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# Ethephon role in maize yield and lodging through plants morphological and chemical changes

**Dušan Dunđerski[1]* · Goran Bekavac[1] · Božana Purar[1] · Anja Đurić[1] · Maja Tanasković[2]**

[1] Institute of Field and Vegetable Crops, Novi Sad, Serbia
[2] Kmetijski inštitut Slovenije, Ljubljana, Slovenia

*Corresponding author: dusan.dundjerski@ifvcns.ns.ac.rs

**Summary**: Ethephon, a plant growth regulator that releases ethylene, has emerged as a pivotal tool for improving maize performance under diverse growing conditions. This review synthesizes existing findings on ethephon's role in modulating maize architecture that strongly influence lodging resistance and yield as well as nitrogen uptake. When applied at strategic growth stages and optimal doses between 280 and 840 g $ha^{-1}$, ethephon consistently strengthens stalks, lowers the center of gravity, and mitigates lodging risks, particularly under high-density planting. Although some studies report yield reductions when lodging threats are minimal, others demonstrate considerable yield gains up to 200% under drought and stress conditions, largely by redirecting assimilates toward reproductive structures and enhancing physiological resilience. Ethephon also interacts synergistically with other growth regulators, augmenting stem diameter, lignin deposition, and root anchorage. However, responses vary with genotype, environmental factors, and cultural practices, underscoring the importance of tailored application protocols. Collectively, the evidence points that its integration into maize production systems, especially where lodging pressures and water limitations prevail, offers both agronomic and economic benefits. Although numerous studies have clarified above-ground changes, the impact of ethephon on maize root architecture and nutrient uptake remains largely underexplored. Further refinement of dose–response relationships across diverse germplasm, planting densities, and nitrogen management regimes is essential to develop precise, context-specific guidelines. Systematic screening of hybrids will clarify genotype-by-ethephon interactions, guiding breeders in selecting lines with stable yield and improved lodging tolerance. Combining ethephon with other PGRs besides mostly used diethyl aminoethyl hexanoate should be studied.

**Key words**: ethephon, growth hormones, lodging, maize, yield

## Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops globally, serving both as a staple food and a primary source of livestock feed (Li et al., 2025). While it plays a key role in human diets across Sub-Saharan Africa, Latin America, and parts of Asia, only about 13% of global maize

production is directly consumed by humans. Approximately 61% is used as animal feed, reflecting its vital contribution to the meat and dairy industries (Grote et al., 2021). In the United States, about 40% of maize serves as a major energy source in livestock rations (USDA, 2025). Similarly, in China, maize dominates feed grain use, accounting for more than 70% of coarse grains used in animal feed (Xu et al., 2025). In India, around 47% of maize production is utilized for poultry feed (Kumar et al., 2022), while in developed countries overall, maize production is typically directed toward animal feeding (Erenstein et al., 2022).

Ethephon, chemically known as 2-chloroethyl phosphonic acid, is a widely used plant growth regulator (PGR) that plays an important role in modulating plant physiology. It releases ethylene, a naturally occurring plant hormone involved in processes such as germination (Wang et al., 2020; Corbineau, 2024), fruit ripening (Dhillon and Mahajan, 2011), organ abscission (Ali et al., 2012; Botton and Ruperti, 2019), and response to various stress conditions (Khan et al., 2024). Although the commercial use of ethephon is perhaps most recognizable in horticultural production, its application in other crops has received substantial attention in the literature as well.

Over the years, researchers have investigated the influence of ethephon on yield (Khosravi and Anderson, 1991 – on *Zea mays* L.; Zhao et al., 2021 – on *Zea mays* L.; Zhang et al., 2022a – on *Zea mays* L.; Li et al., 2022 – on *Zea mays* L.; Wang et al., 2025 – on *Zea mays* L.) and lodging resistance (Langan and Oplinger, 1987 – on *Zea mays* L.; Cox and Andrade, 1988 – on *Zea mays* L.; Fritz et al., 1991 – on *Zea mays* L.; Geng et al., 2022 – on *Zea mays* L.; Zou et al., 2024 – on *Zea mays* L.). In addition, ethephon plays an important role in shaping plant architecture (Dunđerski, 2024 – on *Zea mays* L.; Hong et al., 2025 – on *Zea mays* L.; Aragón-Raygoza and Strable, 2025 – on *Zea mays* L.; Mu et al., 2026 – on *Zea mays* L.). Its effect on reproductive development have also been documented (Berhe and Miller, 1978 – on *Zea mays* L.; Karakaya and Padem, 2011 – on *Cucumis sativus* L.; Seesangboon et al., 2018 – on *Jatropha curcas* L.). Ethephon has further been associated with enhanced tolerance to abiotic stresses such as drought (Kasele et al., 1994 – on *Zea mays* L.; Shekoofa and Emam, 2008 – on *Zea mays* L.; Jain et al., 2022 – on *Saccharum officinarum* L.), salt (Iqbal et al., 2017 – on *Brassica juncea* L.); Hussain et al., 2020 – on *Oryza sativa* L.); Xu et al., 2022 – on *Fagopyrum esculentum* Moench), cold (Zhang et al., 2022b – on *Zoysia japonica* Steud.) and heat (Cicchino et al., 2013 – on *Zea mays* L.; Chen et al., 2014 – on *Gossypium hirsutum* L.). In addition, the use of ethephon has been documented in apple trees (Elfving and Cline, 1993; Duyvelshoff and Cline, 2013), cherry trees (Elfving et al., 2001; Elfving et al., 2003) and pear (McArtney and Wells, 1995; Bound, 2015).

