proizvodnju biogasa i dalje je mala zbog tehnoloških, finansijskih i ograničenja vezanih za svest. Proširenje cirkularne poljoprivrede kroz integrisano upravljanje stajnjakom, biljnim ostacima i organskim otpadom moglo bi smanjiti emisije gasova, unaprediti zdravlje zemljišta i ojačati energetsku sigurnost ruralnih područja. Jačanje izgradnje kapaciteta, transfera tehnologija, zelenog finansiranja i javno-privatne saradnje od ključnog je značaja za primenu cirkularne poljoprivrede i podršku održivim poljoprivrednim i energetskim sistemima u Bangladešu.

Ključne reči: strategija stvaranja vrednosti iz otpada, upravljanje biljnim ostacima, proizvodnja biogasa, održiva poljoprivreda.

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[*] Autor za kontakt: e-mail: younus_abg@bau.edu.bd

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GROWTH AND YIELD RESPONSES OF WHITE CABBAGE INFLUENCED BY VERMICOMPOST TEA AND VERMICOMPOST TEA RESIDUE

Hai T.T. Luu[1*], Linh T. Le[1], Nga Huynh[1] and Iain D. Green[2]

[1]Tra Vinh University, School of Agriculture and Aquaculture,
Vinh Long Province, Vietnam
[2]Bournemouth University, Faculty of Science and Technology,
Department of Life and Environmental Sciences, Poole, United Kingdom

Abstract: White cabbage (*Brassica oleracea* var. *capitata*) is one of the oldest known vegetable crops and is commonly grown worldwide. Vermicompost tea (VCT) is considered a biofertiliser and is used in sustainable agriculture to promote crop yield and improve soil properties. This study was conducted to assess the efficacy of VCT and VCT residue (the solid material remaining after producing VCT) and their competency to partly replace inorganic fertilisers for the growth and yield of white cabbage under field conditions. The results showed that the use of VCT at an extraction ratio of 1:5 combined with 50% inorganic fertiliser significantly increased the cabbage head diameter and mean individual weight at harvest compared to the 100% inorganic fertiliser treatment. Noticeably, the application of VCT in a 1:5 combination with VCT residue + 50% inorganic fertilisers and VCT in a 1:10 combination with VCT residue + 50% inorganic fertilisers showed the best performances among treatments, with significant increases in the 3-m^2 plot yield of 24.7%, and 14.3%, respectively, compared to the treatment with 100% inorganic fertilisers. These results demonstrate that VCT combined with VCT residue can replace a substantial proportion of inorganic fertilisers in cabbage cultivation, thereby reducing reliance on these non-sustainable products while recycling waste materials in sustainable agriculture.

Key words: *Brassica oleracea* var. *capitata*, cabbage, organic fertilisers, vermicompost tea, vermicompost tea residue.

Introduction

There is no doubt that agricultural production is influenced by several factors such as soil condition, soil fertility, climate conditions, plant diseases, and irrigation conditions. Inorganic fertiliser is one of the most important input factors contributing to increased crop productivity, thanks to its outstanding

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[*]Corresponding author: e-mail: lthai@tvu.edu.vn

advantages in providing nutrients quickly and accurately. However, it is well-documented that excessive or improper use of chemical fertilisers in intensive cultivation has led to detrimental influences on soil quality, plants, and the environment, such as soil acidification, increased soil compaction, water pollution, increases in pest and disease problems, and a reduction in the number of soil organisms (Chali Abate, 2023). By contrast, organic fertilisers are derived from natural sources such as manure, plant residues, coffee grounds, and spent mushroom material. They are slow-release fertilisers, allowing soil microorganisms time to break down organic materials and release essential plant nutrients such as nitrogen, phosphorus, potassium, and micronutrients. Hence, organic fertilisers provide stable and long-term nutrition, helping plants absorb nutrients steadily and avoiding sudden excesses or deficiencies. In addition, organic fertilisers help supply organic matter and beneficial microorganisms, improve soil structure, increase soil porosity, increase soil water retention and drainage capacity, and improve soil pH (Assefa and Tadesse, 2019). Therefore, managers, scientists, and farmers are interested in finding organic and sustainable alternatives to conventional agrochemicals.

Due to the low nutrient content and slow-release properties of organic fertilisers, using them as a complete replacement for inorganic fertilisers could lead to nutrient deficiencies in modern crop varieties with high nutritional needs. In such cases, a large amount of organic fertiliser must be applied to meet the nutrient requirements of these crops. Research indicates that combining organic and inorganic fertilisers can increase crop productivity and quality, improve soil quality, and enhance nutrient efficiency (Khanam et al., 2022; Phillips et al., 2022; Wang et al., 2025). The sole use of organic or inorganic fertiliser cannot increase crop yields and improve soil health. Wang et al. (2025) indicated that the incorporation of manure and chemical fertiliser in wheat–wheat–maize rotation systems increased the sustainable yield index (SYI) of grain yield of maize and wheat compared to that of chemical application only in three long-term fertilisation experiments in China. Furthermore, a previous study demonstrated that the potential of integrating organic and inorganic fertilisers as a sustainable alternative to conventional inorganic fertiliszation. Combined organic and inorganic fertilisers not only reduced inorganic fertiliser use by 40% while achieving similar tomato fruit quality and quantity, but also improved the soil properties (Hernández et al., 2014).

Vermicompost (VC) is a higher-quality final product produced through the conversion of organic matter into humus-like material by earthworms (Amante, 2024). The macromineral contents of nitrogen, phosphorus, and potassium in VC are 1.5–2.5%, 0.9–1.7%, and 1.5–2.4%, respectively (Kumar et al., 2019). Due to its high content of nutrients, organic matter, humic acid, plant-growth hormones, a low C:N ratio, and a variety of beneficial microorganisms, VC significantly enhances crop growth and productivity while improving soil properties (Mohite et al., 2024; Amante, 2024). Consequently, it is widely recognised as an effective biofertiliser for sustainable agricultural cultivation (Mohite et al., 2024; Amante, 2024).

Vermicompost tea (VCT) is an organic liquid fertiliser produced by fermenting vermicompost with water for a certain period. Both aerated and non-aerated methods can be used in VCT fermentation, with supplemental nutrients such as molasses, sugars, and yeast extract added to enhance microbial activity (Ingham, 2005). Studies have shown that VCT effectively promotes plant growth and yield, improves soil properties, and suppresses plant diseases and pests due to its abundance of beneficial microbes, NPK, and other nutrient elements (Pant et al., 2012; Che Sulaiman and Mohamad, 2020; Alkobaisy et al., 2021). Research by Luu et al. (2023a) demonstrated that spraying 500 mL of 5% VCT every five days increased the individual weight of Chinese kale plants by 27.5% compared to no VCT application. Additionally, the study by Souffront et al. (2022) revealed that using 200 mL of VCT per tomato plant via soil drenching with concentrations of 10% and 20% resulted in heavier tomato fruit weight and higher total marketable yield compared to the 5% VCT treatment and the control (no VCT application). Furthermore, after brewing and filtering to collect VCT, the solid organic material residue (referred to as VCT residue) can be applied to soil or plants. However, no previous studies have demonstrated its efficacy in agricultural cultivation.

White cabbage (*Brassica oleracea* var. *capitata*) belongs to the Brassicaceae family and is one of the oldest known vegetables. Cabbage is a biennial plant, but is commonly grown as an annual crop, characterised by dense-leaved heads (Stefan and Ona, 2020; Chanu et al., 2025). Cabbage is popularly cultivated globally, including Vietnam, and has high commercial value (Chanu et al., 2025). Due to its high content of fibre, minerals, vitamins, and antioxidants, white cabbage provides several health benefits, including anti-cancer activity, improved gastrointestinal health, antioxidant activity, anti-obesity, hypolipidaemic, and hypoglycaemic effects (Stefan and Ona, 2020).

There is strong evidence that VCT has significant potential as an organic foliar fertiliser for various crops, effectively increasing production and supporting the sustainability of agricultural systems. However, no previous studies have assessed the effectiveness of the VCT residue in enhancing crop yield. As a result, the present study investigated the growth-promoting efficiency of VCT and VCT residue on the growth and yield of the plant *Brassica oleracea* var. *capitata*. The study results could demonstrate the effectiveness of VCT individually and in combination with VCT residue in enhancing crop yields by recycling nutrients from waste products. This not only improves crop yields but also helps maintain environmental sustainability in farming.

Material and Methods

This study was conducted under field conditions from October 2024 to January 2025 in Cang Long commune, Vinh Long province, Vietnam. The soil at the experimental site is classified as loam with a pH of approximately 5.5.

Field preparation and fertiliser application

The field was ploughed, levelled, and formed into ridges for transplanting seedlings. Each ridge was 20 cm high above the field surface and 1 m wide. Between two adjacent ridges, there was a 15-cm-wide furrow to facilitate drainage and maintenance of the experiment. The experimental area was divided into plots of 3 m^2.

To produce white cabbage in this experiment, the local cultivation practice followed by the local farmers in Cang Long commune was applied. An inorganic NPK fertiliser (for the top-dressing period) was used with a formula of 180 N, 120 P_2O_5, and 120 K_2O (kg/ha).

Table 1. Top-dressing fertilisers used in the experiment.

Day after planting	Inorganic fertiliser application (kg/ha)							Note
	T1	T2	T3	T4	T5	T6	T7	
10	400	200	200	200	200	200	200	NPK (20–10–10)
20	200	100	100	100	100	100	100	
40	350	175	175	175	175	175	175	NPK (17–17–17)

Source: Authors' calculations. T1–T7: Seven treatments of this experiment.

Noticeably, for basal fertilisation, all treatments applied the same amount and type of fertiliser (per 1 ha), including: 15 tonnes of composted manure, 200 kg of phosphate fertiliser (16%, containing 32 kg of P_2O_5), and 100 kg of calcium-magnesium fertiliser (Sao Vang Mekong Company, Vietnam). Calcium-magnesium fertiliser helps stabilise pH, improve soil, and provide micronutrients for crops. For top-dressing fertilisation, the amount and type of top-dressing fertiliser depended on each treatment. The time and dosage of inorganic top-dressing fertilisers are presented in Table 1.

Vermicompost tea (VCT) was applied by spraying at a rate of 200 mL per plant at different dilution levels corresponding to the treatments. After the cabbage head formed, VCT was irrigated at the plant base to prevent it from remaining on the head. VCT residue was used at a rate of 200 g per plant and distributed around the base of each plant. VCT and VCT residue applications were made every 7 days. The first and last applications of VCT and VCT residue were made 10 days and 44 days after planting, respectively. Treatment T1 received 100% of the top-dressing fertilisers; the remaining treatments (T2 to T7) received inorganic top-dressing fertiliser at 50% of the application rate used in treatment T1, supplemented either with VCT alone or in combination with VCT residue. A 20–10–10 NPK fertiliser (Yaramila PLUS) was used 10 and 20 days after planting, and a 17–17–17 NPK fertiliser (Viet Duc Fertilizer Company, HCM City, Vietnam) was used 40 days after planting.

Preparation of the transplants

This study used heat-tolerant white cabbage seeds (TROPIC-SUNPLUS F1; Chanh Nong Company, Vietnam). The seeds were sown in an 84-hole foam seedling tray with a growing medium consisting of coconut peat, rice husk ash, and clean loam soil in a ratio of 1:1:1. On the 7th and 14th day after seedling, fish fertiliser (concentration of 1%) was applied. Transplants were planted when they had 4–6 true leaves.

Experimental design

To assess the efficiency of vermicompost tea (VCT) and vermicompost tea residue (VCT residue) on the growth and the yield of white cabbage (*Brassica oleracea* var. *capitata*), a one-factor experiment was conducted using a completely randomised design (CRD) under field conditions. The experiment included seven distinct treatments, as follows:

T1: 100% top-dressing inorganic fertilisers (control)

T2: Vermicompost tea at an extraction ratio of 1:5 + 50% inorganic top-dressing fertilisers (VCT 1:5)

T3: Vermicompost tea at an extraction ratio of 1:10 + 50% inorganic top-dressing fertilisers (VCT 1:10)

T4: Vermicompost tea at an extraction ratio of 1:15 + 50% inorganic top-dressing fertilisers (VCT 1:15)

T5: Vermicompost tea at an extraction ratio of 1:5 with adding 200 g plant^{-1} of vermicompost tea residue + 50% inorganic top-dressing fertilisers (VCT 1:5 + VCT residue)

T6: Vermicompost tea at an extraction ratio of 1:10 with adding 200 g plant^{-1} of vermicompost tea residue + 50% inorganic top-dressing fertilisers (VCT 1:10 + VCT residue)

T7: Vermicompost tea at an extraction ratio of 1:15 with adding 200 g plant^{-1} of vermicompost tea residue + 50% inorganic top-dressing fertilisers (VCT 1:15 + VCT residue)

The treatments were replicated three times. Each replication consisted of a plot of 3 m², planted with 10 seedlings at a spacing of 50 cm × 70 cm between plants.

Vermicompost tea preparation

Vermicompost tea (aqueous extract) was freshly prepared every 7 days before application, using the same type of vermicompost. The vermicompost was obtained from Dang Gia Trang Production Trading Services Company Limited (HCM city, Vietnam), and contained 48.4% organic matter, 1.57% nitrogen, 1.24% available phosphorus, and 0.67% available potassium.

The extraction ratios for the tea were 1:5, 1:10, and 1:15 (w/v) of vermicompost to water, employing the aerated method. This preparation method was modified from the method of Ingham (2005). Vermicompost (VC) was placed into a gauze sack, which was then tied tightly and put in a suitable plastic container. Dechlorinated water was added in appropriate volumes to achieve the desired vermicompost tea dilutions, along with 5% molasses (calculated based on the percentage of the vermicompost quantity). The mixture was then actively aerated for a 24-hour extraction period using a mini double-nozzle aerating pump. After the fermentation process, 200 mL of vermicompost tea, with extraction ratios of 1:5 (VCT 20%), 1:10 (VCT 10%), and 1:15 (VCT 6.7%), were used as a foliar fertiliser to spray each plant for the respective treatments. When the plant leaves began to compact to form the cabbage head, the vermicompost tea was applied at the plant base. Vermicompost tea residue remaining after VCT extraction was also applied at a rate of 200 g per plant in treatments T5–T7.

Data collection

Five of the 10 plants in each plot were selected randomly to collect data. The growth parameters, including plant height (cm), stem diameter and foliage diameter (cm) of cabbage plants were recorded every 10 days after planting. The number of cabbage leaves was counted at 10 and 20 days after planting, until the cabbage plants began to form heads. The diameter of the cabbage head was measured at 40, 50, and 56 days after planting. The yield parameters were determined on the harvest day (56 days after planting). In terms of yield parameters, cabbage heads were harvested on the harvest day. The fresh mean weight of cabbage heads was determined from the five selected plants per plot, representing individual plant yield, while plot yield was calculated as the total fresh weight of all ten plants within each plot.

Data analysis

Statistical analysis was conducted using SPSS *v.* 22 (IBM Inc.). One-way ANOVA was used to determine the statistical significance of differences in growth and yield parameters of white cabbage plants among different treatment groups.

Before comparing the means of all treatments, the data sets were analysed for homogeneity of variance with the Levene's test to ensure that all comparison groups had the same variance. When this assumption was not met, the Welch's test was used as an alternative analysis. The significance of the effects of VCT and VCT residue on the growth and yield of cabbage plants among treatments was determined by the Duncan's *post-hoc* test at $p < 0.05$.

Results and Discussion

Effects of vermicompost on the growth parameters of white cabbage

Differences in the plant height, foliage diameter, the number of leaves and the diameter of cabbage head among the seven different treatments during the experimental period are shown in Tables 2, 3, and 4.

In general, insignificant differences in cabbage plant height among treatments were observed at most sampling points during the growing period, the exception being at 20 days after planting (Table 2). At 10 days after planting, there were no significant differences in plant height among treatments. However, the application of VCT and VCT residue at this stage began to influence plant growth. By 20 days after planting, cabbage plants treated with VCT and/or VCT residue had been taller than those in the treatment receiving only inorganic fertiliser, as confirmed by one-way ANOVA (Table 2). The analysis showed significant differences in plant height among treatments, with those receiving VCT and/or VCT residue generally outperforming the control (inorganic fertiliser only), except for treatment T2. From 30 days after planting onwards, the plants began forming cabbage heads, which may explain the reduced variation in plant height among treatments during the later stages (30 to 56 days). Consequently, no significant differences in plant height were detected among treatments during these periods (Table 2).

Vermicompost tea (VCT) and VCT residues positively influenced the foliage diameter of cabbage plants in this study (Table 3). After the application of VCT and VCT residues, the foliage diameter of plants in these treatments was greater than that of plants treated with 100% inorganic fertiliser. Notably, at 20 days after planting, the foliage diameter in the inorganic fertiliser-only treatment was significantly lower than in all treatments that received VCT and/or VCT residues.

Table 2. Effects of vermicompost tea and vermicompost tea residue on the height of white cabbage plants.

Treatments	Plant height (cm) in different growth periods					
	10 days	20 days	30 days	40 days	50 days	56 days
T1 (control)	10.13	13.13b	21.87	24.87	31.20	31.40
T2	9.80	14.07ab	20.20	25.87	31.87	33.80
T3	10.53	15.97a	22.37	25.87	29.4 0	32.33
T4	10.00	16.07a	22.10	29.13	32.27	34.30
T5	10.13	16.20a	22.27	28.53	31.73	33.40
T6	9.07	16.37a	22.80	27.80	31.93	34.00
T7	9.77	16.23a	22.90	27.87	30.93	31.60
$F_{(6,14)}$	0.698	3.274	0.434	1.279	0.873	1.527
Sig.	ns	*	ns	ns	ns	ns
CV (%)	9.5	8.0	10.8	9.0	5.7	5.0

Values are means of three replications; *ns*: non-significant; *: statistically significant at the 5% level; means with different letters are significantly different at $p < 0.05$ according to the Duncan's *post hoc* test.
Source: Authors' calculations.

Furthermore, at 30 days after planting, the foliage diameter of cabbage plants in treatments receiving VCT alone or in combination with VCT residues increased by 17.00% to 31.88% compared with the inorganic fertiliser-only treatment (control). This trend continued up to 40 days after planting. However, by 40 days and at harvest (56 days after planting), the differences in foliage diameter between the VCT and/or VCT residue treatments and the control had decreased considerably (Table 3).

Table 3. Effects of vermicompost tea and vermicompost tea residue on the foliage diameter of cabbage plants.

