REVIEW ARTICLE

Thidiazuron as a defoliant to facilitate mechanical harvesting in cotton: A comprehensive review

Ravi Rajasekar[1], Veerasamy Ravichandran[1]*, Alagarswamy Senthil[1], Alagesan Subramanian[2], Kandhan Thirukumaran[3], Ramasamy Jagadeeswaran[4], Selvaraj Somasundaram[5] & Selvaraj Anandakumar[1]

[1]Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[2]Department of Cotton, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[3]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[4]Department of Remote Sensing and GIS, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

[5]Cotton Research Station, Veppanthattai 621 116, Tamil Nadu, India

*Email: ravi.v@tnau.ac.in

OPEN ACCESS

Additional information

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Abstract

Cotton is primarily cultivated for its commercial fiber, which plays a significant role in India's agro-industrial sector. It is one of the primary raw materials for producing feed, oil, fiber, and biofuel. Currently, farmers in India widely employ machine harvesters to harvest cotton. However, excessive leaf vegetation poses challenges in boll picking, adversely affecting fiber quality and reducing mechanical harvesting efficiency. Various chemical defoliants are applied to remove leaves before harvesting to address this issue. These defoliants promote leaf shedding, minimize debris in the cotton, and enhance boll opening and picking efficiency. Thidiazuron is a potent hormonal defoliant used in cotton to induce defoliation by increasing ethylene production while inhibiting the synthesis and transport of auxins. Notably, it interferes with the crosstalk between the phytohormones, such as cytokinin and ethylene, which regulates cotton defoliation. The method and timing of defoliant application are crucial for improving cotton harvesting efficiency. This review aims to provide a clear understanding of thidiazuron's application in synchronizing harvests, ultimately supporting the mechanization of cotton harvesting.

Keywords

cotton; defoliants; phytohormones; thidiazuron

Introduction

Cotton (*Gossypium spp.*), often called the " king of fiber," is vital in generating agricultural income, boosting export revenue, and creating employment opportunities. It significantly contributes to global agriculture and industry development (1). Annually, around 25 million metric tonnes of cotton are produced worldwide. As the largest cotton producer, India contributes approximately 26% of the world's cotton production despite having a relatively low yield per hectare (2). For the 2023-2024 marketing year, India's production is expected to reach 5.66 million metric tonnes, with 12.7 million hectares under cultivation (3). Cotton is often called "white gold" due to its economic significance, as it generates substantial profits for farmers.

Despite its importance, cotton production faces various global challenges, including erratic weather patterns, soil degradation, weed pressure, pest and disease outbreaks, and the rise of herbicide-resistant weeds (4). Improving cotton yield, productivity, and quality relies heavily on adopting

advanced technologies, particularly in harvesting. The growth of cotton is unpredictable, with bolls maturing at different times and opening late, which can cause labor shortages during harvest. Additionally, the lint quality of late-opening bolls is typically inferior. As a result, cotton harvesting is often labor-intensive, expensive, and time-consuming (5). Mechanized picking can address these challenges in cotton farming by reducing harvesting costs and ensuring timely crop collection (6). Successful mechanical harvesting requires the availability of suitable cotton cultivars, growth hormones, regrowth inhibitors, defoliants, and desiccants (7).

Defoliation promotes the early and uniform opening of cotton bolls, reducing trash in seed cotton, preventing dead leaves from contaminating the cotton lint, and improving both cotton quality and yield. These benefits enhance the overall efficiency of cotton harvesting (8). Defoliants are chemicals that encourage leaf drop, thereby minimizing leaf contamination in harvested cotton fiber and improving picking efficiency. Additionally, defoliants help synchronize the boll-opening process in cotton (9). Among the various defoliants used in cotton production, thidiazuron is particularly effective. It works by creating an abscission zone at the base of the petiole, facilitating leaf drop. Abscission is triggered by signals from the distal parts of plant organs, though the exact mechanism remains unclear. Thidiazuron primarily influences plant hormones, specifically auxins, ethylene, which regulate the process of leaf abscission. Notably, thidiazuron induces cotton leaves to produce large amounts of ethylene, which plays a crucial role in defoliation. However, the efficacy of thidiazuron depends on factors such as crop stage, application method, timing, and the concentration of the defoliant (10). This review explains thidiazuron's role, its effect on abscission zone formation, phytohormone activity, and the optimal application methods. The insights provided will contribute to optimizing thidiazuron use, ensuring effective defoliation, maintaining fiber quality, and maximizing efficiency in mechanical harvesting (11).