Further, ethephon is characterized by its ability to decompose into phosphate and chloride ions when absorbed by plant tissues (Miller et al., 2022; Goudey et al., 1987) (Figure 1). After foliar application, ethephon penetrates to plant cells and undergoes a chemical reaction in the cell's alkaline environment, leading to the controlled release of ethylene. This decomposition is influenced by the pH of the environment; ethephon decomposes more readily in neutral to alkaline conditions (EFSA, 2006). The ethylene released in this process can initiate or regulate various physiological processes, such as:

Cellular signaling that alters gene expression, especially those involved in stress responses. Upon its release, ethylene binds to its receptors, initiating a signal transduction pathway that modulates the expression of numerous genes associated with plant defense mechanisms and stress adaptation (Binder, 2020). Hormonal cross-talk between ethylene and other plant hormones like auxins, cytokinins, and gibberellins, which together coordinate growth and development. This ensures that various physiological processes are harmoniously regulated, allowing the plant to adapt to changing environmental conditions (Cunha et al., 2017).

Ethylene plays a pivotal role in the fruits that keep ripening after you harvest them, regulating processes like color change, fruit softening, and abscission. It also accelerates senescence in various

plant tissues, including leaves and flowers, by modulating gene expression and promoting the degradation of cellular components (Liu et al., 2015).

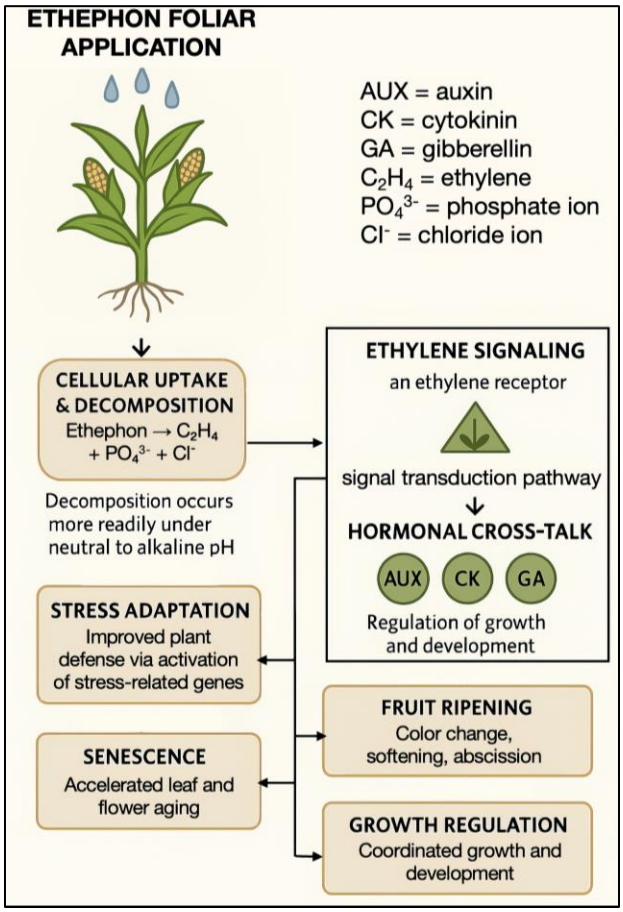


Figure 1. Schematic representation of ethephon foliar application and its physiological effects in plants. The illustration is the author's original work and has not been reproduced from any other source.

Ethephon application is typically foliar by either ground or aerial equipment (Wang et al., 2023), with rates and timing carefully managed according to the crop and target physiological effect. Ethephon is sold under several trade names corresponding to specific uses. Concentrations in these formulations range between 20 and 720 g $l^{-1}$. In addition to standalone usage, combinations with chlormequat chloride are also used for cereals (Ramburan and Greenfield, 2007). Practice limitations include prohibitions against applying ethephon through any type of irrigation system; feeding or grazing livestock in treated areas; and treating 2 to 60 days earlier than harvest begin, depending on the crop (EPA, 1995).