Treatments	Foliage diameter (cm) in different growth periods					
	10 days	20 days	30 days	40 days	50 days	56 days
T1 (control)	17.70	24.07b	36.95	48.43c	55.90	59.57
T2	14.43	27.73a	44.53	48.90bc	60.93	62.70
T3	15.80	27.67a	43.23	51.30abc	56.50	59.13
T4	14.60	27.13a	46.60	54.10a	57.97	61.97
T5	16.83	27.90a	48.03	54.10a	59.30	62.77
T6	16.27	28.57a	47.37	55.47a	59.50	61.73
T7	16.27	28.60a	48.73	53.37ab	58.77	60.80
$F_{(6,14)}$	0.853	5.450	2.777	3.516	2.380	0.959
Sig.	ns	**	ns	*	ns	ns
CV (%)	13.7	4.2	9.4	4.9	3.4	4.2

Values are means of three replications; *ns*: non-significant; *: statistically significant at the 5% level; **: statistically significant at the 1% level; means with different letters are significantly different at $p < 0.05$ according to the Duncan's *post hoc* test.
Source: Authors' calculation.

After VCT and VCT residue application, there were differences in the stem diameter parameter between the inorganic fertiliser-only control and treatments with VCT alone or combined with VCT residue (Table 4). Subsequent statistical analysis confirmed significant differences in the stem diameter among the treatments at 20 days after planting. However, after 20 days, these differences diminished during the following growth periods. Consequently, statistical analysis indicated no significant differences in stem diameter of cabbage plants among treatments between 30 and 56 days after planting (Table 4).

Table 4. Effects of vermicompost tea and vermicompost tea residue on the stem diameter of cabbage plants.

Treatments	Stem diameter (cm) in different growth periods					
	10 days	20 days	30 days	40 days	50 days	56 days
T1 (control)	0.43	0.93b	1.38	2.06	2.24	2.38
T2	0.41	0.99b	1.37	1.93	2.28	2.53
T3	0.47	0.99b	1.41	2.00	2.17	2.47
T4	0.40	1.14a	1.41	1.99	2.26	2.45
T5	0.45	1.13a	1.41	1.95	2.24	2.52
T6	0.43	1.16a	1.42	2.00	2.28	2.40
T7	0.43	1.21a	1.43	2.03	2.26	2.45
$F_{(6,14)}$	0.275	5.881	0.045	0.344	0.846^1	0.513
Sig.	ns	**	ns	ns	ns	ns
CV (%)	17.9	7.2	13.5	6.3	2.4	5.46

Values are means of three replications; *ns*: non-significant; *: statistically significant at the 5% level; **: statistically significant at the 1% level; ^{1}: $F_{(\text{Welch's test})}$; means with different letters are significantly different at $p < 0.05$ according to the Duncan's *post hoc* test.
Source: Authors' calculation.

Differences in the number of cabbage leaves per plant among treatments are shown in Table 5. Since approximately 30% of the cabbage plants had already begun forming heads by 30 days after planting (with leaves compacting to form the cabbage head), leaf count data were recorded only at 10 and 20 days after planting. On day 10, there were no significant differences in the number of leaves among treatments. However, by day 20, treatments involving VCT and VCT residue had shown a higher number of leaves compared to the treatment receiving inorganic fertiliser only. Among these, treatment T6 recorded the highest number of leaves (11.13), representing a 31.40% increase compared to T1 (inorganic fertiliser only). One-way ANOVA analysis confirmed that the number of leaves differed significantly among treatments on day 20, and *post hoc* testing showed that the number of leaves in treatments T5 (50% inorganic fertiliser + VCT 1:5 + VCT residue) and T6 (50% inorganic fertiliser + VCT 1:10 + VCT residue) were significantly higher than in T1(inorganic fertiliser only).

Table 5. Effects of vermicompost tea and vermicompost tea residue on the number of leaves and the diameter of cabbage heads.

Treatments	The number of cabbage leaves		The diameter of cabbage head (cm)		
	10 days	20 days	40 days	50 days	56 days
T1 (control)	6.00	8.47b	9.80	15.10	16.93b
T2	4.80	8.67b	7.47	15.53	18.20a
T3	5.27	9.33ab	9.00	14.27	16.73b
T4	4.93	9.33ab	9.93	14.73	17.07b
T5	5.40	10.73a	10.93	17.20	19.03a
T6	5.73	11.13a	9.40	15.93	18.10a
T7	5.33	10.40 ab	8.67	15.40	16.67b
$F_{(6,14)}$	0.672	3.143	1.052	1.579	7.310
Sig.	ns	*	ns	ns	**
CV (%)	16.6	10.4	19.8	8.4	3.3

Values are means of three replications; *ns*: non-significant; *: statistically significant at the 5% level; **: statistically significant at the 1% level; means with different letters are significantly different at $p < 0.05$ according to the Duncan's significant difference test.
Source: Authors' calculations.

Regarding cabbage head diameter measured at 40, 50, and 56 days after planting, the results indicated variation among treatments (Table 5). Throughout the growth period, treatment T5 consistently produced the largest head diameters, measuring 10.93 cm, 17.20 cm, and 19.03 cm at 40, 50, and 56 days, respectively. Although treatment T2 recorded the smallest diameter at day 40 (7.47 cm), it showed substantial growth and reached the second-largest diameter (18.20 cm) by harvest (56 days). One-way ANOVA analysis revealed no significant differences among treatments at 40 and 50 days; however, significant differences were detected at harvest (56 days after planting).

Vermicompost (VC) and vermicompost tea (VCT) are biofertilizess considered valuable tools in sustainable agriculture. Previous studies have shown that application of VC and VCT had positive effects on the growth and yield parameters of crops (Luu et al., 2023a; Oyege and Bhaskar, 2025), soil properties, soil microbes, and the environment (Mohite et al., 2024; Yatoo et al., 2024; Oyege and Bhaskar, 2024).

In particular, the use of sole VCT or a combination of VCT and VC in agricultural cultivation has significantly promoted crop growth. Research by Yatoo et al. (2024) indicated that VC or VCT, applied alone or in combination, stimulated the height, length, number of branches, and leaf number of tomato plants. The tomato plants treated with VCT had a height of 57.80 cm; those in the VC treatment reached 68.82 cm; while the plants that received both VCT and VC grew to 74.12 cm. In contrast, the control group, which did not receive any VCT or VC, reached only 51.18 cm. The same tendency was recorded in the number of branches per tomato plant, with the highest and lowest numbers recorded in the VCT combined with VC treatment and the control, respectively (Yatoo et al., 2024).

Similarly, Oyege and Bhaskar (2025) conducted a study to evaluate the effects of VCT at varying concentrations (10%, 20%, and 40%), both individually and in combination with VC, applied at a rate of 2.47 t ha^{-1}. The results showed that treatments of VCT application alone and in combination with VC significantly increased the height of maize plants during all growth periods. Additionally, treating maize plants with 10% VCT resulted in greater height compared to treatments using 20% VCT and 40% VCT. Moreover, when 20% VCT and 40% VCT were combined with VC, the maize plants displayed better height performance than when these concentrations of VCT were applied individually (Oyege and Bhaskar, 2025).

The present observations confirm the findings of previous studies, demonstrating the beneficial effects of VC and VCT supplementation. In general, during the early stage of the growth period (20 days), plant growth performance – measured by height, foliage diameter, stem diameter, and number of leaves – was generally significantly higher in the VCT and VCT residue treatments compared to the 100% inorganic fertiliser treatment. In the later stages, only plant height and stem diameter in the VCT and VCT residue treatments were slightly improved compared to those in the 100% inorganic fertiliser treatment (T1). One plausible explanation in this case might be that in the later stages (from 30 days onward), cabbage plants concentrate nutrients on forming and developing the cabbage head (Duarte et al., 2019), so differences in growth parameters among treatments gradually narrowed. Additionally, at the time of harvest (56 days), the diameter of the cabbage head – a key factor directly linked to individual yield – was greater in the treatment combining VCT 1:5 with VCT residue (T5) and in the treatment combining VCT 1:10 with VCT residue (T6). These results were improved compared to the treatments that used only VCT at the respective concentrations (Table 5).

The findings of this study showed that the application of VCT in combination with VCT residue (the solid material remaining after producing VCT from original vermicompost material) resulted in improved growth performance. This aligns with the findings of Oyege and Bhaskar (2025), who demonstrated that VCT combined with VC stimulated maize growth more than VCT alone. These results suggest that the applications of VCT and VCT residue can enhance nutrient uptake, provide growth-promoting hormones, and improve soil properties, leading to increased plant growth performance (Che Sulaiman and Mohamad, 2020; Alkobaisy et al., 2021; Mohite et al., 2024; Amante, 2024).

Effects of vermicompost tea and vermicompost tea residue on the yield parameters of white cabbage head

The results of this study revealed large variations in the average individual weight of cabbage heads at harvest and the total plot yield of white cabbage across the different treatments (Table 6, Figure 1). The average weight of a single cabbage head in treatment T5 (VCT 1:5 + VCT residue + 50% inorganic fertiliser) was the highest, with a mean of 1.24 kg, representing a 49.4% increase compared to the treatment using only inorganic fertiliser (T1). Following T5, treatment T6 (VCT 1:10 + VCT residue + 50% inorganic fertiliser) had a mean cabbage head weight of 1.01 kg. Consequently, one-way ANOVA analysis indicated significant differences in individual cabbage head weight among treatments. Notably, the average individual cabbage head weight in treatment T5 was significantly higher compared to all other treatments (Table 6).

Table 6. Effects of vermicompost tea and vermicompost residue on the individual weight and plot yield of cabbage plants.

Treatments	The individual weight and plot yield of cabbage head (fresh weight)	
	Individual weight (kg cabbage^{-1})	Plot yield of 3 m^2 (kg)
T1 (control)	0.83 ± 0.02cd	7.00 ± 0.15cd
T2	0.96 ± 0.02b	7.50 ± 0.17c
T3	0.81 ± 0.06d	6.90 ± 0.10d
T4	0.79 ± 0.05d	6.80 ± 0.12d
T5	1.24 ± 0.05a	8.73 ± 0.29a
T6	1.01 ± 0.03b	8.00 ± 0.12b
T7	0.94 ± 0.03bc	7.20 ± 0.12cd
$F_{(6,14)}$	16.699	18.279
Sig.	**	**
CV (%)	6.7	3.8

Values are means of three replications; **: statistically significant at the 1% level; means with different letters are significantly different at $p < 0.05$ according to the Duncan's significant difference test.
Source: Authors' calculations.

In terms of plot yield, the highest total cabbage yield, 8.73 kg per 3 m² plot, was recorded in treatment T5 (VCT 1:5 + VCT residue + 50% inorganic fertiliser), while the lowest yield, 6.80 kg per 3 m² plot, was observed in treatment T4 (VCT 1:15 + 50% inorganic fertiliser). In treatment T1 (inorganic fertiliser only), the cabbage yield reached 7.00 kg per 3 m^2 plot, which was 1.73 kg lower than the plot yield in treatment T5. Consequently, the yield in treatment T5 was 24.7% higher compared to treatment T1 (inorganic fertiliser only). Meanwhile, the cabbage yield in treatment T2 (applications of VCT 1:5 and 50% inorganic fertiliser) increased by only 7.1% compared to treatment T1. These results indicated the effectiveness of utilising by-products (i.e., VCT residue) in agriculture (Table 6, Figure 1). Statistical analysis confirmed that plot yields in treatments T5 and T6 were significantly higher than those in the other treatments, including the inorganic fertiliser-only treatment (T1).

Figure 1. Sizes of cabbage head in different treatments.

T1 (control): 100% inorganic fertilisers; T2: VCT 1:5 + 50% inorganic fertilisers; T3: VCT 1:10 + 50% inorganic fertilisers; T4: VCT 1:15 + 50% inorganic fertilisers; T5: VCT 1:5 + VCT residue + 50% inorganic fertilisers; T6: VCT 1:10 + VCT residue + 50% inorganic fertilisers; T7: VCT 1:15 + VCT residue + 50% inorganic fertilisers. Source: Authors' photograph.

In terms of potential use of VCT alone or combined with VC to boost crop productivity, previous studies have demonstrated that VCT supplementation increased the yield of pak choi (Paint et al., 2012), broccoli (Alkobaisy et al., 2021), sugar beet (Ghaffari et al., 2022), Chinese kale (Luu et al., 2023a), tomato (Yatoo et al., 2024), and maize (Oyege and Bhaskar, 2025).

In the present study, the mean individual fresh weight of cabbage head in the VCT 1:5 treatment (20% VCT) was higher than that in the treatments of VCT 1:10 and VCT 1:15 (10% VCT and 6.7% VCT, respectively). In addition, the combination of VCT and VCT residue significantly improved the individual weight of the cabbage head. Specifically, the average individual weight of cabbage head in the treatment of VCT 1:5 combined with VCT residue (T5) achieved 1.24 kg, compared to only 0.96 kg per cabbage head in the VCT 1:5 treatment (T2), an increase of 29.2%. Similarly, increases of 24.7% and 19.0% were found in VCT 1:10 combined with VCT residue (T6) in comparison with VCT 1:10 alone (T3), and in VCT 1:15 combined with VCT residue (T7) compared with VCT 1:15 alone (T4), respectively.

A similar trend was also observed in plot yield (Table 6; Figure 1). Notably, the mean individual weight and 3-m² plot yield of cabbage heads in treatments T5 (VCT 1:5 + VCT residue) and T6 (VCT 1:10 + VCT residue) were significantly higher than in the other treatments, including the control (inorganic fertiliser only). The findings of this study highlighted the potential for partially replacing inorganic fertilisers with organic fertilisers. In this case, using VCT alone or in combination with VCT residue can reduce the use of inorganic fertiliser in the top dressing period by 50% without affecting crop productivity. Specifically, using VCT 1:5 (20% VCT) with 50% inorganic fertilisers (T2) increased individual weight and plot yield of 3 m^2 by 15.7% and 7.1%, respectively, compared to the control (100% inorganic fertilisers). Furthermore, 20% VCT combined with VCT residue (T5) improved individual weight and 3-m^2 plot yield by 49.3% and 24.7%, respectively, compared to the control. In contrast, treating VCT 1:10 (10% VCT) and 50% inorganic fertilisers (T3) decreased plot yield by 1.4% in comparison to the control, but in combination with VCT residue, plot yield increased by 14.3% compared to the control. This confirmed the results of a previous study, which found that integrating liquid fertiliser and solid organic fertiliser improved crop yield compared to using liquid fertiliser alone (Hatibie and Garantjang, 2022). The reason for this is that the combined application helps improve soil quality, enhance microbial activity, and retain nutrients for longer, thereby increasing nutrient uptake efficiency and crop growth compared to using liquid fertiliser alone (Luu et al., 2023b).

The results of this study were consistent with the findings of previous studies and confirmed the positive effects of VCT and VCT residue on crop yield. For example, Alkobaisy et al. (2021) demonstrated that spraying 1% VCT (used as irrigation water) combined with 50% inorganic fertilisers improved the weight of the main broccoli flower disc by 30.6% compared to the 100% inorganic fertiliser treatment. Moreover, treating VCT with VC was even more effective, resulting in a 35.4% increase in broccoli flower disc weight in comparison to the 100% inorganic fertiliser treatment (Alkobaisy et al., 2021). Meanwhile, Pant et al. (2012) demonstrated that 10% VCT supplementation had better effects on the yield of pak choi (*Brassica rapa*) than 5% VCT application under both greenhouse and field conditions.

To sum up, VCT and VCT residue contribute to improved growth and yield in various crops. This highlights that VCT and VCT residue contain high content of macronutrients (N, P, K), micronutrients, beneficial microorganisms, and plant growth regulators (Pant et al., 2012; Che Sulaiman and Mohamad, 2020; Alkobaisy et al., 2021; Arosha and Sarvananda, 2022). Moreover, VCT residue, the solid by-product remaining after the production of VCT from the original vermicompost material, possesses slow-release properties and a high organic content, allowing crops to absorb nutrients more effectively and enhancing soil properties (Oyege and Bhaskar, 2023). Consequently, adding VCT in combination with VCT residue in agricultural cultivation effectively promoted the growth and yield of crops. It is clear that the effects of VCT depend on the type of crops, original vermicompost material, the method of preparing VCT, and the applied method (Pant et al., 2012; Alkobaisy et al., 2021; Oyege and Bhaskar, 2024; Oyege and Bhaskar, 2025). However, this study has shown beneficial effects on cabbage yield when applied under appropriate conditions.

Conclusion

Vermicompost tea (VCT) and VCT residue had positive effects on the growth and yield of white cabbage. VCT 1:5 with 50% inorganic fertilisers resulted in significant improvements in the cabbage head diameter and average individual weight at 56 days in comparison to the treatment with inorganic fertilisers only. In contrast, the treatments of VCT 1:10 and VCT 1:15 did not show better effects on cabbage growth and yield than the inorganic fertiliser treatment alone. Noticeably, significant increases in plot yield of 24.7% and 14.3% were recorded in the treatments of VCT 1:5 in combination with VCT residue + 50% inorganic fertilizsers (T5) and VCT 1:10 in combination with VCT residue + 50% inorganic fertilisers (T6), respectively, compared to the treatment with 100% inorganic fertilisers (T1). These results revealed that VCT combined with VCT residue can replace up to 50% of inorganic fertilisers in cabbage cultivation. Consequently, the findings of this study demonstrate that a combination of VCT and VCT residue is highly effective in improving crop productivity and highlights the potential for recycling waste materials in sustainable agriculture.

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UTICAJ TEČNOG EKSTRAKTA GLISTENJAKA I NJEGOVOG OSTATKA NA RAST I PRINOS KUPUSA

Hai T.T. Luu[1*], Linh T. Le[1], Nga Huynh[1] i Iain D. Green[2]

[1]Tra Vinh University, School of Agriculture and Aquaculture,
Vinh Long Province, Vietnam
[2]Bournemouth University, Faculty of Science and Technology,
Department of Life and Environmental Sciences, Poole, United Kingdom

Rezime

Kupus (*Brassica oleracea* var. *capitata*) jedna je od najstarijih poznatih povrtarskih kultura i često se gaji širom sveta. Tečni ekstrakt glistenjaka (engl. *vermicompost tea – VCT*) smatra se biođubrivom i koristi se u održivoj poljoprivredi za povećanje prinosa useva i poboljšanje svojstava zemljišta. Ovo istraživanje sprovedeno je sa ciljem procene efikasnosti tečnog ekstrakta glistenjaka i ostatka tečnog ekstrakta glistenjaka (čvrstog materijala koji ostaje nakon proizvodnje tečnog glistenjaka), kao i njihove sposobnosti da delimično zamene mineralna đubriva u pogledu rasta i prinosa kupusa u poljskim uslovima. Rezultati su pokazali da primena tečnog ekstrakta glistenjaka i ostatka tečnog ekstrakta glistenjaka u odnosu 1:5 u kombinaciji sa 50% mineralnim đubrivom značajno povećava prečnik glavice kupusa i njenu prosečnu pojedinačnu masu pri berbi u poređenju sa tretmanom gde su primenjena samo mineralna đubriva. Posebno je uočeno da je primena tečnog ekstrakta glistenjaka u kombinaciji 1:5 sa ostatkom tečnog ekstrakta glistenjaka + 50% mineralnih đubriva, kao i tečnog ekstrakta glistenjaka u kombinaciji 1:10 sa ostatkom tečnog ekstrakta glistenjaka + 50% mineralnih đubriva, pokazala najbolje rezultate među tretmanima, sa značajnim povećanjem prinosa na parceli od 3 m² za 24,7%, odnosno 14,3% u poređenju sa tretmanom gde su primenjena samo mineralna đubriva. Ovi rezultati pokazuju da tečni ekstrakt glistenjaka u kombinaciji sa ostatkom tečnog ekstrakta glistenjaka može zameniti značajan deo mineralnih đubriva u uzgajanju kupusa, čime se smanjuje oslanjanje na ove neodržive proizvode, uz istovremeno recikliranje otpadnih materijala u održivoj poljoprivredi.