Thidiazuron and its role as a defoliant

Thidiazuron, also known as N-phenyl-N-(1, 2, 3-thidiazol-5-yl) urea, is a synthetic cytokinin-like compound that stimulates the production of hormones such as ethylene and abscisic acid, as well as hydrolytic enzymes that break down cell walls (12). When applied in combination with diuron [3-(3,4-Dichlorophenyl) 1,1-dimethylurea], it inhibits photosynthetic electron transport, which significantly impacts juvenile leaves by promoting abscission while preventing regeneration (13). Higher doses of diuron and thidiazuron lead to extended periods of regrowth inhibition (14). Thidiazuron plays a crucial role in sustainable cotton production as a defoliant (15). While defoliants do not directly affect boll ripening, their use with a boll opener, such as ethrel, ensures effective defoliation and boll opening (16). Applying thidiazuron alongside ethrel results in a higher defoliation rate and faster boll opening within seven days (17). However, weather conditions and canopy density greatly influence the efficiency of defoliation and

boll opening. The effectiveness of thidiazuron depends on timing, dosage, temperature, and the condition of the cotton plants (18). Table 1 displays different dosages of thidiazuron utilized for cotton defoliation.

Table 1. The effect of thidiazuron on cotton defoliation

Dosage	Effects	References
500 g ha^{-1} (0.1%)	Loss of leaf water content at 3rd day. Increased H_2O_2 content to 66% within 3 days after spraying.	(11, 19)
	Abscission zone formation within 4 days after spraying	
	Decreased the photosynthetic rate, transpiration rate and stomatal conductance within 3 days	

Mechanism of abscission zone formation

Abscission zones (AZs) are small, dense cells connected by plasmodesmata, which form only after the initiation of abscission and are responsible for the separation of plant organs (19, 20). The development and regulation of AZs in plants involve a complex physiological process. The development of AZ is induced by the activation of particular genes and the differentiation of cells in a localized area at the base of the leaf or organ. This process is regulated by several signals, with hormone signals playing a pivotal role. Among these, signals related to auxin and ethylene are very significant in modulating the abscission process.

The formation of AZs is shaped by the levels of endogenous auxin, particularly indole-3-acetic acid (IAA), which typically inhibits abscission by promoting cell adhesion and blocking the activation of genes related to cell separation. Higher auxin levels at the abaxial region inhibit the formation, positioning, and size of the AZ. Changes in auxin transport can alter its distribution across the leaf, triggering cell activation or differentiation within the AZ (21). While auxin plays a primary role, its effect is concentration-dependent and is modulated by ethylene and abscisic acid, which help shape the auxin gradient (11).

Thidiazuron primarily stimulates the activity of the IAA-oxidase system, reducing auxin concentration by inhibiting its transport, thereby promoting abscission. Ethylene also plays a key role by enhancing the production of cell wall-degrading enzymes (CWDEs) such as pectinase, polygalactosidase, and cellulose (22). These enzymes weaken and degrade the cell walls and the middle lamella, leading to cell separation and organ shedding. Increased peroxidase activity has also been linked to abscission, particularly in forming the abscission layer (23, 24). Abscisic acid further accelerates the senescence process by inducing ethylene production, inhibiting auxin transport, and increasing cellulase activity. For instance, during defoliation, defoliants like thidiazuron disrupt the normal role of auxin by inhibiting its synthesis or transport, causing a hormonal imbalance in the plant (25). The reduced auxin levels in the AZ activate enzymes such as cellulase and polygalacturonase, which hydrolyze cell walls and weaken cell adhesion, thus promoting leaf abscission.

Thidiazuron induces cotton leaf abscission zone formation

Thidiazuron has garnered significant attention for its ability to induce cotton leaf abscission effectively. It facilitates the natural separation of leaves from the stem upon absorption, making it a highly efficient defoliant. Numerous studies have explored the mechanisms of plant abscission, particularly under environmental stress (26, 27). Common side effects of this process include reduced chlorophyll content and changes in leaf water potential (28). Additionally, the excessive production of reactive oxygen species (ROS) plays a crucial role in activating cell wall-degrading enzymes (CWDEs), which contribute to cell wall digestion and leaf abscission (Fig. 1).
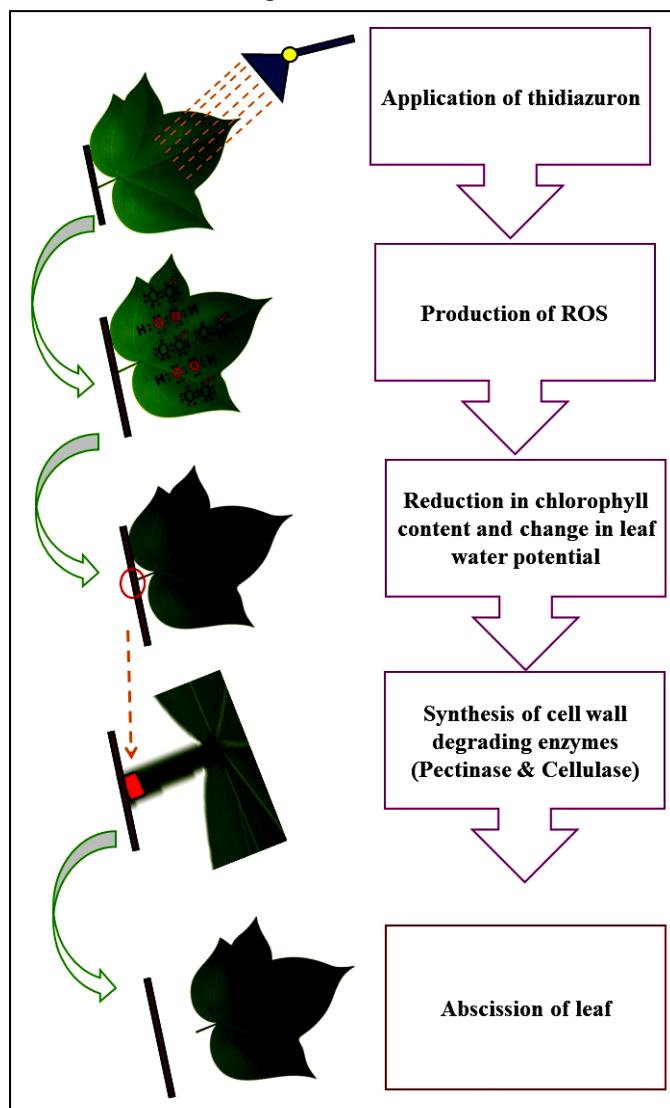