In the context of maize and other field crops, application is often made during specific growth stages to achieve desired outcomes. In maize, applications can vary but generally occur from the vegetative stages through early reproductive stages (Konsler and Grabau, 1989). In cereals such as wheat, barley, rye, and triticale, ethephon is typically applied during the stem elongation phase (37 to 45 on the Zadoks scale), which corresponds to the period from the just visible flag leaf to booting

stages. Applying ethephon during this period helps reduce plant height and strengthen stems, thereby mitigating lodging risks.

In maize cultivation, the application of ethephon has been thoroughly researched for its efficacy in improving lodging tolerance, which is a crucial aspect in high-density planting systems. Lodging, which refers to the bending or breaking of plant stems, can severely impact yield and complicate harvest. Research indicates that ethephon application can improve stalk strength (Ren et al., 2022) by inhibiting internode elongation, leading to thicker stems and a lower center of gravity (Wei et al., 2011; Avat and Yahya, 2008; Yao et al., 2018). This morphological adjustment reduces the risk of lodging under dense planting conditions (Geng et al., 2022). Despite decades of trials across diverse environments and genotypes, responses to ethephon in maize remain variable, and its integration into nutrient-management regimes and PGR combinations is far from standardized. Here, we present a comprehensive review of ethephon's role in maize cultivation, summarizing global findings on yield, lodging resistance, physiological responses, and critically assessing how genotype, dose, planting density, and environmental stress shape its efficacy. We conclude by identifying key knowledge gaps in root-system effects, nitrogen interactions, and novel PGR synergies—and propose a framework for future research to refine ethephon-based recommendations in commercial maize production.

## Ethephon use in maize production

*Influence on yield*

One of the primary objectives for the plant growth regulators applications is to optimize or increase yield. Research has shown mixed outcomes regarding ethephon's effect on maize yield, owing to variations in genotype and environmental conditions (Xie et al., 2023). For instance, research indicates that ethephon application decreased grain yield by 1.83–5.74%. The reductions of 2.79% and 5.04% in grain numbers were noted in specific years, along with decreases in grain weight of 1.05% and 1.25%. This decrease was attributed to lower biomass and nitrogen uptake under ethephon treatments (Zhang et al., 2022a). Besides, the application of ethephon has been shown to decrease the concentrations of nonstructural carbohydrates in maize stems and grains, which are critical for energy storage and yield formation. The levels of nonstructural carbohydrates correlate with reduced kernel numbers per ear. This decline may adversely affect the plant's ability to accumulate energy necessary for optimal growth and yield (Tang et al., 2022).

In one study, ethephon application in maize reduced grain yield per plant in a dose-dependent manner (Zhang et al., 2014). Although the number of leaves per plant remains relatively stable across treatments, the decline in yield can be linked to several morphological changes. First one is plant height which decreases by 17%, 23%, and 30% with increasing doses, relative to the untreated control. Second, leaf area per plant is reduced by 14% at the highest dose, indicating a notable decline in photosynthetic surface. In contrast, stem diameter increases by about 6%, suggesting a slight enhancement in structural reinforcement. These shifts in vegetative traits suggest that while ethephon improves stem robustness, its inhibitory effects on height and leaf area likely contribute to the observed yield reductions.

Increasing the dose of ethephon may result in a dose-dependent reduction in maize grain yield under irrigated conditions when lodging pressure is low, as higher concentrations can suppress kernel number and grain weight (Yu et al., 2025).

Grain yield responses to ethephon application vary depending on hybrid genotype (Cox and Andrade, 1988). On average, ethephon increases grain yield by 6% in the hybrid Cornell 281, while it reduces by 11% in Pioneer 3901. These contrasting outcomes are accompanied by kernel weight changes. Across both hybrids, ethephon reduces plant height by 22%, lowers ear placement on the

plant by 13%, and decreases the percentage of lodged plants by 64%. It also promotes the formation of aerial roots, with an average increase of 56%. These results highlight the importance of genotype-specific evaluation when considering ethephon as a growth regulator in maize. The reduction in the number of kernels per ear caused by ethephon application was accompanied by a decrease in grain yield per unit area (Cicchino et al., 2013), but only in plants that were not exposed to heat stress (Bullock and Raymer, 1989). An exception was observed in variants where plants were exposed to heat stress and treated with ethephon, resulting in grain yield increase. This outcome is similar to the findings of Dunđerski (2024) highlighting the interaction between environmental stressors and ethephon treatment.