Ključne reči: *Brassica oleracea* var. *capitata*, kupus, organska đubriva, tečni ekstrakt glistenjaka, ostatak tečnog ekstrakta glistenjaka.

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[*] Autor za kontakt: e-mail: lthai@tvu.edu.vn

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INFLUENCE OF FRUIT RIPENING STAGE, POST-HARVEST SEED DEVELOPMENT, AND GENOTYPIC VARIATION ON THE MASS OF 1000 SEEDS IN EGGPLANT (*SOLANUM MELONGENA* L.)

Vukašin V. Popović[*], Slobodan A. Vlajić[1] and Adam J. Takač

Institute of Field and Vegetable Crops, Novi Sad, Serbia

Abstract: This study examined the effects of fruit ripening stage and post-harvest seed development on the mass of 1000 seeds in eggplant (*Solanum melongena* L.) across three morphologically distinct varieties (Serbian, Chinese, and Italian). Field experiments were conducted over three years (2017–2019) at the Institute of Field and Vegetable Crops in Novi Sad, Serbia. Fruits were harvested at unripe, semi-ripe, and fully ripe stages, then stored for 10 or 20 days at 20–25°C prior to seed extraction. Seeds were obtained following a three-day fermentation process and evaluated according to ISTA Rules. Fruit ripening stage was the predominant factor, explaining over 97% of the variation in seed mass. Seeds from fully ripe fruits consistently exhibited the highest mass, up to 68% greater than those from unripe fruits. Post-harvest storage increased seed mass across all ripening stages, indicating continued seed filling after harvest. Seeds extracted after 20 days showed significantly higher mass than those extracted after 10 days. The Serbian variety achieved the highest mass of 1000 seeds at full ripeness, while the Italian variety reached peak values at the semi-ripe stage following both storage durations. In contrast, the Chinese variety consistently exhibited the lowest values, highlighting genotypic differences in seed development potential. These results confirm that fruit physiological ripening and post-harvest storage significantly influence seed quality. Delaying seed extraction is an effective strategy to enhance the mass of 1000 and seed vigor, offering practical implications for breeding and seed production.

Key words: seed filling, post-harvest storage, physiological ripening, seed extraction timing, seed quality.

Introduction

Eggplant (*Solanum melongena* L.) is one of the globally important vegetable crops in the Solanaceae family, valued for both its fruit yield and seed quality, which directly influence the mass of 1000 seeds, germination capacity, seedling

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[*] Corresponding author: e-mail: vukasin.popovic@nsseme.com

vigour, and subsequent plant performance. Eggplant seeds are small, flattened, and kidney-shaped, typically concentrated in the lower half of the fruit (Gvozdenović et al., 2011).

Most researchers agree that, for seed production purposes, fruits should be harvested at advanced ripening stages to ensure optimal seed quality. For example, Popović et al. (2022) have demonstrated that the mass of 1000 seeds significantly increases in fully ripe fruits compared to earlier ripening stages. Under standard seed production conditions, the mass of 1000 seeds ranges from 4.0 to 5.3 g (Passam et al., 2010), reaching its maximum when fruits are harvested at later developmental stages and after a postharvest ripening period. Similar findings were reported by Ranaweera et al. (2021), who have shown that delaying seed extraction (via post-harvest ripening) from early-harvested fruits improves germination percentage and seed vigour. In contrast, seeds extracted too early (prior to full physiological ripening) may perform poorly. Franquiera (2015) has found that physiological seed ripening in eggplant occurs around 50 days after anthesis, when dry seed mass peaks before declining. Extraction timing after harvest also plays a critical role: Tetteh et al. (2023) observed that waiting 4 to 6 days after harvest before seed extraction improved the mass of 1000 seeds, seed vigour, and emergence across several cultivars.

The mass of 1000 seeds is considered a key indicator of seed quality. It plays a critical role in determining sowing rates and is closely related to seed vigour. Seeds with a higher mass of 1000 seeds typically contain more nutrient reserves, germinate more quickly and uniformly, are more tolerant to environmental stresses, and tend to produce more robust seedlings. Consequently, such seeds are also more suitable for long-term storage.

Despite existing knowledge on seed ripening in eggplant, there is still a lack of integrative and quantitative analyses addressing the combined and interactive effects of fruit ripening stage, post-harvest storage duration, and genotypic variation on the mass of 1000 seeds. This gap limits both the physiological understanding of seed development and the optimisation of seed production practices. Therefore, this study was designed to provide a systematic and comparative evaluation of these factors across three morphologically distinct eggplant genotypes under controlled experimental conditions. It was hypothesised that delayed fruit harvest and extended post-harvest storage would enhance seed mass through continued seed filling, with genotype-specific responses. The findings are expected to contribute to improved seed production strategies and to provide a basis for optimising harvest timing and post-harvest handling in eggplant seed systems.

Material and Methods

Field experiment

The field experiment was conducted over a three-year period (2017–2019) at the experimental station of the Institute of Field and Vegetable Crops, situated in Rimski Šančevi near Novi Sad, Serbia (E45°19'52.2"N, 19°50'10.4"E). This site, characterised by a temperate continental climate and fertile loamy soils, was used consistently throughout the trial period to ensure uniform agroecological conditions. Seeds were sown in a controlled greenhouse at the beginning of April each year. Transplanting to open-field conditions took place in the second half of May, following a randomised block design with five replicates. Each variety was represented by 250 plants (50 plants per replicate), arranged in rows spaced 70 cm apart, with 50 cm between plants within rows.

Plant material

Three morphologically distinct eggplant varieties were used in the study: Domaći srednje dugi, Chinese snake-like (Chinese variety) and Violeta lunga di Romagna (Italian variety).

1. Domaći srednje dugi (Serbian variety) – Fruits are oval-shaped, dark purple to bluish in colour, with green calyx lobes. The average fruit length is 18.6 cm, width is 8.5 cm, and the mean weight of unripe fruits is 243 g (Figure 1).

Figure 1. Domaći srednje dugi (Serbian variety).
Source: Authors’ own photograph.

2. Chinese snake-like (Chinese variety) – The fruit is elongated, glossy, and dark purple to black in colour. The average fruit length is 29.3 cm, width is 6.5 cm, and the mean fruit weight is 228 g (Figure 2).

Figure 2. Chinese snake-like (Chinese variety).
Source: Authors' own photograph.

3. Violeta lunga di Romagna (Italian variety) – The fruit is large, elongated, and purple to dark purple in colour, with green calyx lobes. The average fruit length is 21.3 cm, width is 7.4 cm, and average fruit weight is 315 g (Figure 3).

Figure 3. Violeta lunga di Romagna (Italian variety).
Source: Authors' own photograph.

Seed extraction and determination of the mass of 1000 seeds

To assess the mass of 1000 seeds of eggplant (*Solanum melongena* L.), fruits were harvested at three physiological ripening stages: unripe (fully developed with dark purple epidermis), semi-ripe (light purple skin), and fully ripe (brownish-yellow skin indicating physiological ripening) (Figure 4).

Figure 4. Three stages of fruit ripening.
Source: Authors' own photograph.

Immediately after harvest, fruits were divided into two treatment groups based on post-harvest storage duration before seed extraction:

Group 1: Fifty fruits from each ripening stage were stored in a shaded warehouse at ambient temperature (20–25°C) for ten days after harvest.

Group 2: Another fifty fruits per ripening stage were stored under identical conditions for twenty days after harvest.

Following the designated storage period, all fruits were manually chopped into smaller pieces to facilitate pulp breakdown. The macerated fruit material was then placed in sterile plastic containers and left to ferment for three days at room temperature (22–25°C). Fermentation promotes the enzymatic degradation of the fruit pulp, enabling easier detachment of seeds. After fermentation, seeds were manually separated by thoroughly rinsing with tap water over a fine-mesh sieve (1 mm), ensuring the removal of any adhering pulp or mucilage. Cleaned seeds were air-dried under ambient laboratory conditions (22–25°C, 40–60% relative humidity) for seven days, avoiding direct sunlight to prevent thermal damage. Once completely dry, seeds were stored in paper envelopes in a dry, dark room for 60 days before analysis, to ensure physiological stabilisation.

Measurement of the mass of 1000 seeds

The mass of 1000 seeds was determined following the guidelines of the International Rules for Seed Testing (ISTA Rules, 2017). The procedure was as follows: For each sample (ripening stage × storage duration × variety), eight replicates of 100 seeds were counted manually using an optical seed counter to ensure accuracy and avoid mechanical damage. Each replicate of 100 seeds was weighed using a calibrated precision analytical balance (Mettler Toledo, ±0.001 g accuracy), previously zeroed and tested with certified calibration weights. The arithmetic mean of the eight replicate measurements was expressed in grams per

100 seeds (g) and reported as the mass of 1000 seeds. During measurement, ambient humidity and temperature were monitored and kept stable to avoid fluctuations in seed moisture content. This method ensured accurate and repeatable evaluation of the mass of 1000 seeds, allowing for statistically robust comparisons between treatments and varieties.

Statistical analysis

The statistical analysis of experimental data was conducted using the Statistica 13 software package (2015), developed by StatSoft, Inc., Tulsa, OK, USA. The results were processed using appropriate statistical procedures, including analysis of variance (ANOVA) at significance levels of α =0.01 and α=0.05, Fisher's Least Significant Difference (LSD) test at α=0.01 and α=0.05, and Tukey's Honestly Significant Difference (HSD) test at α=0.01. Data are presented in both tabular and graphical formats and served as the basis for drawing conclusions relevant to the research problem.

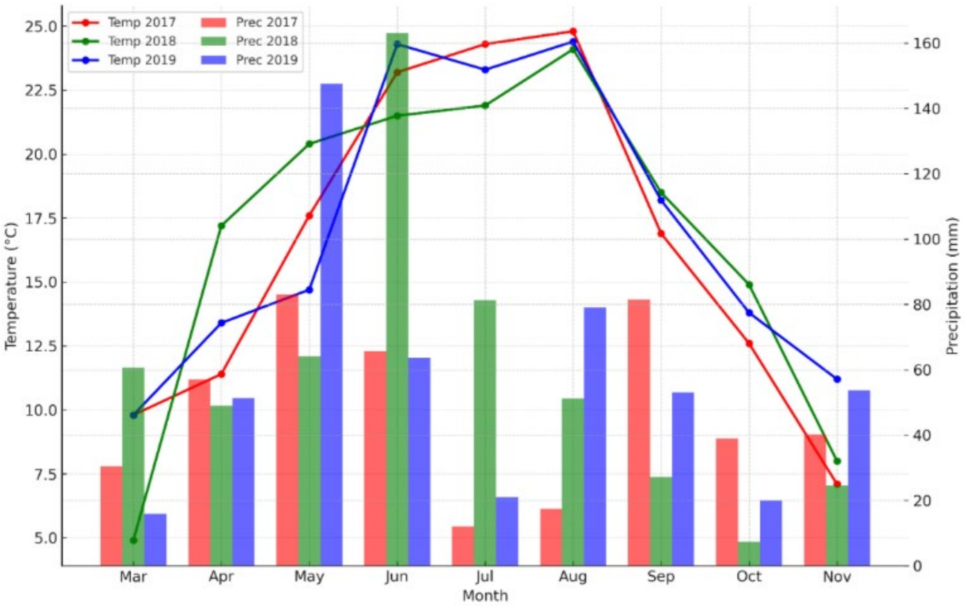

Figure 5. Climatic conditions at Rimski Šančevi during eggplant (*Solanum melongena* L.) growing seasons (2017–2019), represented by a Walter-style diagram of monthly temperature and precipitation.

Source: Meteorological data on air temperature and precipitation were obtained from the Republic Hydrometeorological Service of Serbia (2025).

Meteorological data

Meteorological data on air temperature and precipitation for the study period were obtained from the Republic Hydrometeorological Service of Serbia (Republic Hydrometeorological Service of Serbia, 2025) and are presented in Figure 5, which displays monthly mean values for temperature and precipitation across the three growing seasons (2017–2019). Average air temperatures exhibited relatively consistent patterns over the observed years, with August being the warmest month in all seasons (mean: 24.4°C). In contrast, precipitation levels were more variable, with 2017 recording notably lower rainfall overall, while June 2018 and May 2019 had the highest precipitation within their respective years.

Results and Discussion

The evaluation of the mass of 1000 seeds in three eggplant varieties – Serbian, Chinese, and Italian, across different ripening stages and two post-harvest extraction times revealed clear and consistent developmental patterns (Figure 6; Tables 1 and 2). Seeds extracted from unripe fruits displayed the lowest mass, while those from fully ripe fruits reached the highest levels, confirming the expected physiological progression of seed filling during fruit ripening. On the tenth day after harvest, mean values ranged from 1.76 to 2.17 g in unripe fruits, from 3.08 to 3.28 g in semi-ripe fruits, and from 4.39 to 4.69 g in fully ripe fruits (Figure 6).

When extraction was delayed to the twentieth day, all values increased, reaching 2.39–2.66 g, 3.41–3.64 g, and 4.58–4.88 g for unripe, semi-ripe, and fully ripe fruits, respectively (Figure 6). These increments demonstrate that seed development continues during post-harvest storage, even without a vascular connection to the mother plant. Such post-harvest increases were especially pronounced in seeds from unripe fruits, whose mass rose from 2.00 to 2.54 g (Table 1), whereas seeds from fully ripe fruits showed smaller yet still significant gains (4.55 to 4.76 g; Table 1), reflecting their proximity to physiological ripening.

Variance analysis further underscored the dominant role of ripening stage in determining the mass of 1000 seeds. In both extraction periods (Table 2), ripening accounted for more than 97% of total variability, while the effects of variety and production year were statistically significant but comparatively minor.

Interactions among factors were generally non-significant, except for the strong combined effects of extraction time and ripening stage observed in the integrated analysis (Table 1), which confirmed that the magnitude of post-harvest seed filling depends heavily on whether fruits were harvested at an early, intermediate, or advanced stage. Among varieties, the Chinese genotype consistently produced seeds with significantly lower mass than the Serbian and

Italian varieties, regardless of ripening stage or extraction time (Figure 6; Tables 1 and 2). This pattern suggests intrinsic genotype-specific differences in assimilate allocation and seed-filling efficiency.

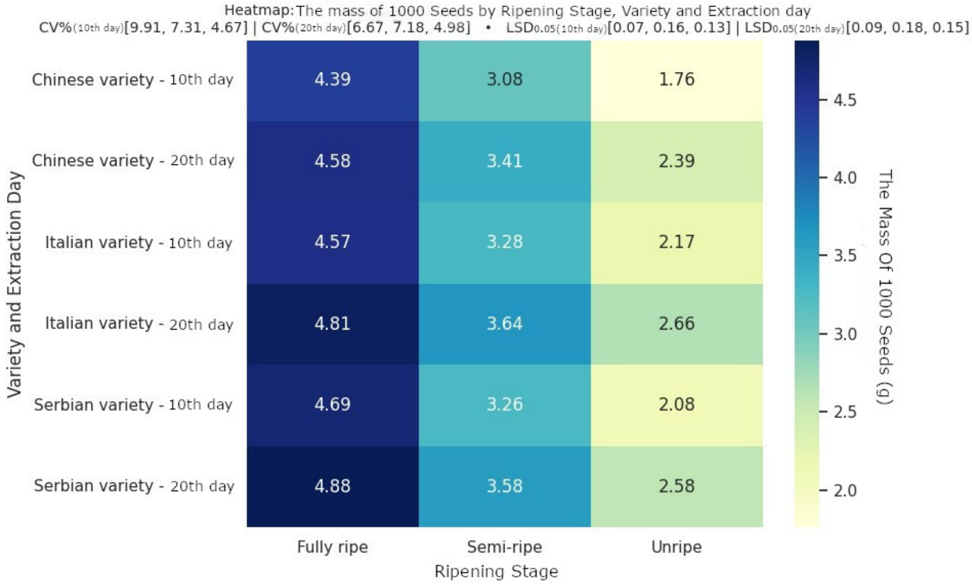

Figure 6. Variation in the mass of 1000 seeds of eggplant (*Solanum melongena* L.) in relation to fruit ripening, extraction time, and variety.

*Values represent means ± standard error (SE). Data were collected for three eggplant varieties (Serbian, Chinese, and Italian) at three fruit ripening stages (unripe, semi-ripe, fully ripe), and two seed extraction times (10^{th} and 20^{th} day after fruit harvest). Coefficients of variation (CV%) and least significant differences ($LSD_{0.05}$) are provided for each combination to aid in the interpretation of statistical differences. Source: Authors' own data

The biological interpretation of these results aligns well with established concepts of seed ripening. Fully ripe fruits produced seeds that were approximately 68% heavier than those from unripe fruits on the tenth day after harvest, indicating extensive reserve accumulation and advanced embryonic development. These findings correspond with earlier observations in eggplant and other Solanaceae crops, where progressive ripening enhances dry matter deposition in seeds (Passam et al., 2010; Takač et al., 2015). Furthermore, the continued increase in seed mass during storage supports the concept of late post-harvest ripening, as described by Nonogaki et al. (2010), whereby biochemical ripening and reserve stabilisation persist after fruit detachment. This pattern of continued filling until a physiological plateau is reached reflects the classical model of mass ripening and transition into desiccation tolerance (Bewley et al., 2013).

Table 1. Analysis of variance of the effect of seed extraction timing on the mass of 1000 seeds. Tukey's honestly significant difference (HSD) test (α=0.01).