Fig. 1. Effect of thidiazuron application in the leaf abscission of cotton. Thidiazuron application produces excess reactive oxygen species (ROS), lowering the chlorophyll content, leaf water potential, and stimulating the cell wall degrading enzymes such as cellulase and pectinase, ultimately causing leaf abscission in cotton.

Research has shown that ROS-triggered asymmetrical programmed cell death (PCD) at the abscission zone (AZ) is one of the main factors regulating leaf abscission (29). There is a well-established correlation between ROS and the regulation of leaf shedding in plants. In cotton, thidiazuron induces leaf abscission by promoting the accumulation of hydrogen peroxide (H_2O_2) at the AZ, a common ROS involved in cell death and AZ formation. The production of H_2O_2, mediated by respiratory burst oxidase homologs (RBOH), has been identified as a key factor in thidiazuron-induced leaf abscission (27).

Thidiazuron promotes gene expression of auxin synthesis and signaling in cotton

Phytohormones such as ethylene, auxin, and cytokinins play a crucial role in regulating the process of leaf abscission in plants, as is well established (30). Ethylene, a gaseous hormone, is involved in several plant functions, including flower abscission and leaf senescence. Its interaction with other hormones, like auxin, further influences leaf abscission (31). Cytokinins, on the other hand, regulate both leaf growth and abscission. Through their complex interactions, phytohormones govern the intricate process of leaf abscission. For instance, thidiazuron, which mimics cytokinin activity, stimulates ethylene production and alters the cytokinin balance. This leads to changes in endogenous hormone levels, ultimately inducing leaf abscission and promoting boll opening (32).