Some authors recommend the application of ethephon when there is a risk of plant lodging and under non-irrigated maize production conditions, where the success of production depends on the distribution and amount of precipitation. The result of two-year study shows that the greatest reduction in maize plant height was caused by an ethephon dose of 840 g $ha^{-1}$ in comparison to the control treatment. Increasing the ethephon dose from 0 g $ha^{-1}$ to 840 g $ha^{-1}$ results in a linear decrease in dry matter per plant. Under non-irrigated conditions, an increase in grain yield from 75% to 200% occurs following the application of ethephon. In a drier condition, the highest grain yield can be achieved with the lowest dose of ethephon at 280 g $ha^{-1}$. The increase in grain yield after ethephon application can be attributed to several factors: an approximately 168% increase in the number of kernels per unit area, a 12.5% increase in kernel weight, a 140% increase in the number of ears per plant, and a 24% increase in ear length (d'Andria et al., 1997). Similarly, another study demonstrated that ethephon can enhance maize yield, particularly when applied at rates below 200 g $ha^{-1}$ (Langan and Oplinger, 1987).

The application of ethephon from V6 to V12 growth stages in low-density maize can lead to a reduction or disruption in flower formation, resulting in a decrease in the number of kernels per ear and grain yield (Huang et al., 2017). However, ethephon application in the V6 and V12 growth stages in high-density can increase grain yield by up to 5% because of increased kernel number per ear, which is likely a consequence of improved plant architecture in the top and middle canopy layers, creating diamond shape canopy. Improved light penetration also contributes to an increase in stem diameter, rind penetration resistance, and stem bending strength. As a result, ethephon application reduces the percentage of lodged plants by up to 44.6% and increases grain yield by 3.6% to 8% (Geng et al., 2022).

When there is no risk of crop lodging, the use of ethephon is not recommended, as it can lead to a reduction in grain yield (Simmons et al., 1988; Ramburan et al., 2007). However, although lodging-related factors were not present, the author showed increase in grain yield following the application of ethephon in dry year (Dunđerski, 2024). The increase in grain yield can be attributed to a reduction in competition for assimilates between the ear and other actively growing organs (e.g., tassel and stem), as well as the direct effect of ethephon on pollen development (Cicchino et al., 2013). Ethephon-treated maize plants exhibit higher relative water content and leaf water potential compared to untreated plants during drought conditions. This indicates that ethephon aids in maintaining hydration levels, which is vital for plant survival and growth under abiotic stress (Yu et al., 2017). By modulating physiological processes, ethephon-treated plants exhibit better water use efficiency and maintain higher photosynthetic rates under drought conditions (Kasele et al., 1994).

*Ethephon's role in lodging resistance*

While this review focuses on ethephon as a single growth regulator, studies involving its combination with other regulators will be discussed here to provide context on how ethephon-driven responses may be modified under integrated PGR strategies. Combining ethephon with other

growth regulators has been explored to maximize benefits. For instance, the mixture of ethephon and diethyl aminoethyl hexanoate (EDAH) has been shown to reduce maize lodging and increase crop yield, indicating a synergistic effect that enhances overall plant performance (Zou et al., 2025).

The application of the EDAH increases the cross-sectional area of the stem by 23.4% compared to the control in the hybrid Xundan20 and by 14.5% in the hybrid Zhengdan958 (Xu et al., 2017). Similar results were obtained by Zhang et al. (2019) with the application of ethephon and by Li et al. (2020) with the application of coronatine. Xu et al. (2017) emphasizes that the increase in cross-sectional area achieved with the EDAH preparation was due to its effect on reducing the area of upper leaves, thereby increasing solar radiation reaching the lower leaves. This facilitates greater dry matter accumulation in the lower internodes, leading to an increased cross-sectional area and improved mechanical properties of the stem. The reason behind the increase in internode diameter following ethephon is because it increases ethylene accumulation in stems, lowers auxin and gibberellin levels, and up-regulates genes involved in building lignin-rich secondary cell walls (Zhang et al., 2020). Besides reducing internode elongation, ethephon promotes brace (nodal) root development and root system architecture, enhancing anchorage strength and significantly reducing lodging risk (Mu et al., 2026).

The application of diethyl aminoethyl hexanoate + ethephon (DHEAP) reduces the leaf angle above the ear by 26.21% to 38.33%, allowing better light penetration into the lower crop canopy layers. This also reduces internode length while increasing internode diameter, specific density, cellulose, hemicellulose, lignin content, and the surface area of vascular bundles in the lower internodes (Huang et al., 2021). In the lodging-tolerant hybrid, DHEAP application results in a 22.28% increase in grain yield, but only at higher planting densities. In the lodging-sensitive hybrid, the treatment increases grain yield regardless of planting density. The increase in grain yield can be attributed to several factors: an increase in the 1000-kernel weight at both lower and higher planting densities, an increase in the number of kernels per ear at higher densities, and a reduction in the percentage of barren plants at higher densities.