Ripening stage	Extraction time	Mass of 1000 seeds (g)
Unripe	10th day after harvest	2.00 b
	20th day after harvest	2.54 a
Semi-ripe	10th day after harvest	3.20 b
	20th day after harvest	3.54 a
Fully ripe	10th day after harvest	4.55 b
	20th day after harvest	4.76 a
Extraction time (ET)		**
Ripening stage (RS)		**
Variety (V)		**
ET x RS		**
ET x V		ns
RS x V		**
ET x RS x V		ns

Source: Authors' own data.

Similar dynamics have been reported in sweet pepper, where a seven-day fruit resting period significantly improved seed mass and protein content (Colombari et al., 2022), and in zucchini, where delayed extraction from 3 to 12 days enhanced seed dry weight and vigour (Aguilar et al., 2024). Studies on pumpkin (Pattar et al., 2025) and cereals, such as *Kengyilia melanthera* (Ling et al., 2023) and durum wheat (Jawad et al., 2025), provide broader evidence that delayed harvest or delayed extraction favours seed quality across taxa.

Table 2. Analysis of variance of main effects and their interactions on the mass of 1000 seeds at two post-harvest extraction periods (10th and 20th day).

Source of variation	Degrees of freedom	10th day			20th day		
		MS#	SS	SS (%)	MS	SS	SS (%)
Total	14	10.72	150.03	100.00	8.16	114.17	100.00
RS*	2	73.17**	146.33	97.53	55.47**	110.94	97.17
V	2	1.06**	2.13	1.42	0.82**	1.63	1.43
Y	2	0.53**	1.06	0.71	0.58**	1.16	1.02
RS×V	4	0.08	0.32	0.21	0.03	0.12	0.11
V×Y	4	0.05	0.19	0.13	0.08	0.32	0.28
Error	120	0.02	2.43	-	0.03	3.35	-

**(p<0.01) # Variability explained as percentage of sum of squares (SS %); mean square (MS); *Ripening stage (RS); Variety (V); Year (Y).

Source: Authors' own data.

Recent studies further illuminate the physiological mechanisms underlying these trends. Tetteh et al. (2023) demonstrated that delaying seed extraction by 4–6 days in eggplant significantly improved seed weight, vigour, and germination.

Ranaweera et al. (2021) have confirmed that post-harvest storage of fruits improves seed quality, especially in less ripe fruits, closely paralleling the strong responses observed in unripe and semi-ripe fruits (Table 1). In addition, newly published research highlights the influence of post-harvest environmental conditions, namely Özmen and Kenanoğlu (2024) have shown that temperature regimes during fruit storage markedly affect seed viability and antioxidant composition, suggesting that the benefits of delayed extraction might be further optimised by controlling storage conditions.

Beyond physiology, emerging genetic evidence provides new context for interpreting varietal differences. QTL mapping in eggplant has recently identified several loci associated with seed dormancy and late-ripening traits, including dr1.1, dr2.1, and dr6.1, with the WRKY-domain gene Smechr0201082 proposed as a candidate regulator influenced by ABA and GA signalling (Ai et al., 2024). Although seed mass was not explicitly mapped in that study, the hormonal pathways involved overlapped substantially with those regulating seed filling and desiccation, suggesting potential genetic bases for the consistently lower mass observed in the Chinese variety in our study (Figure 6). A recent synthesis on eggplant seed biology has also emphasised that genotype-driven differences in dormancy and seed-filling potential represent essential targets for future breeding efforts (Popović et al., 2022). Integrating genetic markers with physiological strategies such as delayed extraction could therefore represent an effective dual approach to improving seed quality.

Environmental conditions across production years, although accounting for less than 2% of the variation (Table 2), still exerted a significant influence, consistent with observations by Rahman et al. (2017), who reported seasonal effects on seed mass and yield in Bangladesh. Given that temperature and radiation affect fruit photosynthesis and assimilate partitioning, even small year-to-year fluctuations may translate into measurable differences in seed development.

Altogether, the results of this study demonstrate that both fruit ripening stage and post-harvest extraction time were decisive for determining seed mass in eggplant, with ripening stage being overwhelmingly dominant but extraction time providing a practical means to enhance seed quality. The consistency between our findings and recent research across Solanaceae, Cucurbitaceae, and cereals reinforces the universality of the process in which seeds continue to accumulate reserves after harvest while still enclosed within the fruit. From a practical perspective, storing fruits for 10–20 days before seed extraction represents a low-cost, efficient strategy to improve the mass of 1000 seeds, particularly when fruits are harvested before reaching full physiological ripening. When combined with informed genotype selection and optimised post-harvest storage conditions, this approach offers a robust pathway toward improving seed quality and overall reproductive performance in eggplant.

Conclusion

This study demonstrates that fruit ripening stage is the primary determinant of the mass of 1000 seeds in eggplant, with fully ripe fruits producing the heaviest seeds across all varieties. Furthermore, post-harvest storage of fruits for up to twenty days enables continued seed filling, significantly increasing seed mass regardless of initial ripening. These findings emphasise the critical roles of both physiological ripening and post-harvest handling in optimising seed development. The demonstrated capacity for continued nutrient accumulation after harvest presents a practical opportunity to refine seed extraction protocols, improve seed vigour, and enhance overall seed yield. Together, these insights contribute to a deeper understanding of eggplant seed biology and provide valuable guidance for breeders and seed producers seeking to improve seed quality and crop productivity. Based on these results, it is recommended to harvest fruits at full physiological ripening and delay seed extraction for at least 20 days after harvest, storing them in a shaded warehouse at ambient temperature (20–25°C), particularly for less ripe fruits and genotypes with lower seed-filling potential, in order to maximise seed mass and vigour.

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UTICAJ FAZE ZRELOSTI PLODA, DOZREVANJA SEMENA NAKON BERBE I GENOTIPSKE VARIJABILNOSTI NA MASU 1000 SEMENA KOD PLAVOG PATLIDŽANA (*SOLANUM MELONGENA* L.)

Vukašin V. Popović[*], **Slobodan A. Vlajić i Adam J. Takač**

Institut za ratarstvo i povrtarstvo, Novi Sad, Srbija

Rezime

Ova studija ispitivala je uticaj faze zrelosti ploda i dozrevanja semena nakon berbe na masu 1.000 semena plavog patlidžana (*Solanum melongena* L.) kod tri morfološki različite sorte (srpska, kineska i italijanska). Tokom trogodišnjeg perioda (2017–2019), poljski ogledi su izvedeni na Institutu za ratarstvo i povrtarstvo u Novom Sadu. Plodovi su brani u fazama nedozrelosti, poluzrelosti i pune zrelosti, a zatim čuvani 10 ili 20 dana na 20–25°C pre ekstrakcije semena. Seme je izdvajano nakon trodnevne fermentacije i analizirano prema ISTA pravilima. Rezultati su pokazali da je zrelost ploda ključni faktor, sa više od 97% učešća u varijabilnosti mase semena. Seme iz potpuno zrelih plodova imalo je najveću masu, i do 68% veću u odnosu na seme iz nedozrelih plodova. Dozrevanje nakon berbe povećalo je masu semena u svim fazama, potvrđujući nastavak njegovog razvoja. Seme izdvojeno nakon 20 dana imalo je značajno veću masu u poređenju sa semenom izdvojenim nakon 10 dana. Najveće vrednosti mase 1.000 semena zabeležene su kod srpske sorte u punoj zrelosti, dok je italijanska sorta postigla najviše vrednosti u poluzreloj fazi nakon dozrevanja. Kineska sorta imala je najniže vrednosti u svim tretmanima, što ukazuje na genotipske razlike. Rezultati potvrđuju značaj zrelosti ploda i dozrevanja nakon berbe za kvalitet semena. Odlaganje ekstrakcije predstavlja efikasnu meru za povećanje mase i vitalnosti semena, pružajući značajne smernice oplemenjivačima i proizvođačima semena u cilju unapređenja kvaliteta semena plavog patlidžana.

Ključne reči: nalivanje semena, skladištenje nakon berbe, fiziološka zrelost, vreme izdvajanja semena, kvalitet semena.

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[*] Autor za kontakt: e-mail: vukasin.popovic@nsseme.com

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Original scientific paper

SEED PRODUCTION FROM DIFFERENT DEVELOPMENTAL STAGES OF CABBAGE POST VERNALISATION

Janko F. Červenski[1*], Dario Đ. Danojević[1], Boris D. Adamović[2], Slobodan A. Vlajić[1], Đorđe S. Vojnović[2] and Ivana I. Tošić[3]

[1]Institute of Field and Vegetable Crops, Novi Sad, Republic of Serbia
[2]University of Novi Sad, Faculty of Agriculture, Novi Sad, Republic of Serbia
[3]Agricultural Institute of the Republic of Srpska, Banja Luka,
Bosnia and Herzegovina

Abstract: Cabbage is a biennial vegetable species and, as such, it requires vernalisation to transition from the vegetative to the generative phase. This study compared and analysed the quality and seed production after overwintering and vernalisation of cabbage in the open field at several developmental phenophases. The first treatment was carried out at the technologically mature head (TMH) formation phenophase of cabbage. The second treatment included cabbage plants at the fully-developed leaf rosette (LR) phenophase, while the third treatment included cabbage plants after the development of all rosette leaves and the removal of head leaves (OIS). In the first and third treatments, the plants overwintered in the ground, whereas in the second treatment, the plants were allowed to grow and develop naturally in the open field. Average total seed weight per plant (the main component in the seed production) varied between 26.0 g under the outer and inner stem treatment and 81.3 g under the fully developed leaf rosette treatment. As anticipated, this trait differed significantly across all three treatments. The fully developed leaf rosette treatment produced a markedly higher seed weight per plant compared with both the technologically mature head and outer and inner stem treatments.

Key words: cabbage, temperature, vernalisation, seed.

Introduction

To obtain the appropriate marketable quality of cabbage heads, seed production plays an important role in the production itself. Cabbage seed production aims to create high-quality, healthy, certified and varietally pure seeds. The production is carried out under the professional supervision of agronomists to ensure optimal conditions for the development of the cabbage seed crop.

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[*]Corresponding author: e-mail: janko.cervenski@ifvcns.ns.ac.rs

In continental climates, cabbage seed production is mostly carried out in two ways. The first method involves burying/covering technologically mature heads with their root systems in a vertical position in the soil in the open field. The second method is overwintering in the open field, with vernalisation of the plant at the 7–10-leaf rosette stage (Červenski and Medić-Pap, 2018).

The goal of seed production is to obtain high-quality seeds. Cabbage seeds should have the highest germination energy and germination rate, the appropriate absolute weight, and the highest possible seed mass per plant. Seed quality plays a pivotal role not only in achieving the desired commercial quality of cabbage heads, but also in the production of any plant species (Poštić et al., 2022). However, the seed must also meet the minimum germination rate requirement of 75%, as prescribed by the Law on Seed (Demir et al., 2008; Official Gazette of SFRY and FRY, 2013).

The entire process of cabbage seed production in the open field is greatly influenced by climatic factors, both in the vegetative and the generative phases of production. During the winter-spring period, low temperatures are possible, ranging from 0°C to below -10°C, with mild or severe frosts. The vegetative cabbage head can undergo vernalisation at 4–5°C, while the most intensive processes occur at the temperature of 5–6°C. The vernalisation period ranges from 30 to 60 days. Vernalisation lasts about 7 weeks with 12 hours of daylight and a temperature of 6°C (Červenski et al., 2025).

Cabbage seeds are mainly produced using one of the two methods mentioned above, but due to climate change, seed production may undergo certain modifications. The first modification is overwintering, with vernalisation of cabbage during the phenophase of a fully developed leaf rosette when the head is formed and folded. The second modification requires removing all leaves of the rosette and those of the developed head, leaving intact only the inner stem of the cabbage head with the base of each true leaf, the central bud and the entire root system.

The aim of the paper was to examine the seed quality, analyse the mutual relationships, and compare the possibilities of cabbage seed production after overwintering and vernalisation using three different methods of seed production in the open field.

Materials and Methods

Experimental site

The field trial was set up in 2024–2025 at Rimski Šančevi, on a chernozem soil type, under an irrigation system at the Department of Vegetable and

Alternative Crops, Institute of Field and Vegetable Crops, Novi Sad (45°19'55.7"N, 19°50'14.9"E, and 86 masl).

The study included the late white cabbage variety Futoški, originating from Serbia and adapted to the continental European climate. Due to its high sugar content and thin leaves, the Futoški variety is commonly used for fresh consumption and pickling.

Sowing for the production of TMH seedlings started on 12 June, by dense sowing in rows. On 19 June, young plants were placed into boxes with space for 66 plants. Seedlings were grown in boxes until the stage of 6–7 true rosette leaves, which is the ideal time for transplanting. Transplanting into the open field, with interrow spacing of 70 cm and 50 cm, was conducted on 16 July 2024.

Sowing of the seeds for the production of LR seedlings started by dense sowing in rows on 7 August. On 19 August, young plants were placed into boxes, each accommodating 66 plants. The production of seedlings in boxes continued until the stage of 6–7 true rosette leaves, which is the ideal time for transplanting. Transplanting into the open field, with interrow spacing of 70 cm and 50 cm, was carried out on 10 September 2024.

The trial aimed to compare the possibilities of producing cabbage seeds using three different cultivation methods in open-field conditions, following vernalisation and overwintering. The trial included three different treatments (Figure 1).

Figure 1. Three tested treatments: TMH=first treatment, LR=second treatment, OIS=third treatment.
Source: Authors' own photograph.

The first treatment (technologically mature head – TMH) involved burying cabbage plants at the phenophase of technologically formed/rolled heads, without rosette leaves.

The second treatment (fully developed leaf rosette – LR) was modified in terms of plant development. We used plants with technologically unformed (loose) or unrolled heads (head growth and rolling phase) and a complete leaf rosette, in the natural climatic conditions of an open field, without burying and without protection from low temperatures.

The third treatment (outer and inner stem – OIS) involved selecting plants from the first treatment, from which we manually removed all rosette leaves and most of the head leaves with a knife, leaving only the inner core of the cabbage head with the base of each true leaf (2–3 cm), with dormant buds (lateral buds), and the central bud. The plants prepared in this way were then buried into the ground.

The plants from the first and third treatments were buried in a vertical position, with the upper part of the plant at the soil surface or 5 cm below. After placing the cabbage plants from the first and third treatments in the dug hole, we covered them with the excavated soil and, where necessary, made a mound/elevation of the soil above the buried plant, up to a maximum of 5–10 cm above the soil surface.

The interrow spacing was 60 cm in all three treatments. The intrarow spacing was 50 cm in all three methods.

Each treatment included 60 cabbage plants, totalling 180 plants. Plant height (in cm), defined as the height of the flowering stem from the soil surface to the highest flower on the plant, was measured during the intensive flowering phase. During the physiological maturity of the seeds, each plant was individually cut with scissors and placed in a paper bag for seed collection. The seed husks were hand-picked from each plant at physiological maturity. Seed extraction and threshing were performed manually, using scissors as needed. After extracting the seeds, the number of seeds per plant and the seed weight per plant (in grams) were measured, after which the seeds were placed in labelled paper bags. The labelled paper bags were stored in the Department's seed storage cold chamber at a constant air temperature of 5°C.

After completing all the samples, we removed the seeds from the chamber and analysed their physical and physiological properties: 1000-seed weight (g), germination energy (%) and total germination rate (%). The first count (germination energy) was recorded after 5 days, and the final count (total germination rate) was recorded after 10 days. The seed germination was determined following the guidelines of the International Rules for Seed Testing (ISTA Rules, 2017).

Climatic conditions

The seedlings were buried on 2 December 2024 in dry weather conditions in the first and third treatments. The winter season in continental Europe starts on 21 December and lasts until 20 March. Cabbage vernalisation occurred in the winter season in all three treatments. The mounds/elevations of the soil above the buried plants were loosened on 25 February 2025. The winter dormancy/overwintering period (from burying to loosening) lasted 85 days in all three treatments.

Table 1. Average temperatures over a ten-day period during the vegetative and generative phases of cabbage.

Ten-day month periods	Years/Months											
	2024						2025					
	Vegetative phase					Vernalisation			Flowering/seed production			
	VII	VIII	IX	X	XI	XII	I	II	III	IV	V	VI
01–10	25	24.8	25.4	15.4	8	4.3	5.3	2.7	9	8.7	16.6	23.6
11–20	30	29.7	16	13.8	3.5	4.2	-1.4	0.6	9.4	15.7	13.7	22.1
21–31	25.2	26.8	18.5	13.7	6.1	1.7	7.5	5.3	12.2	16.7	16.4	24.6
Average	26.7	27.1	20.0	14.3	5.9	3.4	3.8	2.9	10.2	13.7	15.6	23.4
Average 2014–2023	23.6	23.6	19.1	13.9	8.6	3.9	2.0	5.3	8.1	12.7	17.2	21.8

Source: Republic Hydrometeorological Service of Serbia, https://www.hidmet.gov.rs/.

During winter dormancy (vernalisation) from 2 December 2024 to 25 February 2025, the average air temperature in the open field ranged from -1.4 to 7.5°C. Because there were no serious frosts or low temperatures during this period, cabbage plants from all three treatments successfully vernalised and continued their generative development (Table 1).

Similar temperatures during the winter months were also recorded in the previous ten-year period, ranging from 2.0 to 5.3°C (Table 1).

In the study, the minimum soil temperature at a depth of 5 cm ranged from 1°C to 0°C in November and December 2024. From January to March 2025, the minimum soil temperature at a depth of 5 cm was 0°C, 0°C, and 2°C, respectively (Table 2).

Table 2. Minimum soil temperature (°C) at a depth of 5 cm.

Years	Months		Years	Months		
	XI	XII		I	II	III
2024	1	0	2025	0	0	2
Average 2014–2023	1.4	-0.4	Average 2014–2024	-1.4	-0.8	1.0

Source: Republic Hydrometeorological Service of Serbia, https://www.hidmet.gov.rs/.

Over the ten-year average, minimum soil temperature at a depth of 5 cm ranged from 1.4 to -0.4°C in November and December, and -1.4, -0.8 and 1.0°C in January, February and March (Table 2).

The timing for removing the soil mounds/elevation above the buried plants was determined by the onset of warmer weather in mid- to late February. During this period, the buried cabbage plants started to grow slowly, and the flowering stem emerged above the soil surface. Moreover, the plants in the second treatment, which had spent the winter in open-field conditions without burial or protection from low temperatures, also started to grow during this period.

Statistical analysis

Five replicates (plants) were analysed for each treatment. Statistical significance was assessed using the Bonferroni multiple test interval, with the significance level set at $p < 0.05$, to compare differences between treatments. A correlation study was conducted to assess the relationships between the evaluated traits. Pearson correlation coefficients were determined at the 0.05 and 0.01 probability levels. Data were processed in the software Statistica 13.2 (Dell Inc., USA).