Indole-3-acetic acid (IAA), the principal auxin in higher plants, is crucial in plant growth and development and is synthesized from the amino acid tryptophan (Trp) (33, 34). Auxin, particularly IAA, is essential for coordinating several growth processes in plants, including leaf retention and attachment, by inhibiting the activation of the abscission zone (AZ), which is vital for overall plant development. High levels of auxin generally prevent the activation of enzymes that facilitate cell separation in the AZ, thus promoting leaf retention. Conversely, lower levels of IAA in the older parts of the plant trigger AZ development, leading to leaf abscission. Therefore, auxin concentration gradients regulate AZ formation, and the position and size of the AZ are determined by auxin transport and signaling pathways (20). Thidiazuron disrupts the typical function of auxin in cotton plants, leading to defoliation by inhibiting auxin synthesis or transport within the plant. This disruption promotes AZ activation, causing leaf detachment and shedding (19). Ethylene also plays a significant role in the defoliation process triggered by auxin (35). Auxin-response genes, such as *Aux*/IAA, Small Auxin Upregulated RNAs (*SAUR*), Gretchen Hagen 3 (GH3), and Auxin Response Factors (*ARF*s), are critical elements in auxin signaling. The abscission process, which converts active free IAA into an inactive conjugated form, is mediated by *ARF* and *GH3* genes. These genes are potential targets through which thidiazuron promotes leaf abscission and reduces IAA content in cotton leaves. Auxin transporter genes also play an essential role in thidiazuron-induced leaf abscission by precisely controlling auxin transport (20). Molecular investigations have confirmed that thidiazuron application in cotton affects the expression of 68 genes linked to auxin signaling. These include eight *ARF*s, four *GH3* proteins, thirteen *SAUR* family proteins, nine genes encoding transport inhibitor response 1 (TIR1), twenty-nine *AUX*/IAA genes, and two genes for the auxin influx carrier (*AUX*1), all of which were downregulated within 24 hours of thidiazuron treatment (36). Additionally, thidiazuron can affect auxin transport by downregulating key auxin signaling components like AUX and tryptophan transport proteins (*TRP* 1) (20) (Fig. 2).
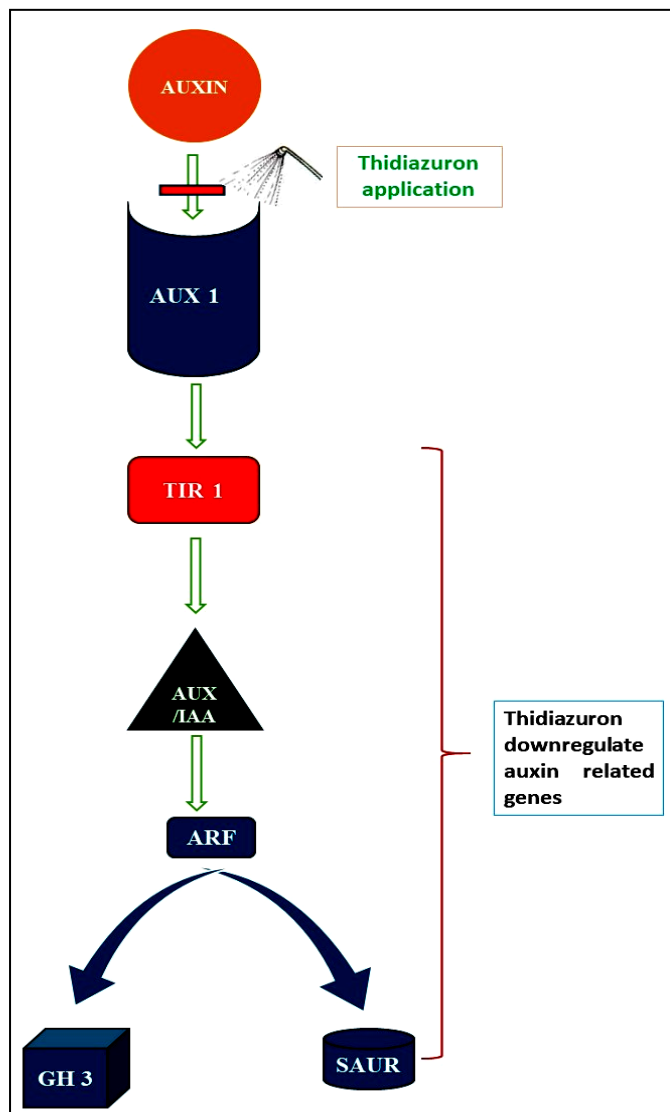
Fig. 2. Effect of foliar spray of thidiazuron on auxin signalling. Thidiazuron inhibits auxin transport by *AUX1* in the cell membrane, preventing the auxin from binding to the *TIR 1* receptor, an F-box protein functioning as an auxin receptor. This downregulation of *Aux/IAA* protein resulted in blocking ARF transcription factors involved in transcription of downstream corresponding auxin response genes and affecting GH3 and SAUR, decreasing leaf auxin content and promoting leaf abscission. *AUX1* : Auxin influx carrier proteins, *TIR 1* : Transport inhibitor response 1, *Aux/IAA* : Auxin/Indole-3-acetic acid family, *ARF* : Auxin response factors, *GH3* : Gretchen hagen 3, *SAUR* : Small auxin-up-regulated RNAs.

Thidiazuron promotes gene expression of cytokinin synthesis and signaling in cotton

Cytokinin is another vital plant growth hormone that regulates various biological processes, including plant development, growth, and the delay of senescence (36, 37). It also significantly enhances stress tolerance by increasing soluble sugar content, acting as an osmoprotectant. Moreover, cytokinin is crucial in crop defoliation through its interaction with the ethylene signaling pathway and regulation of leaf abscission (Fig. 3). The application of chemical defoliants, such as thidiazuron and ethrel, significantly affects cytokinin levels in cotton, leading to plant defoliation (38).