Ethephon, compared to other growth regulators, was the only one to significantly reduce plant height in maize (Spitzer et al., 2015). The reduction in plant height was greater at higher planting densities. A reduction in plant height caused by ethephon was also reported by (Cicchino et al., 2013). The authors applied ethephon at the V11 and V16 growth stages and found that earlier application results in greater reductions in plant height, because of more substantial reductions in vegetative organs (Earley and Slife, 1969; Cox and Andrade, 1988; d'Andria et al., 1997; Shekoofa and Emam, 2008). One of the reasons for plant height reduction is the reduction in the length of the third internode (Chandiposha and Chivende, 2014; Huang et al., 2021; Geng et al., 2022; Wei et al., 2016). The reduction in internode length can be attributed to the inhibition of cell elongation and the promotion of lateral cell growth. The authors noted that longitudinal and cross-sections of internodes revealed that cells in ethephon-treated plants were shorter and thicker. This reduction can be explained in the same way as increase in internode diameter — ethephon mitigates the negative effects of higher planting densities by facilitating the accumulation of ethylene in the stem, reducing the concentration of auxins and gibberellins, and increasing the expression of secondary cell wall genes involved in secondary cell wall formation, including those in the lignin biosynthesis pathway. This reduces lodging by increasing rind penetration resistance, which in the study by Zhang et al. (2019) increased from 19.1% to 24.3% compared to the control.

Application of ethephon could optimize maize morphology, stem strength, and rooting capacity, which can influence the optimal ear height-to-plant height ratio. Optimal ratio of ear height to plant height for achieving high grain yield and lodging tolerance ranges from 0.366 to 0.394 (Zhao et al., 2022). This was confirmed by Dunđerski (2024).

Ethephon applied at 15-leaf stage under high density reduces the upper leaf area and angle (Zhang et al., 2019), increases pollen density, boosts the number of grains and increases kernel weight, delays the senescence of leaves and functional period of the leaves, optimizes light resource utilization, and ultimately enhances the maize yield (Xu et al., 2024). Ethephon acts by increasing the expression of certain genes related to growth regulation, such as ZmGA2ox3 and ZmGA2ox10, which are involved in the modulation of auxin and gibberellin levels in plants. This alteration in hormone levels leads to changes in leaf development and orientation (Ritonga et al., 2023). Hybrids with upright leaves can achieve better light distribution across crop canopy layers, which can enhance the specific density of internodes and improve stem lodging tolerance. Since plant width depends on leaf length (i.e., leaf size) and leaf angle, it is possible that studies demonstrating the effect of ethephon on reducing these two traits indirectly confirm a reduction in plant width. Such research has been conducted by Zhang et al. (2019), Zhao et al. (2021) and Dunđerski (2024).

Higher density plants rapidly close the rows, leading to premature mutual shading of the leaves in the middle and lower layers of the crop canopy. This reduces the amount of photosynthetically active radiation reaching these parts of the vegetation and shortens the period of dry matter accumulation in the third internode compared to lower density plants. These findings were observed in wheat research (Baker et al., 1998; Berry et al., 2000). However, the application of ethephon in maize can mitigate the negative effects of high planting density on the specific density of the third internode, increasing it from 4.84% to 69.39%, depending on the year, ethephon dose, and planting density (Dunđerski, 2024). The positive effect of growth retardants on the specific density of internodes with increasing planting density was also reported by Huang et al. (2021) and Geng et al. (2022). This indicates that plants treated with ethephon generally have a greater biomass per unit of length, such as in the case with winter barley (Sanvicente et al., 1999).

In sweet corn (*Zea mays convar. saccharata var. rugosa*), the application of ethephon can significantly reduce root lodging and decreased plant height and is recommended in sweet corn crops with genotypes prone to lodging (Fritz et al., 1991). In dry years, the authors noted that the application of ethephon may not be necessary, as plants naturally tend to have reduced height under such conditions. This recommendation is important from an economic perspective, as ethephon did not significantly reduce productivity in dry years.

*Ethephon's integration with nitrogen*

Studies have shown that ethephon application may reduce total nitrogen uptake, while simultaneously increasing nitrogen utilization efficiency, suggesting a shift toward more efficient allocation and utilization of absorbed nitrogen for grain production. This dual effect suggests that ethephon may modulate nitrogen metabolism in maize, potentially leading to more efficient use of available nitrogen resources (Zhang et al., 2022a). Recent high-density field trials in Northeast China showed that pairing ethephon with a nitrogen rate of 200 kg N $ha^{-1}$ increased root-bleeding sap flux, signaling a pronounced rise in root physiological activity and nutrient uptake capacity (Liu et al., 2022).

In the study by Sun et al. (2022), nitrogen doses and DHEAP as main effects significantly reduced plant height and ear height, but the interaction of nitrogen and the growth retardant was not significant. The authors concluded that nitrogen doses did not significantly affect the ratio of ear height to plant height, whereas the growth retardant had a significant influence on this trait. On the other hand, Ye et al. (2016) reported that nitrogen, as well as the ethephon and nitrogen interaction, did not have a significant effect on plant height or ear height. However, the combined effect of ethephon and nitrogen application influenced both the diameter and length of the basal internodes, suggesting that nitrogen availability can modify how ethephon affects stem structure.