Results and Discussion

Mean values for plant height (height of the fully developed flowering stem at flowering) ranged from 45.3 cm (OIS treatment) to 85.4 cm (LR treatment). Based on the height of the flowering stem, a significant difference was observed among the three treatments. Treatment LR produced a significantly taller flowering stem than the other two treatments (TMH and OIS). The lowest flowering stem height was recorded in treatment OIS (Figure 2-A).

Mean values for the number of seeds per plant ranged from 5016 seeds (OIS treatment) to 26203 seeds (LR treatment). The number of seeds per plant also showed significant differences among the three treatments. Treatment LR had the highest value for this trait compared to the other two treatments (TMH and OIS). The lowest number of seeds per plant was recorded in the OIS and TMH treatments (Figure 2-B).

Mean values for the total seed weight per plant ranged from 26.0 grams (OIS treatment) to 81.3 grams (LR treatment). As expected, seed weight per plant showed significant differences among the three treatments. The LR treatment recorded a significantly higher value for this trait compared to the other two treatments (TMH and OIS) (Figure 2-C).

Mean values for 1000-seed weight ranged from 3.3 grams (TMH and LR treatments) to 6.0 grams (OIS treatment). This trait showed slightly different results between the treatments compared to the previous traits. The OIS treatment had a significantly higher value for 1000-seed weight compared to the TMH and LR treatments, which had significantly lower values. However, no significant difference was observed between the TMH and OIS treatments, indicating that both treatments had similar values for this trait (Figure 2-D).

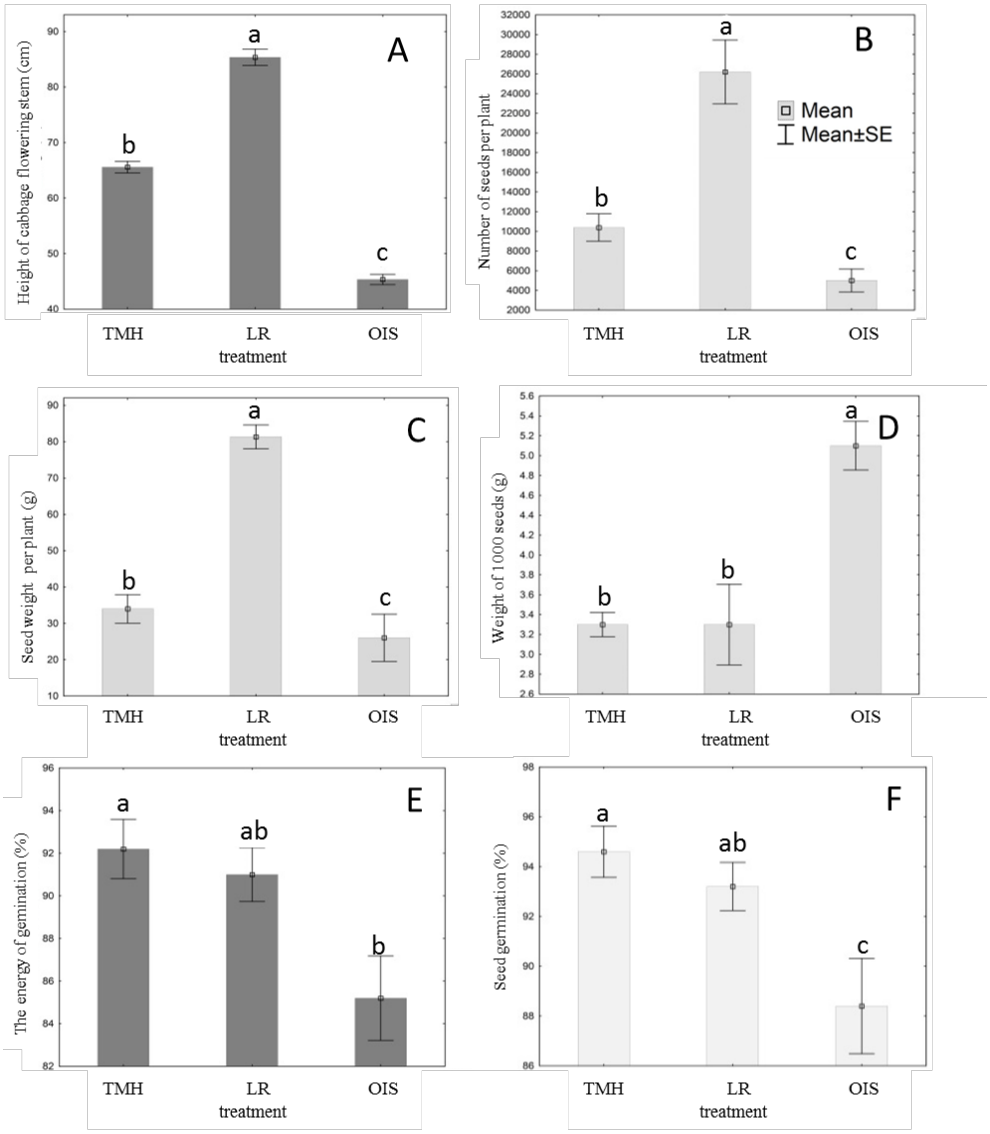

Figure 2. Mean values and standard errors for six investigated traits: A=height of cabbage flowering stalk (cm); B=number of seeds per plant; C=seed weight per plant (g); D=weight of 1000 seeds (g); E= germination energy (%); F=seed germination (%).

Source: Authors' own data and analysis.

Mean values for seed germination energy per plant ranged from 85.2% (OIS treatment) to 92.2% (TMH treatment). Seed germination energy was significantly highest in the TMH treatment, but only compared to the OIS treatment. The OIS treatment had the significantly lowest value for this trait compared to the TMH treatment (Figure 2-E).

Mean values for seed germination per plant ranged from 88.4% (OIS treatment) to 94.6% (TMH treatment). Treatment differences in seed germination were similar to those for germination energy. The highest seed germination was achieved in the TMH treatment, but only in comparison to the OIS treatment, which had a significantly lower seed germination value only in comparison to the TMH treatment (Figure 2-F).

The highest mean values for plant height, number of seeds per plant and seed weight per plant were achieved in the LR treatment. This means that the climatic conditions were quite suitable for the plants in this treatment.

Observing the mean values of the analysed traits across the treatments in Figure 2, it is evident that only the 1000-seed weight reached its highest value in the third treatment (OIS), while the mean values for the other studied traits were the lowest in this treatment compared to the other traits and treatments. This phenomenon is also illustrated in subfigures 2A, 2B, and 2C, where the third treatment (OIS) exhibited the lowest flowering stem height, the lowest number of seeds per flowering stem, and the lowest seed weight per plant. Since it had the lowest values among all treatments, the plants from the third treatment (OIS) produced fewer seeds per plant, which resulted in a higher absolute seed weight in this treatment (OIS) (Figure 2-D).

Plant height showed highly significant positive correlations with seed weight per plant (0.86) and number of seeds per plant (0.82). Significant positive correlations were also observed between plant height and germination energy (0.53) and seed germination (0.51). Plant height had a highly significant negative correlation with 1000-seed weight (-0.66).

Cabbage is a biennial plant species that forms heads in the first year and develops generative organs in the second year of production (Červenski et al., 2022).

Utilising the vernalisation phase for stable seed production is possible in continental climate conditions; however, the seasonal factor can be limiting due to the occurrence of extremely low negative temperatures that can destroy the crop (Adžić et al., 2023).

Cabbage seeds can be produced in several ways, but in continental conditions, two methods are most common. The first method involves producing technologically mature cabbage heads and burying/covering the heads underground in the first year, followed by vernalisation, flower formation, and seed production in the second year. The second method is the open field production, where cabbage plants form 7–10 true leaves of the rosette.

Table 3. Correlations between the studied cabbage traits.

Variable	Seed weight per plant (g)	Number of seeds per plant	1000-seed weight (g)	Seed germination energy (%)	Seed germination (%)
Plant height (cm)	0.86 **	0.82 **	-0.66 **	0.53 *	0.51 *
Seed weight per plant (g)		0.89 **	-0.42	0.29	0.34
Number of seeds per plant			-0.69 **	0.43	0.41
1000-seed weight (g)				-0.67 **	-0.56 *
Seed germination energy (%)					0.94 **

Significance level: *=0.05; **=0.01.
Source: Authors' own calculations.

This research examined the possibility of overwintering, vernalisation and production of cabbage seeds from three different treatments under the open-field growing conditions. During vernalisation, all three treatments were influenced by the temperature conditions of the open field. The average daily temperatures during this period, i.e., from December to the end of February, ranged from -1.4 to 7.5°C.

The vernalisation process, which affects the timing of flowering, depends on the temperature conditions. The most intensive vernalisation occurs at temperatures of 5–6°C. Before cabbage becomes susceptible to low temperatures (4–10°C) for 4–12 weeks, it must reach a certain developmental stage (7 to 9 leaves or 5–6 mm in stem diameter) (Červenski and Medić-Pap, 2018; Murat Dogru et al., 2020; Wohlfeiler et al., 2022; Bute et al., 2023). The results of this study are in agreement with the cited studies, and plants from all three treatments successfully overwintered, underwent vernalisation and formed a flowering stem with seeds.

However, the production of cabbage seeds under abiotic stress conditions, such as winter freezing with prolonged frost, can affect plant structure and the quality of traits that constitute the components of yield (Adžić et al., 2025).

Vernalisation is a physiological process that occurs due to the influence of low temperatures on cabbage plants. Further changes in environmental temperatures enable stem development, flowering and seed formation. During the winter-spring period, low temperatures can range from 0 to -10°C with varying degrees of frost. Such conditions can damage or even destroy individual plants in the open field (Červenski et al., 2022).

Cabbage plants are sensitive to subzero temperatures during the head formation phenophase, which limits seed production from cabbage heads. The Mediterranean region of Europe is well suited for cabbage seed production due to the short periods of subzero temperatures, during which cabbage heads do not require any covering (Adžić et al., 2023).

The height of the flowering stem ranged from 42.9 to 89.9 cm in this study, and from 135.68 to 188.04 cm in the research by Sharma et al. (2025). The differences between our results and those cited are due to the use of different varieties in the trials, variable climatic conditions, and applied agricultural techniques.

The number of seeds per plant varied from 2140 to 36800 in our study, and from 2050.28 to 5369.88 in the research by Sharma et al. (2025). The number of seeds per plant is a varietal characteristic and is influenced by both climatic and agrotechnical conditionsTaller flowering plants usually form more shells with a greater number of seeds per plant, which was probably the reason for this variability. The number of seeds per plant had a highly significant negative correlation with 1000-seed weight (-0.69). This correlation means that if a plant produces a large number of seeds, the mass of 1000 seeds will be lower, and vice versa.

The mass of seeds per cabbage plant in this study ranged from 10.7 to 92.1 grams. The obtained values are consistent with the findings of other authors, where the seed weight per plant ranged from 5.3 to 113.42 g/plant (Bhat et al., 2017; Murat Dogru et al., 2020; Adžić et al., 2025; Sharma et al., 2025). The similarity in seed mass per plant is likely due to the comparable habitus of the plants at the time of grain filling and harvest. Seed weight per plant (g) showed a highly significant positive correlation (0.89) with the number of seeds per plant. This correlation confirms the fact that a higher number of seeds per plant directly increases the seed mass per plant.

The 1000-seed weight of the three tested treatments ranged from 2.0 grams to 6.0 grams. The results are in agreement with those obtained by other studies, where 1000-seed weight ranged from 2.77 to 6.17 g (Demir et al., 2008; Adžić et al., 2012; Bhat et al., 2017; Bute et al., 2023; Sharma et al., 2025). It should be emphasised that a larger 1000-seed mass also means a larger seed volume, but seeds of different sizes can be found within the same shell. The 1000-seed weight had a highly significant negative correlation (-0.67) with germination energy, and a significantly negative correlation (-0.56) with seed germination. This means that a greater 1000-seed mass may be associated with lower germination energy and a reduced germination rate.

The seed germination energy obtained from all three treatments ranged from 82% to 95% in this study, and from 75.5 to 96% in similar studies conducted by other researchers (Adžić et al., 2012; Poštić et al., 2022). Seed germination ranged from 82% to 97% and was within the range of 85.5% to 99% reported by similar studies (Demir et al., 2008; Adžić et al., 2012; Bhat et al., 2017; Poštić et al., 2022; Bute et al., 2023). Seed germination energy showed a highly significant positive correlation (0.94) with seed germination (Table 3). Higher germination energy in cabbage contributes to more uniform seed germination and initial growth of cabbage seedlings.

Significant positive correlations with seed germination were found for seed weight per plant (0.60) and germination energy (0.57). A highly significant positive correlation was also found between germination energy and seed germination (0.97) (Adžić et al., 2021).

A highly significant positive correlation was found between germination energy and seed germination (0.847) (Poštić et al., 2022).

The aforementioned authors have further stated that the oldest plants always overwinter best, but also that plants with a small amount of vegetative biomass are unsuitable for overwintering (Adžić et al., 2023).

The "seed-to-seed" method is the most commonly used method in seed production for cabbage (Murat Dogru et al., 2020).

Temperatures below 0°C are not effective for vernalisation, so they were not included in the calculation of heat sums (Murat Dogru et al., 2020).

It should also be noted that cabbage plants contain over 92% water, and prolonged exposure to temperatures below 0°C can have a detrimental effect on the plant. For this reason, the climatic conditions of seed production environments must be well understood.

Conclusion

Comparing the mean values of seed quality across three different treatments, after overwintering and vernalisation, the TMH treatment (buried technologically mature heads) and the LR treatment (plants with fully-developed leaf rosettes, where heads were formed in the natural climatic conditions of an open field without burial), achieved better seed quality and seed production compared to the third treatment (OIS).

For this reason, the TMH and LR treatments can be recommended for cabbage seed production, resulting in good seed quality in continental open-field conditions.

The third treatment (OIS) can be used for seed production only in exceptional cases, if the TMH and LR treatments are not feasible.

Under the current climatic conditions, it is essential to become as familiar as possible with local production conditions to maximise theseed potential of each individual cabbage plant.

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PRODUKCIJA SEMENA NAKON PROLASKA JAROVIZACIJE RAZLIČITIH RAZVOJNIH FAZA KUPUSA

Janko F. Červenski[1]*, Dario Đ. Danojević[1], Boris D. Adamović[2], Slobodan A. Vlajić[1], Đorđe S. Vojnović[2] i Ivana I. Tošić[3]

[1]Institut za ratarstvo i povrtarstvo, Novi Sad, Srbija
[2]Univerzitet u Novom Sadu, Poljoprivredni fakultet, Novi Sad, Srbija
[3]Poljoprivredni institut Republike Srpske, Banja Luka,
Bosna i Hercegovina

Rezime

Kupus je dvogodišnja povrtarska vrsta u pogledu proizvodnje semena i potrebna mu je jarovizacija za prelazak iz vegetativne u generativnu fazu. U istraživanju su upoređeni i analizirani kvalitet i produkcija semena nakon prezimljavanja i prelaska jarovizacije različitih razvojnih fenofaza kupusa na otvorenom polju. Prvi tretman je uključivao fenofazu kupusa sa tehnološki zrelom glavicom (TZG), drugi tretman je uključivao fenofazu kupusa sa potpuno razvijenom lisnom rozetom ali sa nerazvijenom glavicom (LR), treći tretman je uključivao fenofazu kupusa sa odsečenim svim listovima rozete i listovima glavice (SUK). Prvi i treći tretman su prezimljavali sa jarovizacijom ukopani u zemlju, a drugi tretman je prezimljavao sa jarovizacijom bez ukopavanja u prirodnom rastu i razvoju na otvorenom polju. Prosečna ukupna masa semena po biljci (glavna komponenta u proizvodnji semena) varirala je između 26,0 g kod tretmana spoljašnjeg i unutrašnjeg stabla i 81,3 g kod tretmana potpuno razvijene lisne rozete. Kao što se i očekivalo, ova osobina se značajno razlikovala između sva tri tretmana. Tretman potpuno razvijene lisne rozete proizveo je znatno veću masu semena po biljci u poređenju sa tretmanima tehnološki zrele glave i spoljašnjeg i unutrašnjeg stabla.

Ključne reči: kupus, temperatura, jarovizacija, seme.

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*Autor za kontakt: e-mail: janko.cervenski@ifvcns.ns.ac.rs

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ETHNOBOTANICAL SURVEY OF MEDICINAL PLANTS UTILISED BY THE PEOPLE OF BHOLA DISTRICT IN BANGLADESH

Rifat Hasan Rabbi[1*] and Farjana Talukder[2]

[1]Department of Agricultural Science, Daffodil International University, Birulia,
Savar, Dhaka, Bangladesh
[2]Department of Apparel Engineering, Barishal Textile Engineering College,
Barishal Sadar, Barishal, Bangladesh

Abstract: This ethnobotanical survey documents medicinal plant diversity and traditional knowledge in Bhola District, Bangladesh, a deltaic ecosystem underrepresented in ethnobotanical literature. Semi-structured interviews were conducted with 100 informants between June and December 2025, recording plant species, preparation methods, and therapeutic applications. In total 39 medicinal plant species from 28 families were documented, with Combretaceae and Lamiaceae being the most prevalent families (7.69% each). Trees (35.9%) and herbs (33.3%) were the dominant growth forms, while leaves (43.3%) and fruits (22.4%) were the most utilised plant parts. Decoction (46.2%) and juice extraction (23.1%) were the primary preparation methods. Relative frequency of citation (RFC) analysis revealed *Allium sativum* (0.85), *Aloe vera* (0.82), and *Curcuma longa* (0.73) as the most culturally significant species. Informant consensus factor (ICF) values ranged from 0.67 to 0.91, with digestive disorders (0.91), respiratory diseases (0.88), and skin diseases (0.86) showing the highest consensus. These findings provide baseline data for the evidence-based integration of traditional medicine into healthcare frameworks and identify priority species for phytochemical investigation and conservation management in this vulnerable deltaic ecosystem.

Key words: medicinal plants, traditional knowledge, ethnobotany, agricultural knowledge, Barisal Division in south-central Bangladesh.

Introduction

Traditional medicine serves as the primary healthcare resource for approximately 80% of the global population, particularly in developing countries with limited access to modern medical facilities (Ikhoyameh et al., 2024; WHO, 2013). The WHO Traditional Medicine Strategy 2025–2034 and Traditional

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[*]Corresponding author: e-mail: rabbi2301101012@diu.edu.bd

Medicine Global Summit recognise traditional and complementary medicine as essential for achieving Universal Health Coverage (Wong et al., 2025), reflecting mounting evidence supporting ethnomedicinal efficacy in primary healthcare delivery (Hoenders et al., 2024).