Thidiazuron, in particular, downregulates genes involved in the cytokinin signaling pathway, including histidine kinase (*HK*) and histidine phosphotransferase (*HP*) proteins (36). Specifically, thidiazuron treatment in cotton plants downregulated the expression of 53 cytokinin signaling genes, which included 11 cytokinin histidine kinase
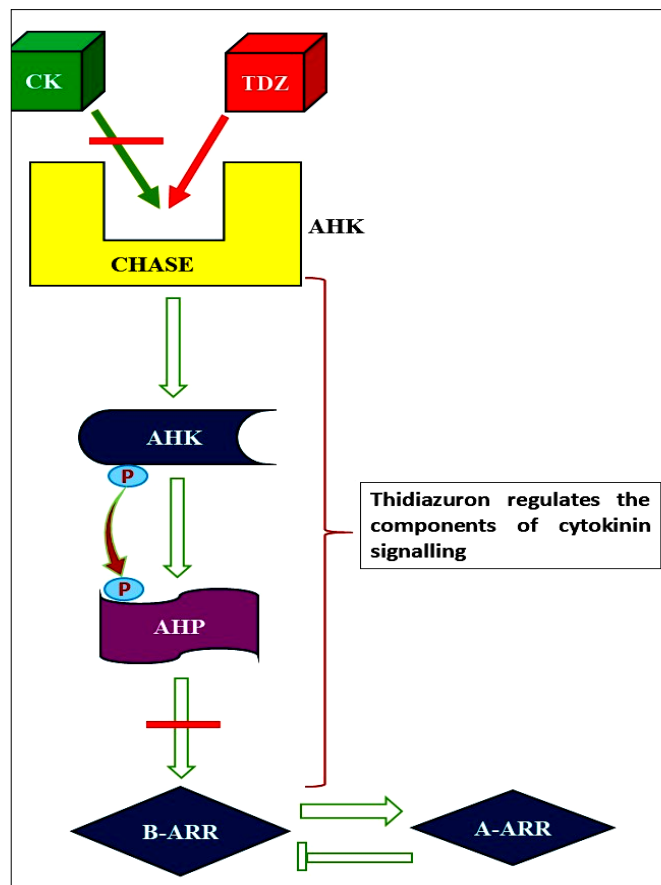

Fig. 3. Effect of foliar application of thidiazuron on cytokinin signalling. Thidiazuron (TDZ) inhibit the cytokinins signal transduction initiated through the perception of cytokinins by sensor *AHK*, preventing phosphorylation signalling cascade and phosphoryl group transfer from *AHK* to *AHP*. This inhibits the translocation of *AHP* from the cytoplasm to the nucleus, thereby inhibiting the activation of *ARR* transcription, reducing cytokinin production and promoting leaf abscission. **CK**: Cytokinin, **AHK** : *Arabidopsis* histidine kinase, **AHP** : *Arabidopsis thaliana* histidine phosphotransfer proteins, **A-ARR** : Type A - *Arabidopsis* response regulators, **B-ARR** : Type B - *Arabidopsis* response regulators.

receptor genes (*AHK*), one histidine-containing phosphotransferase gene (*AHP*), and 41 type-B cytokinin response regulators (*B-ARR*s). Cytokinin oxidase/ dehydrogenase (*CKX*) is responsible for the oxidation and degradation of cytokinins, thereby controlling cytokinin homeostasis. The CKX gene is an important regulatory component in thidiazuron-induced leaf abscission by regulating cytokinin levels. Consequently, thidiazuron induces explicitly a decline in cytokinin content in cotton leaves (39). Furthermore, thidiazuron suppresses the expression of B-ARR (36).

Thidiazuron promotes gene expression of ethylene signaling in cotton

Ethylene is a multifunctional gaseous hormone commonly associated with defoliation. It plays a role in the defoliation process induced by various compounds, including auxins and cytokinins (35). Additionally, cotton leaf abscission in response to chemical defoliants is regulated by the interaction between the cytokinin and ethylene signaling pathways (40). Specifically, the application of thidiazuron mediates cotton defoliation by elevating endogenous ethylene production and disrupting the plant's balance of auxin and cytokinin hormones (20, 39). Numerous hormone-signalling genes are upregulated and downregulated in response to thidiazuron treatment. Thidiazuron

application increases the expression of ethylene signaling genes, such as aconitase 3 (*ACO3*), acetyl-CoA synthetase (*ACS*), ethylene insensitive (*EIN*s), ethylene response factor 2 (ERF2), and ethylene receptor 1 (ETR1). Furthermore, cytokinin signaling genes, like cytokinin oxidase/dehydrogenase (*CKX*), are upregulated, while the cytokinin response regulatory factors from Arabidopsis thaliana (*ARR*s) are downregulated. The downregulation of Transport Inhibitor Response 1 (*TIR*1) and Auxin Response Factor (*ARF*) affects auxin transport (12) (Fig. 4).