The application of ethephon, combined with DTA-6, stimulated key enzymes involved in lignin biosynthesis, including phenylalanine ammonia-lyase, tyrosine ammonia-lyase, 4-coumarate:CoA ligase, and cinnamyl alcohol dehydrogenase (Liu et al., 2021). These enzymatic changes increased lignin, cellulose, and hemicellulose contents in the basal internodes, thereby strengthening stem structure. In the same study, the response to nitrogen was not linear, and the intermediate rate of 200 kg N $ha^{-1}$ produced better results than the highest N rate. Chemical regulation also improved brace-root morphology, including root number, diameter, angle, volume, and dry weight, while promoting grain filling, starch accumulation, and final grain yield. The highest yield was recorded in the treatment combining chemical regulation with 200 kg N $ha^{-1}$, indicating that growth regulation may improve the balance between lodging resistance and yield formation under high nitrogen and high-density conditions.

*Mechanistic convergence*

Across the yield, lodging-resistance and nitrogen-interaction studies reviewed above, a common mechanistic thread emerges: ethephon-derived ethylene re-balances hormonal cross-talk, lowering auxin/gibberellin activity and reallocates carbon, thereby shortening internodes, thickening stem walls through enhanced lignin–cellulose deposition, and moderating source–sink competition under stress. These structural changes simultaneously (i) curb excessive vegetative growth, freeing assimilates for kernels when water or N is limiting, (ii) raise stem bending strength and aerial-root formation, slashing lodging risk, and (iii) improve nitrogen-use efficiency despite lower total N uptake. The agronomic outcome — yield loss, neutral response, or gain—therefore hinges on how genotype, dose, density, and abiotic stresses modulate that ethylene-driven balance.

**Knowledge gaps and future research directions**

Ethephon has proven to be a valuable agronomic tool for managing maize architecture in stressful conditions, yet its use raises several questions that warrant further research. A review of the literature suggests the areas for future investigation and improvement:

*Systematic hybrid screening for ethephon response*: Given the variability in genotypic responses, there is a need for broad screening of modern maize hybrids and inbred lines to categorize their reaction to ethephon. Such trials would involve applying ethephon across diverse genetic backgrounds and recording changes in plant architecture, lodging, and yield. The goal would be to identify traits or hybrid types that correlate with a positive response or minimal negative impact to ethephon. For example, it would be useful to know if hybrids with certain traits (e.g. naturally lower ear height, stronger rind, particular stay-green characteristics) derive less benefit from ethephon than hybrids that are extremely tall or have a weak stalk. A systematic screening program could guide farmers on which hybrids are "Ethephon-friendly" and could inform breeders if selection for ethephon responsiveness is desirable (Sheoran et al., 2022). Moreover, multi-environment testing of these hybrids with and without ethephon would clarify genotype × environment interactions: does a hybrid that responds well in one environment do so in others? Ultimately, such research may allow the development of decision-support systems where the choice to use ethephon is optimized for the particular hybrid and conditions being grown. An alternative approach to large-scale hybrid classification is the use of machine learning models trained on structured, smaller datasets that capture key sources of variation. By integrating morphological traits, management factors (e.g., planting density and nitrogen rate), and environmental descriptors, such models could be used to predict hybrid-specific responses to ethephon and identify generalizable trait–response relationships. This approach would shift the focus from cataloguing individual hybrids to modeling response patterns across trait space. However, the

reliability of such models depends strongly on the diversity and representativeness of the training data, particularly with respect to genotype × environment × management interactions. Therefore, carefully designed multi-factor experiments remain essential to support robust model development and validation.

*Interaction between nitrogen rate and ethephon:* High nitrogen (N) fertilizer rates are commonly used to maximize maize yield, but they also promote increased vegetative growth, which can elevate lodging risk. Ethephon application modifies plant architecture and may alter nitrogen dynamics, with some studies reporting reduced total N uptake alongside improved nitrogen use efficiency (Zhang et al., 2022a). This suggests that ethephon may influence the balance between vegetative growth and reproductive allocation under varying N regimes. However, the interaction between N rate and ethephon application remains insufficiently understood. Existing studies indicate that responses depend on N level, planting density, and environmental conditions, with some evidence that moderate N rates combined with ethephon can improve both yield stability and lodging resistance compared with higher N inputs (Sun et al., 2022). Further research is therefore required to systematically evaluate N × ethephon interactions across a range of management conditions. In particular, factorial experiments combining multiple N levels with ethephon treatments would help determine whether reduced N inputs can be offset by ethephon-induced changes in plant architecture and resource allocation.