Medicinal plants represent an invaluable repository of phytochemical diversity, with approximately 50% of approved pharmaceuticals derived from natural products or semi-synthetic derivatives (Pirintsos et al., 2022). Ethnobotanical approaches demonstrate remarkable predictive power, with phylogenetically clustered medicinal plants exhibiting convergent therapeutic applications across disparate regions (Chele et al., 2025), leading to landmark discoveries from artemisinin to taxol (Soejarto et al., 2005).

Bangladesh, located within the Indo-Burma biodiversity hotspot, contains over 5,000 vascular plant species (Mukul et al., 2018) and rich ethnobotanical heritage among the Garo, Chakma, Marma, and Bengali populations (Faruque et al., 2018). However, the country faces unprecedented biodiversity loss due to habitat destruction, agricultural expansion, climate change, and urbanisation (Biswas, 2025), with 24% of animal species and 39.4% of plant species facing imminent extinction (Haseeb, 2024). The progressive erosion of traditional knowledge among younger generations driven by globalization, rural-urban migration, and a preference for allopathic medicine necessitates urgent documentation before this invaluable heritage disappears (Voeks and Leony, 2004).

Bhola District, in Bangladesh’s south-central deltaic region, presents a unique ecology characterised by riverine ecosystems, alluvial plains, and coastal influences supporting specialised flora adapted to periodic flooding and saline intrusion. Despite its ecological significance and substantial population, Bhola remains underrepresented in ethnobotanical literature, with no comprehensive documentation of its medicinal plant diversity and traditional knowledge systems, impeding conservation planning and bioprospecting initiatives (Chen et al., 2016).

This investigation addresses this gap through a comprehensive ethnobotanical survey with specific objectives: (1) documenting the diversity and taxonomic composition of medicinal plant species; (2) recording preparation methods, plant parts used, and therapeutic applications; (3) quantifying cultural consensus through ethnobotanical indices including RFC and ICF; (4) identifying priority species for phytochemical investigation and conservation. This research provides fundamental data linking traditional knowledge with scientific validation, while supporting sustainable biodiversity conservation and community healthcare advancement in this vulnerable deltaic ecosystem.

Material and Methods

The ethnobotanical survey was conducted in Bhola District, Barisal Division, south-central Bangladesh (21°54' to 22°52' N and 90°34' to 91°01' E). As Bangladesh's largest island district, Bhola encompasses 3,403.48 km² (BBS, 2024), and is bounded by Lakshmipur and Barisal districts to the north, the Bay of Bengal to the south, the lower Meghna River and Shahbazpur Channel to the east, and Patuakhali District and Tetulia River to the west (Bhuiyan et al., 2024).

Ethnobotanical data were collected between June and December 2025 using convenience and snowball sampling techniques (Tongco, 2007), following standard protocols (Alexiades & Sheldon, 1996). Semi-structured interviews and focus group discussions were held with 100 informants including local residents, traditional healers, and community elders. Free and prior informed consent was obtained following the International Society of Ethnobiology Code of Ethics (International Society of Ethnobiology, 2006).

Demographic data (age, gender, occupation) and ethnobotanical information (local names, plant parts used, preparation methods, administration frequency, and ailments treated) were collected. Field observations and participatory plant walks ensured accurate plant identification (Cotton, 2002).

Plant specimens were collected, pressed, dried, and deposited as voucher specimens in the Agricultural Herbarium, Department of Agricultural Science, Daffodil International University, with unique codes (DIU-AH-BH-XXX). Plant identification was conducted using taxonomic keys, online databases (Plants of the World Online: http://plantsoftheworldonline.org/), and relevant literature (Uddin et al., 2003), following World Flora Online nomenclature (http://www.worldfloraonline.org/).

Ethnobotanical data were organised using Microsoft Excel 2019. Plants were arranged in descending order of relative frequency of citation (RFC) values. Quantitative ethnobotanical indices were used to assess cultural significance and informant consensus (Heinrich et al., 1998).

RFC quantified the local importance and frequency of use for each species (Tardío and Pardo-de-Santayana, 2008):

$$\mathrm{RFC} = \frac{\mathrm{FC}}{\mathrm{N}} \quad (1)$$

where FC is the number of informants citing a species and N is the total number of informants (N = 100). RFC values range from 0 to 1; values ≥ 0.70 indicate high cultural significance.

ICF assessed agreement among informants for specific ailment categories (Ahmad et al., 2014):

$$\mathrm{IFC} = \frac{\mathrm{Nur} - \mathrm{Nt}}{\mathrm{Nur} - 1} \quad (2)$$

where Nur is the number of use reports per illness category and Nt is the number of species used. ICF values range from 0 to 1; values near 1 indicate high consensus and effective information exchange, while values near 0 indicate low consensus.

Results and Discussion

Demographic characteristics of informants

A total of 100 informants participated, comprising 64 males (64%) and 36 females (36%). The age distribution showed that 39% were 20–40 years, 44% were 41–60 years, and 17% were 61–80 years. Farmers constituted the majority (52%), followed by employed individuals (23%), housewives (12%), religious leaders (8%), and retired persons (5%) (Table 1). The predominance of male informants and middle-aged participants reflects patterns in South Asian ethnobotanical studies, where traditional knowledge is concentrated among older males due to cultural practices and agricultural activities (Ahmad et al., 2014; Islam et al., 2014). The lower participation of younger informants raises concerns about knowledge erosion, emphasising urgent documentation needs.

Table 1. Demographic profile of informants from Bhola District, Bangladesh.

Category	Sub-category	Number (%)
Gender	Male	64 (64%)
	Female	36 (36%)
Age (years)	20-40	39 (39%)
	41-60	44 (44%)
	61-80	17 (17%)
Occupation	Farmer	52 (52%)
	Employed	23 (23%)
	Housewife	12 (12%)
	Religious leader	8 (8%)
	Retired	5 (5%)

Source: Authors' field survey.

Taxonomic diversity and family distribution

The survey recorded 39 medicinal plant species from 28 botanical families (Table 2). Combretaceae and Lamiaceae showed the highest representation with 3 species each (7.69%), followed by Acanthaceae, Apocynaceae, Arecaceae, Cucurbitaceae, Piperaceae, Rutaceae, and Zingiberaceae each with 2 species (5.13%). The remaining 19 families were represented by a single species each. The dominance of Combretaceae and Lamiaceae aligns with global ethnobotanical patterns; these species possess diverse phytochemical profiles including flavonoids, alkaloids, and saponins (Wink, 2013). The prominence of Zingiberaceae, particularly *Curcuma longa* (RFC 0.70) and *Zingiber officinale* (RFC 0.68), reflects traditional Asian ethnopharmacology valuing rhizomatous plants rich in curcuminoids and gingerols with validated anti-inflammatory and antioxidant properties (Kocaadam & Şanlier, 2017). This distribution is similar to findings from other Bangladesh studies (Faruque et al., 2018; Islam et al., 2014; Uddin et al., 2003).

Table 2. Documented medicinal plants in Bhola District including voucher no., local name, scientific name, family, growing method, parts used, medicinal uses, preparation method and RFC.

Local name (voucher no.)	Scientific name	Family	Habit	Parts used	Medicinal uses	Method of preparation	RFC
Rasun (DIU-AH-BH-001)	*Allium sativum* L.	Amaryllidaceae	Herb	Bulb	Gastric problems, hypertension	Paste; orally	0.85
Ghritokumari (DIU-AH-BH-002)	*Aloe vera* (L.)	Asphodelaceae	Herb	Leaf	Skin diseases, dermatitis, burns, wounds	Leaf paste applied externally	0.82
Neem (DIU-AH-BH-003)	*Azadirachta indica*	Meliaceae	Tree	Leaf, bark	Acne, diabetes, malarial fever, itches	Decoction; orally/topically	0.78
Paan (DIU-AH-BH-004)	*Piper betle* L.	Piperaceae	Climber	Leaf, petiole	Digestive problems, bronchitis	Chewing; paste; orally	0.76
Amloki (DIU-AH-BH-005)	*Phyllanthus emblica* L.	Phyllanthaceae	Tree	Fruit	Coughs, hair loss	Juice extraction; orally	0.75
Narikel (DIU-AH-BH-006)	*Cocos nucifera* L.	Arecaceae	Tree	Root, fruit	Stomach ache, rheumatism	Decoction; orally/topically	0.73
Tulsi (DIU-AH-BH-007)	*Ocimum tenuiflorum* L.	Lamiaceae	Herb	Leaf	Coughs, fever	Juice extraction; orally	0.72
Karela (DIU-AH-BH-008)	*Momordica charantia* L.	Cucurbitaceae	Climber	Fruit, leaf	Diabetes, blood sugar control	Juice extraction; orally	0.71
Holud (DIU-AH-BH-009)	*Curcuma longa* L.	Zingiberaceae	Herb	Rhizome	Skin diseases, wounds	Paste/powder; topically	0.70
Supari (DIU-AH-BH-010)	*Areca catechu* L.	Arecaceae	Tree	Root, seed	Diarrhea, helminthiasis	Chewing; orally	0.70
Telakucha (DIU-AH-BH-011)	*Coccinia grandis* (L.) Voigt	Cucurbitaceae	Climber	Leaf	Diabetes	Juice extraction; orally	0.69
Ada (DIU-AH-BH-012)	*Zingiber officinale*	Zingiberaceae	Herb	Rhizome	Coughs, gastric problems	Paste/juice; orally	0.68

Table 2. Continuation.

Local name (voucher no.)	*Scientific name*	Family	Habit	Parts used	Medicinal uses	Method of preparation	RFC
Sojne data (DIU-AH-BH-013)	*Moringa oleifera* Lam.	Moringaceae	Tree	Leaf, bark, fruit	Hypertension, arthritis	Juice extraction; orally	0.68
Amm (DIU-AH-BH-014)	*Mangifera indica* L.	Anacardiaceae	Tree	Leaf, root, bark	Dental problems, diarrhea	Decoction; orally/topically	0.67
Bel (DIU-AH-BH-015)	*Aegle marmelos* (L.) Corr.	Rutaceae	Tree	Fruit, leaf	Constipation, dysentery	Juice/direct consumption; orally	0.66
Bashok (DIU-AH-BH-016)	*Justicia adhatoda* L.	Acanthaceae	Shrub	Leaf, root	Diabetes, coughs	Decoction; juice; orally	0.65
Peyara (DIU-AH-BH-017)	*Psidium guajava* L.	Myrtaceae	Tree	Leaf, fruit, seed	Diabetes, diarrhea	Decoction; juice; orally	0.64
Sarpagandha (DIU-AH-BH-018)	*Rauvolfia serpentina* (L.) Benth.	Apocynaceae	Herb	Root	Hypertension, insomnia	Decoction; powder; orally	0.63
Arjun (DIU-AH-BH-019)	*Terminalia arjuna*	Combretaceae	Tree	Bark	Heart disorders, bone fracture	Decoction; paste; orally	0.62
Lebu (DIU-AH-BH-020)	*Citrus aurantifolia*	Rutaceae	Shrub	Fruit	Fever, coughs	Juice extraction; orally	0.61
Bohera (DIU-AH-BH-021)	*Terminalia bellirica*	Combretaceae	Tree	Fruit, leaf	Constipation, anemia	Powder; orally	0.60
Haarzora (DIU-AH-BH-022)	*Cissus quadrangularis* L.	Vitaceae	Climber	Whole plant	Body pain, wounds	Paste; topically	0.60
Apang (DIU-AH-BH-023)	*Achyranthes aspera* L.	Amaranthaceae	Herb	Root, leaf, seed	Diarrhea, jaundice	Juice extraction; orally	0.59
Thankuni (DIU-AH-BH-024)	*Centella asiatica*	Apiaceae	Herb	Whole plant	Stomach disorders, dysentery	Juice extraction; orally	0.58
Horitoki (DIU-AH-BH-025)	*Terminalia chebula* Retz.	Combretaceae	Tree	Fruit, leaf	Constipation, asthma	Powder; decoction; orally	0.58
Sonalu (DIU-AH-BH-026)	*Cassia fistula* L.	Fabaceae	Tree	Fruit, leaf	Constipation, skin diseases	Direct consumption; paste; orally	0.57
Kalomegh (DIU-AH-BH-027)	*Andrographis paniculata*	Acanthaceae	Herb	Leaf, whole plant	Malaria, diabetes	Juice extraction; orally	0.56
Papaya (DIU-AH-BH-028)	*Carica papaya* L.	Caricaceae	Tree	Fruit, leaf	Dysentery, ring worm, digestive problems	Direct consumption; paste; orally/topically	0.55
Chalta (DIU-AH-BH-029)	*Dillenia indica* L.	Dilleniaceae	Tree	Fruit, bark	Digestive problems, diabetes	Direct consumption; decoction; orally	0.55

Table 2. Continuation.

Local name (voucher no.)	*Scientific name*	Family	Habit	Parts used	Medicinal uses	Method of preparation	RFC
Mehedi (DIU-AH-BH-030)	*Lawsonia inermis* L.	Lythraceae	Shrub	Leaf	Wounds, diabetes	Paste; juice; orally/topically	0.54
Bandhanya (DIU-AH-BH-031)	*Clerodendrum viscosum* Vent.	Lamiaceae	Shrub	Leaf	Jaundice, helminthiasis	Juice extraction; orally	0.53
Shatamul (DIU-AH-BH-032)	*Asparagus racemosus*	Asparagaceae	Climber	Whole plant, root	General weakness, reproductive health	Decoction; orally	0.52
Nirgundi (DIU-AH-BH-033)	*Vitex negundo* L.	Lamiaceae	Shrub	Leaf, root	Rheumatic pain, wounds	Paste; decoction; orally	0.51
Gol morich (DIU-AH-BH-034)	*Piper nigrum* L.	Piperaceae	Climber	Fruit	Fever, digestive problems	Powder; orally	0.50
Anaras (DIU-AH-BH-035)	*Ananas comosus* (L.) Merr.	Bromeliaceae	Herb	Leaf, fruit	Helminthiasis, jaundice	Juice extraction; orally	0.49
Bishalyakarani (DIU-AH-BH-036)	*Kalanchoe pinnata* (Lam.) Pers.	Crassulaceae	Herb	Leaf	Kidney stones, wounds	Juice extraction; paste; orally	0.48
Nayantara (DIU-AH-BH-037)	*Catharanthus roseus* (L.) G.Don	Apocynaceae	Herb	Leaf, flower	Diabetes, hypertension	Juice extraction; orally	0.47
Kumarilata (DIU-AH-BH-038)	*Smilax zeylanica* L.	Smilacaceae	Climber	Stem	Indigestion, weakness	Direct consumption; orally	0.46
Dhutra (DIU-AH-BH-039)	*Datura metel* L.	Solanaceae	Herb	Leaf, seed	Mental disorders, asthma	Paste; topically (caution: toxic)	0.45

Source: Authors' field survey.

Growth form distribution

Trees constituted the dominant category with 14 species (35.9%), followed by herbs with 13 species (33.3%), climbers with 7 species (17.9%), and shrubs with 5 species (12.8%) (Figure 1). The predominance of trees contrasts with numerous Bangladeshi ethnobotanical surveys where herbs typically dominate (Faruque et al., 2018), likely reflecting Bhola's unique deltaic ecosystem with extensive riverine forests. Trees accumulate higher concentrations of bioactive metabolites due to their prolonged growth (Wink, 2008); however, this preference raises sustainability concerns as harvesting bark and roots causes permanent damage. The substantial herb representation (33.3%) shows balanced utilization of different growth forms.

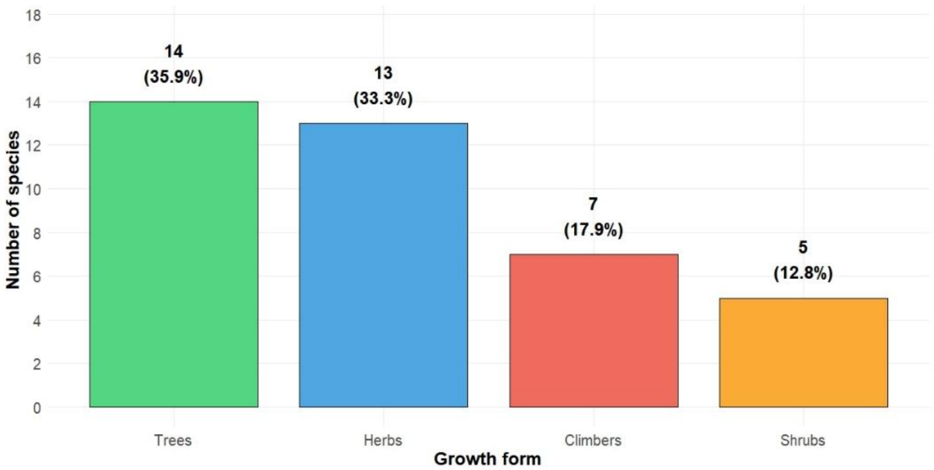

Figure 1. Distribution of medicinal plants by growth form.
Source: Authors' calculations based on field survey data.

Leaves were the most utilised plant part (43.3%, 29 uses), followed by fruits (22.4%, 15 uses), roots (11.9%, 8 uses), bark and seeds (9.0% each, 6 uses), rhizomes (3.0%, 2 uses), and bulbs (1.5%, 1 use) (Figure 2).

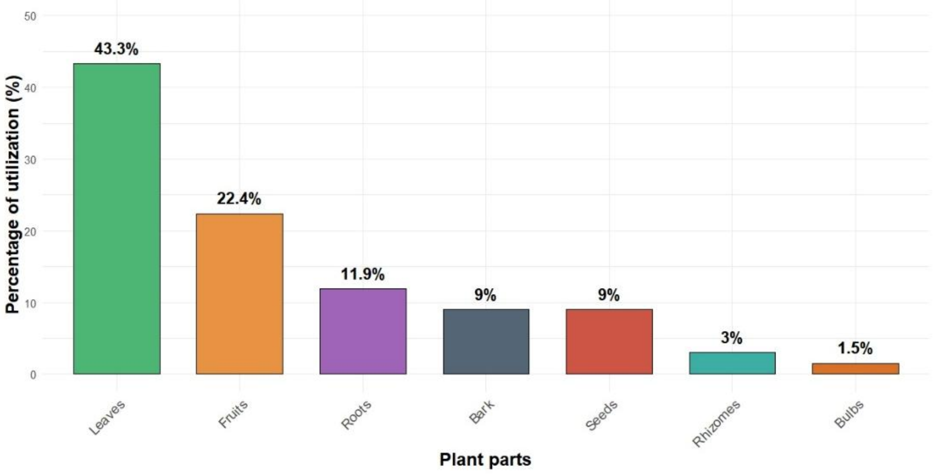

Figure 2. Frequency of utilisation of different plant parts.
Source: Authors' calculations based on field survey data.