damage during application while requiring less water and a lower dilution ratio (46,47). Applying thidiazuron using conventional sprayers yields a defoliation rate comparable to that of UAVs (48). However, applying thidiazuron through UAVs enhances the defoliation rate, meeting the requirements for mechanical harvesting (49). When thidiazuron is sprayed on cotton using a multi-rotor UAV, a gradual increase in the defoliation rate is observed, with the most significant effects noted between five and fifteen days after treatment (50).
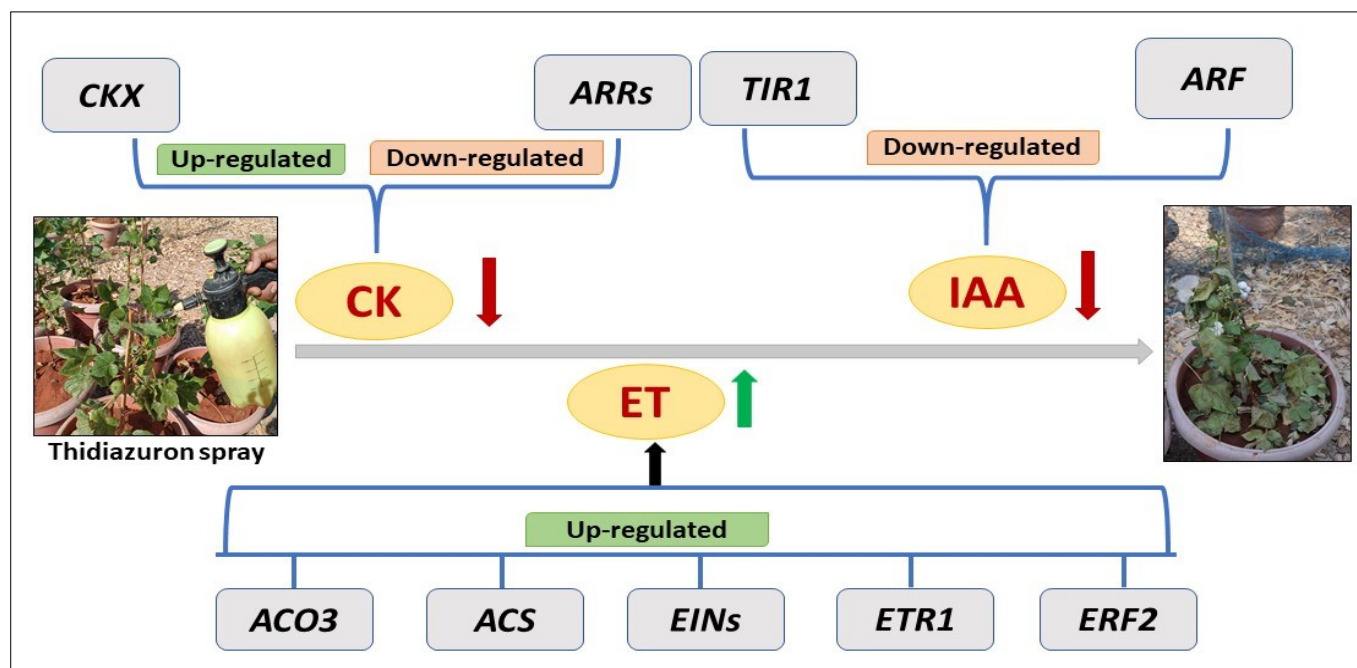

Fig. 4. Defoliant application influences phytohormonal gene expression. Thidiazuron induces ethylene production by upregulation of ethylene-related genes of aconitase 3 (**ACO3**), acetyl-CoA synthetase (**ACS**), ethylene insensitive (**EINs**), ethylene receptor1 (**ETR1**), ethylene response factor2 (**ERF2**) and cytokinin oxidation by upregulation cytokinin oxidase/dehydrogenase (**CKX**) in leaves. Additionally, thidiazuron downregulates cytokinin response regulatory factor, Arabidopsis (*Arabidopsis thaliana*) response regulators (**ARRs**), and Auxin related genes like transport inhibitor response 1 (**TIR 1**) and auxin response factors (**ARF**) results in lowering auxin and cytokinin production and promotes leaf abscission. Red down arrow and Green upward arrow indicate a decrease and increase in the production of phytohormones such as cytokinin (**CK**) and indole acetic acid (**IAA**) as well as ethylene (**ET**), respectively.

Method of thidiazuron application

The application of defoliants is crucial for the efficiency of cotton defoliation. Defoliants are typically applied during the 60-80% boll bursting stage. Enhancing the coverage of defoliants on cotton plants is crucial in improving their efficacy. However, many farmers still rely on human-operated machinery or ground equipment, such as conventional sprayers or tractor-mounted sprayers, which yield lower defoliation rates than aerial applications (14, 41). This inefficiency arises because the wheels of conventional ground-based sprayers can roll over cotton plants as they move through the fields, damaging branches and separating bolls. Such damage can lead to significant yield losses and excessive water usage to cover a given crop area (42).

Currently, researchers are utilizing unmanned aerial vehicles (UAVs) equipped with sprayers to apply defoliants to cotton, along with forecasting application amounts through remote sensing images (28). In UAVs, using ultra-low volume (ULV) sprayers has proven to be highly effective for defoliation in cotton (43, 44). The main advantages of ULV sprayers include reduced application rates, minimized drift, and less waste (45). ULV sprayers accurately deposit defoliants on the target crop area, avoiding physical

Conclusion

Thidiazuron is a potent defoliant that has become essential in modern cotton production. It significantly alters cotton plants' physiological and hormonal balance to induce abscission, which is necessary for efficient mechanical harvesting. Thidiazuron enhances leaf abscission and limits leaf regeneration, producing cleaner cotton with less contamination during harvesting. Thidiazuron also stimulates leaf drop by promoting ethylene production and inhibiting auxin transport, which are crucial for forming abscission zones. Whether aerial or ground spraying, application methods have proven effective in enhancing defoliation rates and yield during mechanization. Maximum effectiveness in cotton defoliation is achieved when thidiazuron is applied at 60 to 80% boll opening. In conclusion, thidiazuron is an effective defoliant contributing to sustainable cotton production, particularly when combined with mechanization.