*Understanding root and soil interactions*: The root-related effects of ethephon remain less understood. Future research should address how ethephon influence deep root penetration versus shallow root branching? Does ethephon application affect maize's ability to uptake less mobile nutrients (Kim et al., 2008) or to tolerate waterlogging (Vidoz et al., 2010)? Field trials that include root excavations or imaging could quantify changes in rooting depth, density, and morphology under ethephon application. Another aspect is soil moisture and irrigation – since ethephon-treated plants use water differently, it may be worthwhile to investigate irrigation scheduling for treated crops. Perhaps less water could be applied early, reserving more for later. Controlled experiments varying water supply with and without ethephon could yield guidelines for dry regions. Essentially, a more holistic picture of the root–shoot balance under ethephon is needed.

*Refining application techniques and PGR combinations:* Future agronomic research may also explore novel ways to apply ethephon or new formulations. For instance, micro-dosing or localized application directed only at the upper stalk could reduce unwanted effects on lower leaves. In terms of PGR combinations, there is possibilities to test other promising mixtures, beyond the commonly used diethyl aminoethyl hexanoat. A combination that maintains photosynthetic leaf area while ethephon handles internode shortening could further minimize yield drag. Such combinations need field verification to ensure they are economically viable and safe.

*Ethephon in integrated pest and mycotoxin management:* Studies that examine if foliar applications of ethephon can reduce tunnelling by *Ostrinia nubilalis* are lacking. This is more than a mechanical-lodging issue: every tunnel bored by the insect is a doorway for *Aspergillus* and *Fusarium* species, the chief producers of aflatoxins and fumonisins. By limiting stalk damage, ethephon could indirectly limit fungal colonization, safeguarding both grain quality and feed safety—an increasingly urgent concern under warmer, drier European summers that favour mycotoxin outbreaks. Building on these, we envision a sensor-guided implement (Figure 2) that pairs two complementary stimuli: (i) targeted release of green-leaf volatiles (GLVs). High-resolution RGB–NIR cameras and on-board AI can now

pinpoint the position and orientation of each expanded leaf at tractor speeds (Raja et al., 2023). A precision blade or air-jet could remove a predefined strip of tissue (Campbell et al., 2022), triggering a release of GLVs that repel ovipositing moths and attracts natural predators. Since GLVs in maize spreads in 9m$^2$ (Skoczek et al., 2017), it means that one plant on every 3m forward and side should be mechanically stimulated in a classical 0.75m row spacing environment. (ii) Synchronous foliar dosing of ethephon. The same pass would spray ethephon solution onto the canopy. As ethephon converts to ethylene, it amplifies the GLV signal (Ruther and Kleier, 2005) and reinforces stalk tissues, further discouraging larval entry and the subsequent fungal cascade. Such an approach would turn cutting-edge sensing technology into a practical tool for integrated pest and disease management—delivering healthier maize, a cleaner environment and compliance with the EU aim of halving chemical-pesticide use by 2030.

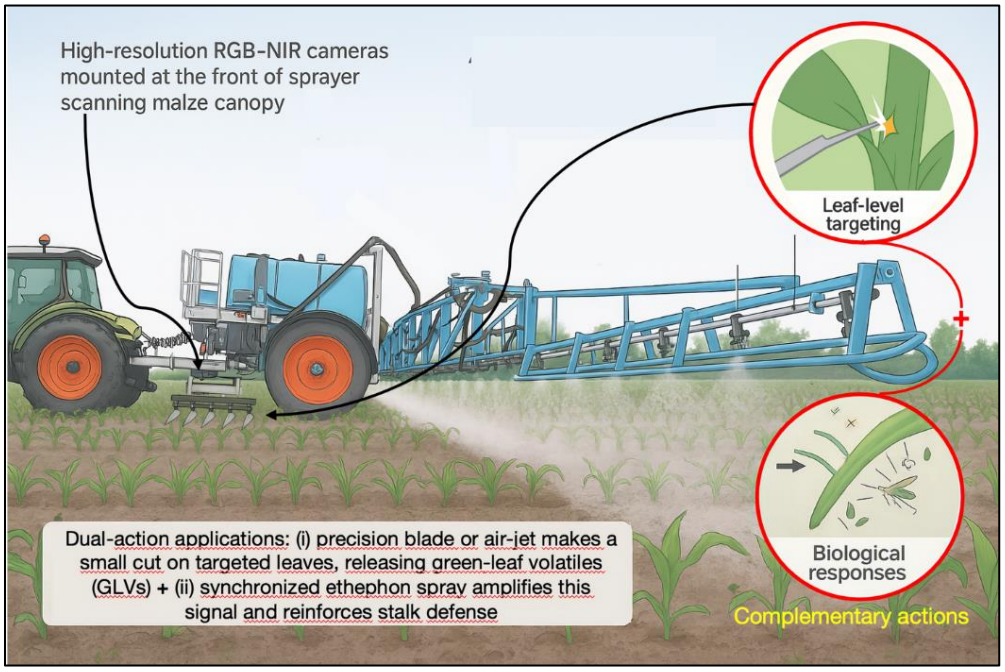


Figure 2. Sensor-guided dual-action sprayer prototype for maize protection. RGB–NIR cameras enable real-time canopy analysis and targeted application of two stimuli: localized mechanical leaf injury to induce green-leaf volatiles (GLVs), and simultaneous foliar application of ethephon to enhance signaling and improve stalk strength. The illustration is the author's original work and has not been reproduced from any other source.