The predominant leaf utilisation aligns with global ethnobotanical patterns and reflects both ecological sustainability and phytochemical considerations. Leaves are easily accessible, regenerate rapidly, and contain high concentrations of bioactive secondary metabolites including flavonoids, alkaloids, and terpenoids. The use of fruits as the second-most used represents an ecologically sustainable practice minimising plant mortality while maximising phytochemical access, as leaves are the primary sites for secondary metabolite biosynthesis (Ncube & Van Staden, 2015).

Methods of preparation

Decoction was the most prevalent preparation method (46.2%), followed by juice extraction (23.1%), paste/crushed application (15.4%), direct consumption (7.7%), powder (5.1%), and chewing (2.6%). Decoction effectively solubilises polar bioactive compounds, including glycosides, alkaloids, and saponins through thermally-assisted extraction (Zhang et al., 2018), demonstrating empirical understanding of pharmaceutical principles aligning with modern phytochemical isolation techniques. Juice extraction (23.1%) preserves thermolabile compounds such as ascorbic acid and volatile constituents that degrade during heating (Tapsell et al., 2006), reflecting sophisticated knowledge regarding optimal extraction techniques for different therapeutic applications.

Relative frequency of citation (RFC)

RFC values ranged from 0.45 to 0.85, indicating substantial variation in cultural importance. *Allium sativum* exhibited the highest RFC (0.85), followed by *Aloe vera* (0.82), *Azadirachta indica* (0.78), *Piper betle* (0.76), and *Phyllanthus emblica* (0.75). Species with RFC ≥0.70 were considered highly significant. The highest RFC for *Allium sativum* reflects its multifunctional applications, validated by research demonstrating antimicrobial, antihypertensive, and immunomodulatory activities from organosulfur compounds (Bayan et al., 2014). *Azadirachta indica* (RFC 0.78) recognised as a ‘village pharmacy’ with documented antibacterial, antifungal, antimalarial, and immunostimulant properties from limonoids and azadirachtin (Alzohairy, 2016). *Aloe vera* demonstrates strong consensus for treating skin diseases and burns, supported by pharmacological studies validating its wound-healing and anti-inflammatory properties (Sánchez et al., 2020).

Informant consensus factor (ICF) for ailment categories

Medicinal plants were classified into 12 major ailment categories. ICF values ranged from 0.67 to 0.91, demonstrating high consensus (Table 3). Digestive system disorders exhibited the highest ICF (0.91, 35 use reports, 12 species), reflecting the prevalence of gastrointestinal complaints in rural Bangladesh and extensive therapeutic repertoires (Kadir et al., 2013). Respiratory diseases showed an ICF of 0.88 (28 use reports, 9 species), while skin diseases recorded an ICF of 0.86 (24 use reports, 8 species). These elevated values suggest selective use of specific species for particular ailments, reflecting coherent traditional medical knowledge warranting priority for pharmacological investigation (Beressa et al., 2024).

Table 3. Disease categories and ICF values of medicinal plants from Bhola District.

Ailment category	Diseases/ailments	Number of plant species used	ICF
Digestive system disorders	Constipation, diarrhoea, dysentery, stomach ache, gastritis, indigestion	12	0.91
Respiratory diseases	Cough, cold, asthma, bronchitis, fever	9	0.88
Skin diseases	Wounds, skin infections, eczema, ringworm, burns, acne	11	0.87
Metabolic disorders	Diabetes, blood sugar control	8	0.86
Cardiovascular diseases	Hypertension, high blood pressure, heart disease	6	0.84
Musculoskeletal disorders	Bone fracture, body pain, arthritis, rheumatism, back pain	7	0.82
Infectious diseases	Malaria, chicken pox, measles, typhoid	5	0.80
Urogenital disorders	Urinary problems, kidney stones, burning sensations	4	0.77
Hepatic disorders	Jaundice, liver problems	4	0.75
Dental problems	Toothache, dental infections	3	0.71
Nervous system disorders	Headache, mental disorders, insomnia	3	0.69
General symptoms	Weakness, hair loss, general debility	3	0.67

Source: Authors' calculations based on field survey data.

Phytochemical and pharmacological validation

Many documented species have undergone scientific investigation. *Phyllanthus emblica* (RFC 0.75) demonstrates antidiabetic, hepatoprotective, and immunomodulatory activities attributed to tannins and gallic acid derivatives (Chaphalkar et al., 2017). *Terminalia chebula* exhibits antimicrobial and laxative properties due to chebulinic acid (Bag et al., 2013). However, several species with moderate RFC values remain underexplored, representing opportunities for bioprospecting. The convergence of high RFC values, elevated ICF scores, and traditional applications provides a rational framework for prioritising species for investigation.

Conservation and knowledge erosion

Bangladesh faces biodiversity loss due to habitat destruction, agricultural expansion, and climate change (Mukul et al., 2018). Species with high RFC values experience increased harvesting pressure, particularly slow-growing trees affected by destructive harvesting practices (Chen et al., 2016). Cultivation protocols, medicinal plant gardens, and community-based conservation are essential for sustainability. Knowledge erosion among younger generations threatens ethnobotanical heritage, emphasising urgent needs for systematic documentation, educational initiatives, and integration into formal healthcare, while respecting intellectual property rights and ensuring benefit-sharing.

This study documented valuable traditional knowledge revealing sophisticated therapeutic understanding within Bhola communities. High ICF and RFC values demonstrate coherent traditional medical systems serving as primary healthcare resources. An integrated approach combining ethnobotanical documentation, scientific validation, sustainable cultivation, community-based conservation, and policy support is essential for preserving biological and cultural heritage while enhancing healthcare access. Future research should employ larger sample sizes, extended survey periods, phytochemical analysis, pharmacological validation, and molecular authentication to substantiate traditional claims and inform conservation strategies (Rivera et al., 2014).

It has been shown that medicinal plants are exceptionally rich in micronutrients. Ethnobotanical studies are essential for identifying ways to use natural plant resources, and such research should be continued in the future (Filipović et al., 2023; Stevanović et al., 2023; Stevanović et al., 2024; Dimitrijević et al., 2024; Miskoska-Milevska et al., 2025).

Conclusion

This ethnobotanical study documented 39 medicinal plant species from 28 families in the Bhola District, Bangladesh’s unique deltaic ecosystem. High informant consensus factor values (0.67–0.91) demonstrate well-established traditional medical systems, particularly for digestive, respiratory, and dermatological conditions. *Allium sativum*, *Aloe vera*, and *Curcuma longa* showed elevated cultural significance, warranting pharmacological investigation. However, limited youth participation signals knowledge erosion, highlighting the need for urgent documentation initiatives. Substantial tree utilisation (35.9%) raises sustainability concerns necessitating community-based conservation strategies. This baseline data supports the evidence-based integration of traditional medicine into healthcare frameworks while identifying priority species for bioprospecting and conservation in this vulnerable ecosystem. Future ethnobotanical studies are essential for understanding how to harness natural plant resources.

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ETNOBOTANIČKO ISTRAŽIVANJE LEKOVITIH BILJAKA KOJE KORISTE STANOVNICI OKRUGA BHOLA U BANGLADEŠU

Rifat Hasan Rabbi[1*] i Farjana Talukder[2]

[1]Department of Agricultural Science, Daffodil International University, Birulia, Savar, Dhaka, Bangladesh
[2]Department of Apparel Engineering, Barishal Textile Engineering College, Barishal, Bangladesh

Ovo etnobotaničko istraživanje dokumentuje raznovrsnost lekovitih biljaka i tradicionalno znanje u okrugu Bhola u Bangladešu, ekosistemu delte koji je nedovoljno zastupljen u etnobotaničkoj literaturi. Sprovedeni su polustrukturirani intervjui sa 100 ispitanika u periodu između juna i decembra 2025. godine, beležeći biljne vrste, metode pripreme i terapijske primene. Ukupno je dokumentovano 39 vrsta lekovitih biljaka iz 28 porodica, pri čemu su porodice Combretaceae i Lamiaceae bile najzastupljenije (po 7,69%). Drveće (35,9%) i zeljaste biljke (33,3%) predstavljali su dominantne oblike rastinja, dok su listovi (43,3%) i plodovi (22,4%) bili najčešće korišćeni delovi biljaka. Dekokt (odvar) (46,2%) i ceđenje soka (23,1%) bili su primarni načini pripreme. Analiza relativne učestalosti navođenja (engl. *relative frequency of citation – RFC*) pokazala je da su *Allium sativum* (0,85), *Aloe vera* (0,82) i *Curcuma longa* (0,73) kulturno najznačajnije vrste. Vrednosti faktora saglasnosti ispitanika (engl. *informant consensus factor – ICF*) kretale su se od 0,67 do 0,91, pri čemu su poremećaji digestivnog trakta (0,91), respiratorne bolesti (0,88) i kožna oboljenja (0,86) pokazali najveći stepen saglasnosti. Ovi nalazi pružaju osnovne podatke za integraciju tradicionalne medicine u zdravstvene okvire zasnovane na dokazima i identifikuju prioritetne vrste za fitohemijska istraživanja i mere očuvanja u ovom osetljivom ekosistemu delte.

Ključne reči: lekovite biljke, tradicionalno znanje, etnobotanika, poljoprivredno znanje, oblast Barisal u južnom centralnom Bangladešu.

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[*]Autor za kontakt: e-mail: rabbi2301101012@diu.edu.bd

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HORIZONTAL AND VERTICAL DISTRIBUTION OF HAZELNUT ROOT SYSTEM

Čedo Đ. Oparnica[1]*, Dragan D. Radivojević[1], Magdalena M. Milićević[2] and Nemanja M. Tešić[1]

[1]University of Belgrade, Faculty of Agriculture, Belgrade, Republic of Serbia
[2]Monarh plantaže, Velika Krsna, Mladenovac, Republic of Serbia

Abstract: The application of agrotechnical and pomotechnical measures in modern fruit production depends on a thorough understanding of the morphological characteristics of both the above- and below-ground organs of hazelnut varieties. This study aimed to determine the horizontal and vertical distribution of the root system in five-year-old bushes of the hazelnut varieties Tonda di Giffoni and Tonda Gentile Romana. The research was conducted in a hazelnut orchard in Velika Krsna (Mladenovac, Serbia) in 2019. The results showed significant differences in root length depending on the distance from the trunk and soil depth in both varieties. In Tonda di Giffoni, the greatest root length was recorded at a depth of 10–20 cm, reaching 1,914 cm (41%) at a distance of 200 cm from the trunk, while at 50–100 cm it was 861 cm (45%). Root length decreased with increasing distance and depth, whereas root diameter increased with depth but decreased with distance from the trunk. The total root length in this variety was 4,672 cm. In Tonda Gentile Romana, the total root length was higher, amounting to 7,212 cm. The highest root length was also observed at a depth of 10–20 cm, reaching 3,279 cm (45%), and 1,470 cm (45%) at 50–100 cm from the trunk. Root diameter increased with depth (2.35–18.5 mm), while the number of roots decreased. The results indicate that root system distribution is strongly dependent on variety.

Key words: hazelnut, root system, horizontal and vertical distribution.

Introduction

The European hazelnut (*Corylus avellana* L.) belongs to the birch family, Betulaceae, of the order Fagales. It is a fruit species native to Europe and Asia Minor, and is commonly found growing wild throughout these regions. The natural distribution and genetic diversity of this species indicate its potential for cultivation over a wide range of temperate environments (Mehlenbacher, 1991). Almost all

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*Corresponding author: email: oparnicacedo@gmail.com

widely used varieties were selected over many centuries from local wild populations of the European hazelnut, *C. avellana* L., in Europe and Turkey (Dale et al., 2012).

Hazelnut has become very popular in the last decade, and a significant number of new plantations have been established in Serbia. The average annual production of in-shell hazelnuts in Serbia for the period from 2016 to 2020 was 5,080 tonnes (FAOSTAT, 2022). Considering that many hazelnut plantations are still young, a significant increase in hazelnut production is expected in the coming years.

The significant nutritional and dietary therapeutic value of hazelnuts has led to a constant increase in demand and consumption by the confectionery industry, which is also the largest consumer. As a result, hazelnuts are becoming an increasingly important agricultural product in international trade.

In most plantations established in Serbia, as well as in other hazelnut-producing countries, hazelnuts are mainly grown on their own roots. In the nurseries, layerage is a very common method of propagation (Solar et al., 1994). Only a small number of plantations have been established with plants grafted onto a *Corylus colurna* rootstock. The Turkish hazelnut (*Corylus colurna* L.) is characterised by vigorous growth and a strong root system, which is important for relatively dry regions (Cerović et al., 2009). The own-rooted hazelnuts exhibit rapid above-ground development with large canopy volume, a high number of sprouts, and earlier yield. The grafted plants show greater below-ground development, with smaller canopy volumes and lower yield. However, later, the higher growth rates of the canopy allow these plants to reach the same size as that of the own-rooted hazelnuts and to enter the fruit production phase (Portarena et al., 2022).

Modern hazelnut orchards require the application of adequate agrotechnical and pomotechnical measures, which is conditioned by knowledge of the morphological characteristics of the above-ground and underground organs of cultivated varieties.

The term "root system architecture" refers to the spatial arrangement of the root system in the environment in which it grows (Koevoets et al., 2016). Hazelnut trees are shallow rooted. Feeder roots are concentrated in the surface layer of the soil, extending outwards from the trunk to beyond the spread of the limbs. Below this level, the number of feeder roots decreases rapidly. Hazelnut trees have very few anchoring roots. Almost all European hazelnut varieties form suckers, but the amount depends on the variety (Dale et al., 2012; Miljković, 2018).

The study of the root system is highly complex and demanding, as excavating it from the soil substrate is a difficult and delicate operation that requires preserving as much of the root mass as possible.

To intensify the production of this increasingly important fruit species, it is essential to understand the structure of the root system. This knowledge enables the most correct soil preparation for the establishment of plantations, ongoing soil maintenance, incorporation of fertilisers at the appropriate depth, as well as the application of other necessary agrotechnical practices.

The aim of this research was to determine the horizontal and vertical distribution of the root system in five-year-old bushes of the most important hazelnut varieties in the agro-ecological conditions of Serbia.

Material and Methods

Research was carried out in the hazelnut orchard in Velika Krsna (Mladenovac) during 2019. The subject of the investigation was the horizontal and vertical arrangement of the root system of hazelnut varieties. The experiment included two hazelnut varieties: Tonda di Giffoni (TDG) and Tonda Gentile Romana (TGR), grown as bushes with 3 to 5 scaffold branches, at a planting distance of 4.5 x 3.5 m. The orchard was established in autumn of 2014 with one-year-old plants on their own roots (saplings), covering an area of 15 ha. The soil was maintained by regular mechanical tillage, without an irrigation system, and standard pest management was applied.

To make the research as realistic and precise as possible, the soil was carefully removed from the root system expansion zone on three bushes per tested variety, after which the root system was washed with water. The root system was measured manually using a measuring tape, where the main roots (>1 mm) were included, however, small roots (absorptive) were not included in the measurements. The diameter of the root system was measured using a calliper. These measurements were carried out in the laboratory of the Faculty of Agriculture in Belgrade. The horizontal arrangement of the roots was determined in four circular rings located at 0–50 cm, 50–100 cm, 100–150 cm and 150–200 cm from the trunk of the bush. The vertical spread of the root system was determined in the same circular rings at depths of 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm from the soil surface.

Results and Discussion

Based on the obtained results, noticeable differences can be observed in the length of roots at different distances from the trunk of the bush, as well as in the depth of root penetration in both tested varieties. In the examined conditions, in the TDG variety, the greatest root system was found at a depth of 10–20 cm, measuring 1,914 cm (41%) at a total distance of 200 cm from the trunk of the bush. At the same depth, but at 50–100 cm from the trunk, the root length was 861 cm (45%). As the distance from the trunk and the depth increased, the root length decreased.

The diameter of the roots increased with depth, and decreased with the distance from the trunk, with the smallest diameter (1.3 mm) observed at a depth of

0–10 cm and 50–100 cm from the trunk. The total root system length was 4,672 cm. The hazelnut root system mainly extends in the surface soil layer, with the largest root mass found at a depth of up to 40 cm (Manušev, 1988; Miljković, 2018; Korać et al., 2020). The results are shown in Table 1.

Table 1. Horizontal and vertical distribution of the root system of the hazelnut variety Tonda di Giffoni.

Depth (cm)		Distance from the trunk (cm)				Sum
		0–50	50–100	100–150	150–200	
0–10	TRL	379.2	41.8			421
	ARD	3.68	1.3			
	NR	23	8			31
10–20	TRL	668	861	342	43	1914
	ARD	7.68	7.14	3.51	1.4	
	NR	25	30	20	7	82
20–30	TRL	336	815	420	53	1624
	ARD	9.2	6.95	3.91	1.5	
	NR	14	28	21	7	70
30–40	TRL	74.8	290	292	54.2	711
	ARD	23.86	14.1	7.2	1.6	
	NR	2	11	15	9	37
Sum	TRL	1458	2007.8	1056	150.2	4672
	NR	64	77	56	23	220

TRL – Total root length (cm); ARD – Average root diameter (mm); NR – Number of roots.
Source: Authors' own research.

The study of horizontal root distribution revealed pronounced differences between the examined hazelnut cultivars. In the TGR cultivar, most of the total root length (TRL) was found in the 0–100 cm zone from the trunk, accounting for about 87%. This indicates a relatively compact root system. In contrast, the TDG cultivar had a more expansive root structure, with a larger proportion of roots extending beyond 100 cm, approximately 26%. A similar trend was observed in the number of roots (NR), with TDG having more roots in the outer zones (100–200 cm), suggesting a greater ability to explore the soil horizontally.

These results align with previous studies showing that root system structure is largely dependent on genotype and plays a critical role in the absorption of water and nutrients. For example, Lynch (1995) has pointed out that plants with broader root systems are better suited to varied soil environments, especially when water is limited. Additionally, Gregory (2006) has found that horizontal root growth significantly aids resource gathering for perennial crops. The greater presence of roots in outer zones for TDG may indicate a stronger ability to use soil resources, particularly in dry conditions.

Furthermore, the distribution pattern matches the findings of Fitter (1987) who has observed that species and cultivars with wider root systems often show increased resilience to environmental stress. They are better at reaching water and nutrients from larger areas of soil. In this regard, the more localised root system of the first cultivar might suggest a stronger reliance on resources near the trunk, while TDG showed qualities associated with better adaptability. These differences are important for improving irrigation methods and orchard management, as highlighted in earlier research on woody perennial crops. In terms of vertical distribution, both cultivars clearly showed a layered root system. Most roots were found in the topsoil layers (0–30 cm), which is typical for hazelnuts and other woody species. However, there were noticeable differences between the two cultivars.

Table 2. Horizontal and vertical distribution of the root system of the hazelnut variety Tonda Gentile Romana.