Future Research Threats

In addition to the importance of thidiazuron in cotton defoliation, it is crucial to understand its mode of action in

modulating plant hormones, including auxin, cytokinin, and ethylene, to ensure optimal application and high-quality cotton fiber production. Future challenges will involve advancing specific application methods to minimize environmental contamination and maximize coverage. Simultaneously, while technologies such as ultra-low volume spraying provide tremendous potential, factors such as flight duration, battery longevity, and mechanization expenses must also be considered. Additionally, there is a need for ongoing efforts toward sustainability, particularly concerning the environmental impact of defoliant use on non-target organisms and soil health. Moreover, achieving sustainable effects from thidiazuron on cotton defoliation requires careful management and continuous monitoring of associated risks to ensure its long-term effectiveness as a solution.

Authors' Contributions

RR and VR designed the paper's approach and structure and wrote the manuscript with input from all authors. AS[1], AS[2], KT, RJ, SS, and SA contributed to conceptualizing and provided academic input for the manuscript. All the authors reviewed, edited, and approved the final version of the manuscript. (AS[1]- Alagarswamy Senthil & AS[2]- Alagesan Subramanian)

Compliance with Ethical Standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Rajput A, Raghuwanshi PS, Chaturvedi P. Dynamics of area, production and productivity of cotton crop in India. Curr Agric Res. 2023;11(2). https://doi.org/10.12944/CARJ.11.2.18

2. Khan MA, Wahid A, Ahmad M, Tahir MT, Ahmed M, Ahmad S, Hasanuzzaman M. World cotton production and consumption. In: Ahmad S, Hasanuzzaman M, editors. Cotton production and uses. Singapore: Springer; 2020. p. 1-7. https://doi.org/10.1007/978-981-15-1472-2_1

3. United States Department of Agriculture (USDA), Foreign Agricultural Service. India: Cotton and Products Update January 2024, Mumbai, India. 2024. https://fas.usda.gov/data/india-cotton-and-products-update-january-2024

4. Jans Y, von Bloh W, Schaphoff S, Müller C. Global cotton production under climate change–Implications for yield and water consumption. Hydrol Earth Syst Sci. 2021; 25(4):2027-44. https://doi.org/10.5194/hess-25-2027-2021

5. Ghaffar A, Habib ur Rahman M, Ali HR, Haider G, Ahmad S, Fahad S, Ahmad S. Modern concepts and techniques for better cotton production. In: Ahmad S, Hasanuzzaman M, editors. Cotton production and uses. Singapore: Springer; 2020. p. 589-628. https://doi.org/10.1007/978-981-15-1472-2_29

6. Mishra SK, Jain MK, Singh VP. Evaluation of the SCS-CN-based model incorporating antecedent moisture. Water Resour Manag. 2004;18:567-89. https://doi.org/10.1007/s11269-004-8765-1

7. Thatikunta R, Ambati S, Sudarshanam A. Yield improvement in rainfed cotton through new plant type concepts–A perspective. In: Proceedings of national symposium on cotton production technologies in the next Decade. Problems and Perspectives; 2020. p.18-24.

8. Song X, Zhang L, Zhao W, Xu D, Eneji AE, Zhang X, Li Z. The relationship between boll retention and defoliation of cotton at the fruiting site level. Crop Sci. 2022;62(3):1333-47. https://doi.org/10.1002/csc2.20721

9. Chandrasekaran P, Ravichandran V, Sivakumar T, Senthil A, Mahalingam L, Sakthivel N. Chemical defoliants promotes defoliation by altering leaf growth parameters and photosynthetic efficiency in high density cotton. J Cotton Res Dev. 2021;35(1):72-78.

10. Chandrasekaran P, Ravichandran V, Senthil A, Mahalingam L, Sakthivel N. Effect of different defoliants and time of application on defoliation percentage and boll opening percentage in high density cotton (*Gossypium hirsutum* L.). Int J Plant Soil Sci. 2020;32:37-45. https://doi.org/10.9734/ijpss/2020/v32i1030337

11. Jin D, Wang X, Xu Y, Gui H, Zhang H, Dong Q, Song M. Chemical defoliant promotes leaf abscission by altering ROS metabolism and photosynthetic efficiency in *Gossypium hirsutum*. Int J Mol Sci. 2020;21(8):2738. https://doi.org/10.3390/ijms21082738

12. Zhou T, Zhang J, Han X, Duan L, Yang L, Zhao S. Mechanism of the mixture of abscisic acid and thidiazuron in regulating cotton leaf abscission. ACS Agric Sci Technol. 2022;2(2):391-401. https://doi.org/10.1021/acsagscitech.2c00011