**Conclusion**

This review has examined the multifaceted role of ethephon in maize cultivation, focusing on its capacity to modulate growth, enhance lodging resistance, and influence yield. By compiling evidence from a wide array of studies, we have illustrated how ethephon reduces internode length, lowers the plant's center of gravity, and adjusts morphological traits which can mitigate lodging in systems prone to lodging. At the same time, results on yield reflect complex interactions with genotype, environmental stressors, and complementary agronomic practices, showing that under water-limited or lodging-prone conditions, ethephon can considerably improve grain production. These insights underscore ethephon's potential in integrated crop management, especially for farmers aiming to maximize standability and yield stability across diverse environments. Additionally, the

review highlights the hormone's ability to bolster drought tolerance and optimize resource allocation to reproductive organs under certain stress scenarios.

Despite significant progress in understanding ethephon's above-ground effects—such as stalk fortification and lodging resistance—its influence on maize root architecture and nutrient uptake remains underexamined. Future work should focus on refining dose–response relationships under varied genotypes, planting densities, and nitrogen regimes to establish more targeted, context-specific protocols. In parallel, systematic screening of maize germplasm can deepen insights into genotype-by-ethephon interactions, enabling breeders to select and develop hybrids that maintain yield stability while mitigating lodging risks. Moreover, exploring synergies with additional plant growth regulators, beyond the commonly used diethyl aminoethyl hexanoate, stands to expand the practical applications of ethephon in contemporary maize production systems.

Ethephon remains a powerful yet nuanced tool, capable of considerable agronomic and economic benefits when harnessed judiciously. By extending research into underexplored avenues and refining current practices, growers and scientists alike can unlock the full potential of ethephon in elevating maize production worldwide.

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# Uloga etefona u prinosu i poleganju kukuruza kroz morfološke i hemijske promene biljaka

**Dušan Dunđerski · Goran Bekavac · Božana Purar · Anja Đurić · Maja Tanasković**

**Sažetak**: Etefon, regulator rasta biljaka koji oslobađa etilen, pokazao se kao važan alat za unapređenje proizvodnje kukuruza u različitim uslovima gajenja. Ovaj pregled sumira postojeće nalaze o ulozi etefona u modifikovanju arhitekture biljke kukuruza, što značajno utiče na otpornost na poleganje i prinos. Kada se primeni u odgovarajućim fazama rasta i optimalnim dozama od 280 do 840 g $ha^{-1}$, etefon dosledno jača stabljike, snižava težište biljke i smanjuje rizik od poleganja, naročito pri gustoj setvi. Iako pojedine studije beleže smanjenje prinosa kada je rizik od poleganja mali, druge pokazuju značajne povećane prinose, čak do 200%, u uslovima suše i stresa. To se uglavnom objašnjava usmeravanjem asimilata ka reproduktivnim organima i jačanjem fiziološke otpornosti. Etefon deluje i sinergistički sa drugim regulatorima rasta, povećavajući prečnik stabljike, sadržaj lignina i stabilnost korena. Ipak, reakcije na etefon zavise od genotipa, spoljašnjih uslova i agrotehničkih mera, što naglašava potrebu za precizno prilagođenim protokolima primene. Sveukupno, dokazi ukazuju da njegovo uključivanje u proizvodne sisteme kukuruza, naročito tamo gde su izraženi problemi sa poleganjem i nedostatkom vode, može doneti i agronomske i ekonomske koristi. Iako je veliki broj istraživanja rasvetlio promene u nadzemnim delovima biljke, uticaj etefona na korenov sistem i usvajanje hraniva ostaje uglavnom neistražen. Potrebna su dalja ispitivanja odnosa doze i odgovora kod različitih genotipova, gustina setve i režima ishrane azotom, kako bi se razvile precizne i kontekstualno prilagođene preporuke. Sistematsko testiranje hibrida pomoći će u razjašnjavanju interakcija između genotipa i etefona, što će oplemenjivačima omogućiti izbor linija sa stabilnim prinosom i boljom otpornošću na poleganje. Takođe, vredno je proučiti kombinovanje etefona sa drugim regulatorima rasta osim najčešće korišćenog dietil-aminoetil-heksanoata.

**Ključne reči**: etefon, kukuruz, poleganje, prinos, regulatori rasta