Depth (cm)		Distance from the trunk (cm)				Sum
		0–50	50–100	100–150	150–200	
0–10	TRL	1013				1013
	ARD	2.35				
	NR	53				53
10–20	TRL	1358	1470	451		3279
	ARD	4.82	4.63	2.23		
	NR	62	65	35		162
20–30	TRL	707	1103	254		2064
	ARD	9.56	8.76	3.1		
	NR	26	37	16		79
30–40	TRL	259	406	137	50	852
	ARD	18.5	7.61	3.1	1.7	
	NR	10	15	9	7	41
Sum	TRL	3337	2979	842	50	7212
	NR	151	117	60	7	335

TRL – Total root length (cm); ARD – Average root diameter (mm); NR – Number of roots.
Source: Authors’ own research.

Experience with *Corylus colurna* L. used as a rootstock in the USA has shown that varieties of this species are more resistant to drought and frost than *Corylus avellana L.* They have a strong root system and can reach depths of 3 to 4 m (Rovira, 2021).

The TGR cultivar had a higher concentration of both TRL and NR in the shallowest layer (0–20 cm), indicating a mostly shallow root system. In contrast, TDG showed a steadier decrease in root presence as soil depth increased, with a relatively higher proportion of roots found deeper (20–40 cm). This suggests a more balanced vertical distribution, allowing better access to water stored in deeper soil layers. This pattern supports the findings of Gregory, P. J. (2006) that deeper root growth enhances plant resilience during droughts, as well as the conclusion of Lynch (1995) that genotypes with better vertical root spread are more efficient at capturing resources from below the surface. Thus, TDG appears to have a functional advantage in variable water conditions, as it can access both surface and deeper layers more effectively.

Research by Miljković (1976) has confirmed that the largest root diameter occurs at a depth of 20–30 cm and 50–100 cm from the bush trunk. It found that there were twice as many roots near the trunk as at 100 cm away, and three times as many as at 150 cm from the trunk. Since hazelnuts typically have relatively shallow root systems, a lack of rainfall or growing them without irrigation negatively affects their growth, yield, and fruit quality.

It is crucial to balance vegetative and generative activities. Achieving this balance requires proper pruning and agricultural practices, such as irrigation, fertilisation, and soil management, tailored to the needs of each variety.

Conclusion

This study highlighted clear genotypic differences in both horizontal and vertical root distribution among the hazelnut cultivars reviewed. TDG displayed a more extensive and spatially distributed root architecture, with more roots extending beyond the trunk area and a balanced vertical distribution throughout the soil layers. In contrast, the first cultivar exhibited a more compact and shallow root system, concentrating most of its root length in the upper layers and near the trunk. These differences represent distinct strategies for acquiring soil resources. Functionally, TDG's larger root system suggests a better ability to take up water and nutrients, especially under uneven water supply. Its capacity to explore deeper and wider soil zones may give it an adaptive advantage during drought conditions, while the first cultivar's more localised root distribution implies a higher dependence on easily accessible resources in the topsoil. These findings agree with previous studies emphasising the role of root system structure in determining a plant's adaptability and efficient resource use in woody perennial species.

Overall, the results stress that root system structure is a key characteristic that impacts the ecological performance and irrigation needs of hazelnut cultivars. The differences between genotypes provide useful insights for improving orchard management methods, particularly regarding irrigation scheduling and soil water management. Selecting cultivars with better root distribution patterns, such as TDG, may enhance resilience and promote more efficient use of soil water resources in changing environmental conditions.

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HORIZONTALNA I VERTIKALNA DISTRIBUCIJA KORENOVOG SISTEMA LESKE

Čedo Đ. Oparnica[1*], Dragan D. Radivojević[1],
Magdalena M. Milićević[2] i Nemanja M. Tešić[1]

[1]Univerzitet u Beogradu, Poljoprivredni fakultet, Beograd, Srbija
[2]Monarh plantaže, Velika Krsna, Mladenovac, Srbija

Rezime

Primena agrotehničkih i pomotehničkih mera u savremenoj voćarskoj proizvodnji zavisi od detaljnog poznavanja morfoloških karakteristika nadzemnih i podzemnih organa sorti leske. Cilj ovog istraživanja bio je utvrđivanje horizontalne i vertikalne distribucije korenovog sistema kod petogodišnjih žbunova sorti leske Tonda di Giffoni i Tonda Gentile Romana. Istraživanje je sprovedeno u zasadu leske u Velikoj Krsni (Mladenovac, Srbija) tokom 2019. godine. Rezultati su pokazali značajne razlike u dužini korena u zavisnosti od udaljenosti od stabla i dubine zemljišta kod obe sorte. Kod sorte Tonda di Giffoni, najveća dužina korena utvrđena je na dubini 10–20 cm i iznosila je 1.914 cm (41%) na udaljenosti od 200 cm od stabla, dok je na 50–100 cm iznosila 861 cm (45%). Dužina korena se smanjivala sa povećanjem udaljenosti i dubine, dok se prečnik korena povećavao sa dubinom, a smanjivao sa udaljenošću od stabla. Ukupna dužina korenovog sistema kod ove sorte iznosila je 4.672 cm. Kod sorte Tonda Gentile Romana, ukupna dužina korenovog sistema bila je veća i iznosila je 7.212 cm. Najveća dužina korena takođe je utvrđena na dubini 10–20 cm, gde je iznosila 3.279 cm (45%), dok je na 50–100 cm iznosila 1.470 cm (45%). Prečnik korena se povećavao sa dubinom (2,35–18,5 mm), dok se broj korenova smanjivao. Rezultati ukazuju na to da je raspored korenovog sistema u velikoj meri zavisan od sorte.

Ključne reči: leska, korenov sistem, horizontalna i vertikalna distribucija.

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[*] Autor za kontakt: e-mail: oparnicacedo@gmail.com

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Table 1. Volume and dynamics of Serbia's foreign trade in meat and meat preparations, 2020–2024.

	Average (t)	Min (t)	Max (t)	CV (%)
Export (000 USD)	105,693	97,583	114,098	5.74
Import (000 USD)	260,256	180,337	343,095	27.52
Trade balance (000 USD)	-154,563	-76,815	-245,513	-47.95
Coverage rate (%)	43.4	57.4	28.4	-

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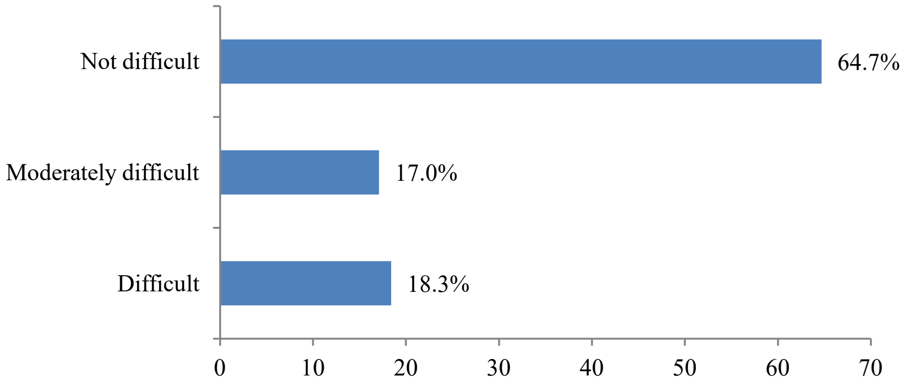

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Afilijacija se piše jedan red ispod naslova, malim slovima, centrirano, bez bolda. Navodi se pun naziv ustanove za svakog autora, uključujući mesto i državu. Ukoliko su autori iz različitih institucija, koriste se odgovarajuće numeričke oznake radi jasnog povezivanja autora i njihovih afiliacija.

Sažetak i ključne reči

Sažetak je kratak informativni prikaz sadržaja članka. Predstavlja opšti uvod u temu i pruža kratak prikaz glavnih rezultata i njihovih implikacija. Piše se bez odeljaka i podnaslova. Sastavni delovi sažetka su cilj istraživanja, metode, rezultati i zaključak. Sažetak treba da ima od 200 do 250 reči. Upotrebu skraćenica treba svesti na minimum, a reference, tabele i slike ne smeju se navoditi.

Ključne reči se navode neposredno ispod sažetka, pišu se malim slovima, razdvojene zarezima, sa tačkom na kraju. Broj ključnih reči može biti od tri do deset i predstavljaju termine ili fraze koje najbolje opisuju sadržaj članka.

Uvod

Uvod treba da sadrži dovoljno informacija, uključujući relevantna prethodna istraživanja, kako bi se jasno definisao istraživački problem i objasnilo šta se datim istraživanjem želi postići. Svi podnaslovi pišu se fontom Times New Roman, veličine 11, bold, centrirano, sa jednim razmakom pre i posle svakog podnaslova. Prilikom citiranja referenci u tekstu navode se prezime autora i godina publikovanja. Svi radovi citirani u tekstu navode se u spisku literature i svi radovi navedeni u poglavlju *Literatura* moraju biti citirani u tekstu.

Materijal i metode

Materijal i metode treba izložiti jasno uz objašnjenje svih primenjenih postupaka u radu. Opšte poznate metode izložiti kratko, dok se detaljnije objašnjavaju samo izmene ili ukoliko se odstupa od ranije objavljenih postupaka. Radovi eksperimentalnog karaktera moraju sadržati jasan opis statističkih metoda korišćenih za obradu podataka. U ovom poglavlju, kao i u poglavlju *Rezultati i diskusija*, po potrebi se mogu navesti i podpoglavlja.

Rezultati i diskusija

U poglavlju *Rezultati i diskusija* interpretiraju se podaci dobijeni na osnovu zapažanja i izvršenih eksperimenata. U komentaru rezultata treba se pozivati na literaturu koja se navodi na kraju rada, čime se obezbeđuje poređenje dobijenih rezultata sa dosadašnjim saznanjima u toj oblasti.

Zaključak

U zaključku treba ukratko navesti najznačajnije rezultate i njihov značaj. Izbegavati nabrajanje rezultata istraživanja sa ponavljanjem brojčanih vrednosti koji su već navedeni u poglavlju *Rezultati i diskusija*. Po potrebi se mogu naznačiti i mogući pravci daljih istraživanja ili primene. Zaključak ne sme da sadrži reference.

Zahvalnica

Zahvalnica treba da sadrži naziv i broj projekta, odnosno naziv programa u okviru koga je rad nastao, kao i naziv institucije koja je finansirala projekat ili program. Navodi se između *Zaključka* i *Literature*.

Literatura

Poglavlje *Literatura* treba da sadrži samo radove citirane u glavnom tekstu. Citiranje u tekstu vrši se navođenjem prezimena autora i godine publikovanja, na sledeći način: jedan autor se navodi kao Simmons (2025) ili (Simmons, 2025), dva autora se navodi kao Kenkel i Holcomb (2024) ili (Kenkel i Holcomb, 2024), a tri i više autora se navodi kao Milone et al. (2024) ili (Milone et al., 2024).

Ako se za određeni problem istovremeno citira više radova onda se oni hronološki nabrajaju. Odvajanje većeg broja citiranih radova van zagrade vrši se zarezom (,) a u zagradi tačkom i zarezom (;).

Ako se citira više radova istog autora oni se navode hronološkim redom, a ukoliko su objavljeni u istoj godini, dodaju se oznake: 2005a, 2005b, 2005c itd.

Citate ličnih komunikacija i neobjavljenih podataka treba izbegavati, osim ako je to apsolutno neophodno. Takvi citati bi trebali da se pojave samo u tekstu (npr. Brown, lična komunikacija), ali ne i u *Literaturi*.

Svi radovi citirani u tekstu moraju biti navedeni u delu *Literatura*, po abecednom redu prema prezimenu autora, bez numeracije. Ako se citira veći broj radova istog autora najpre se navode radovi kada je autor sam, a zatim radovi u koautorstvu, hronološki po godinama unutar svake kategorije.

Svaka referenca treba da sadrži: prezime autora, početno slovo imena, godinu izdanja u zagradi, naslov rada, naziv časopisa, volumen, broj časopisa i broj stranica (prva-poslednja). Prilikom citiranja knjiga navodi se izdavač i mesto izdavanja. U časopisu se koristi APA (Publication Manual of the American Psychological Association) citatni stil.

Spisak literature treba da bude formatiran fontom Times New Roman, veličine 9, bez bolda, obostrano poravnat, bez razmaka pre i posle pasusa, sa jednostrukim proredom i uvučenim drugim redom (indentation 0,75 cm).

Primeri navođenja referenci

Rad u časopisu

Bekić Šarić, B., Paraušić, V., & Nastić, L. (2025). E-Agrar platform: assessment of benefits and usage challenges from the perspective of beekeepers in Serbia. *Journal of Agricultural Sciences*, *70*(2), 205–218. https://doi.org/10.2298/JAS2502205B

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Fajardo-García, G., & Soler-Tormo, F. (2016). The credit cooperative system in Spain. In S. Karafolas (Ed.), *Credit cooperative institutions in European countries* (pp. 213–232). Springer. https://doi.org/10.1007/978-3-319-28784-3_11

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Iakovlev, D., Kolesnikov, A., & Jugović, M. (2025). Forecasting of the tractors fuel consumption with machine learning methods based on remote monitoring data. In A. Dragićević, & M. Milanović (Eds.), *Proceedings of the 7th International Symposium on Agricultural Engineering - ISAE 2025* (pp. 19–24). University of Belgrade – Faculty of Agriculture. https://doi.org/10.5937/ISAE25019I

Teza

Singh, N. K. (1985). *The structure and genetic control of endosperm proteins in wheat and rye.* University of Adelaide.

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Ballard, J. (1998). *Some significant apple breeding stations around the world*. Selah, Washington.

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Platnick, N. I. (2010). The world spider catalog, version 10.5. http://research.amnh.org/entomology/spiders/catalog/index.html *American Museum of Natural History*. Retrieved February 12, 2016, from http://research.amnh.org/entomology/spiders/catalog/index.html

Tabele

Tabele treba da se nalaze na odgovarajućem mestu u tekstu i numerišu se arapskim brojevima po redosledu pojavljivanja. Tabele treba da budu jasne, jednostavne i pregledne. Treba izbegavati vertikalne linije, a broj kolona ograničiti tako da širina tabele ne prelazi 13 cm.

Naslov tabele navodi se sa jednim redom razmaka iznad tabele, poravnat obostrano i sa tačkom na kraju. Tekst unutar tabele piše se fontom Times New Roman, veličine 9, sa jednostrukim proredom. Ispod tabele treba dati izvor, kao i detaljno objašnjenje skraćenica, simbola i oznaka korišćenih u tabeli. Svaka tabela mora biti pomenuta u tekstu.

Primer

Tabela 1. Obim i dinamika spoljne trgovine mesom i prerađevinama od mesa u Srbiji, 2020–2024.

	Prosek (t)	Minimum (t)	Maksimum (t)	CV (%)
Izvoz (000 USD)	105.693	97.583	114.098	5,74
Uvoz (000 USD)	260.256	180.337	343.095	27,52
Bilans (000 USD)	-154.563	-76.815	-245.513	-47,95
Stopa pokrivenosti uvoza izvozom (%)	43,4	57,4	28,4	-

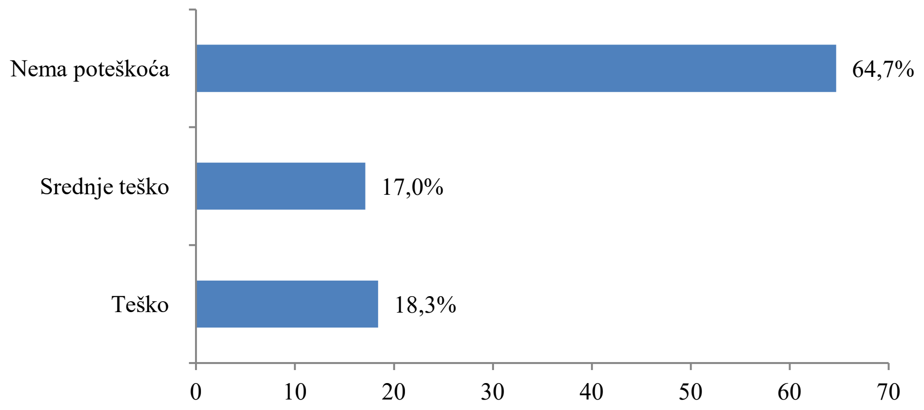
Izvor: Obračun autora

Ilustracije

Sve ilustracije, uključujući dijagrame, fotografije i grafikone, označavaju se kao slike i treba da budu postavljene u tekstu. Grafikoni i dijagrami treba da budu pripremljeni na računaru, koristeći font Times New Roman, veličina 9, sa maksimalnom širinom od 13 cm, kako bi ostali čitki i jasni i nakon redukcije veličine. Treba izbegavati prekomernu upotrebu boja. Za svaki grafikon i dijagram treba dati detaljnu legendu bez skraćenica. Fotografije moraju biti visokog kvaliteta, dostavljene u TIF ili JPG formatu i biće štampane u crno-beloj tehnici.

Naslov svake slike treba da bude centriran, sa jednostrukim proredom, postavljen sa jednim redom razmaka ispod slike, sa tačkom na kraju. Svaka slika mora biti pomenuta u tekstu. Izvor za svaku sliku navodi se ispod naslova.

Primer



Slika 1. Teškoće u korišćenju platforme eAgrar, struktura odgovora, 2023.
Izvor: Obrada autora na osnovu sprovedenog istraživanja.

Skraćenice i jedinice

U radu treba koristiti samo standardne skraćenice. Merne jedinice treba izražavati u internacionalnom sistemu jedinica (SI). Skraćenice se mogu koristiti i za druge izraze pod uslovom da se ti izrazi navedu u punom obliku prilikom prvog pominjanja u tekstu, sa skraćenim oblikom u zagradi. Vrednosti od jedan do devet se izražavaju slovima, a ostali brojevi isključivo numerički. U naslovu rada ne treba koristiti skraćenice.

Nomenklatura

Međunarodni standardi (IUPAC, IUB, ICN itd.) treba da se primenjuju za hemijske, biohemijske, taksonomske i genetičke termine.

Formule

Sve formule i jednačine u radu moraju biti urađene pomoću programa *Microsoft Word Equation Editor* ili *MathType*. Prilikom pisanja jednačina treba dati značenje svih simbola odmah posle formule u kojoj se simbol prvi put koristi. Formule treba da budu numerisane arapskim brojevima, serijski u zagradama, na desnoj strani. Svaka jednačina mora biti pomenuta u tekstu kao Eq. (1), Eq. (2), itd.

Na kraju rukopisa navode se naslov rada, imena autora, afiliacije, sažetak i ključne reči na srpskom jeziku. Za strane autore, prevod na srpski jezik obezbeđuje redakcija.

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