13. Perumal C, Subiramaniyan A, Natarajan A, Arumugam R, Ramasamy A, Sivalingam R, Sivasubramanian K. Dissecting the biochemical and hormonal changes of thidiazuron on defoliation of cotton CO17 (*Gossypium hirsutum*) to enhance mechanical harvest efficiency. J Appl Nat Sci. 2024;16(1):263-70. https://doi.org/10.31018/jans.v16i1.4860

14. Liu Q, Wei K, Yang L, Xu W, Xue W. Preparation and application of a thidiazuron· diuron ultra-low-volume spray suitable for plant protection unmanned aerial vehicles. Sci Rep. 2021;11(1):4998. https://doi.org/10.1038/s41598-021-84459-4

15. Chandrasekaran P, Ravichandran V, Sivakumar T, Senthil A, Ashok S. Plant growth analysis of defoliation in cotton (*Gossypium hirsutum*). Journal of Cotton Research and Development. 2022;36(2):182-92.

16. Yu K, Li K, Wang J, Gong Z, Liang Y, Yang M, Li Z. Optimizing the proportion of thidiazuron and ethephon compounds to improve the efficacy of cotton harvest aids. Ind Crop Prod. 2023;191:115949. https://doi.org/10.1016/j.indcrop.2022.115949

17. Sravanthi S, Rekha MS, Venkateswarlu B, Rao CS, Jayalalitha K. Effect of defoliants on percent defoliation and yield of American cotton (*Gossypium hirsutum*). Research on Crops. 2022;23(2):458-65. https://doi.org/10.31830/2348-7542.2022.062

18. Chandrasekaran P, Ravichandran V, Senthil A, Mahalingam L, Sakthivel N. Impact of chemical defoliants on chlorophyll fluorescence, biochemical parameters, yield and fiber quality of high density cotton. Indian J Agric Res. 2023;57(6):748-54. https://doi.org/10.18805/IJARe.A-5632

19. Li S, Liu R, Wang X, Zhao L, Chen J, Yang C, Zhang L. Involvement of hydrogen peroxide in cotton leaf abscission induced by thidiazuron. J Plant Growth Regul. 2021;40:1667-73. https://doi.org/10.1007/s00344-020-10218-w

20. Li F, Wu Q, Liao B, Yu K, Huo Y, Meng L, Li Z. Thidiazuron promotes leaf abscission by regulating the crosstalk complexities between ethylene, auxin and cytokinin in cotton. Int J Mol Sci. 2022;23(5):2696. https://doi.org/10.3390/ijms23052696

21. Zhao N, Geng Z, Zhao G, Liu J, An Z, Zhang H, Wang Y. Integrated analysis of the transcriptome and metabolome reveals the molecular mechanism regulating cotton boll abscission under low light intensity. BMC Plant Biol. 2024;24(1):182. https://doi.org/10.1186/s12870-024-04862-7

22. Zhu Y, Zhao M, Li T, Wang L, Liao C, Liu D, Li B. Interactions between *Verticillium dahliae* and cotton: Pathogenic mechanism and cotton resistance mechanism to *Verticillium* wilt. Front Plant Sci. 2023;14:1174281. https://doi.org/10.3389/fpls.2023.1174281

23. Logan J, Gwathmey CO. Effects of weather on cotton responses to harvest-aid chemicals. J Cotton Sci. 2002;6(1):1-12.

24. Wang Z, Hussain M, Yin J, Yuan M, Mo Y, Quan M, Tan W. Analysis of droplet deposition and maize (*Zea mays* L.) growth control: Application of ethephon by small unmanned aerial vehicle and electric knapsack sprayer. Field Crops Res. 2023;292:108822. https://doi.org/10.1016/j.fcr.2023.108822

25. Nisler J, Kopečný D, Končitíková R, Zatloukal M, Bazgier V, Berka K, Spíchal L. Novel thidiazuron-derived inhibitors of cytokinin oxidase/dehydrogenase. Plant Mol Biol. 2016;92:235-48. https://doi.org/10.1007/s11103-016-0509-0

26. Sakamoto M, Munemura I, Tomita R, Kobayashi K. Involvement of hydrogen peroxide in leaf abscission signaling, revealed by analysis with an *in vitro* abscission system in *Capsicum* plants. Plant J. 2008;56(1):13-27. https://doi.org/10.1111/j.1365-313X.2008.03577.x

27. Liao WenBin LW, Wang Gan WG, Li YaYun LY, Wang Bin WB, Zhang Peng ZP, Peng Ming PM. Reactive oxygen species regulate leaf pulvinus abscission zone cell separation in response to water-deficit stress in cassava. Sci Rep. 2016;21542. https://doi.org/10.1038/srep21542

28. Chen L, Liu A, Guo Z, Jiang H, Luo L, Gao J, Guo N. Cloning and bioinformatics analysis of GhArfGAP in cotton (*Gossypium hirsutum*) boll abscission layer with ethylene treatment. Front Plant Sci. 2022;13:841161. https://doi.org/10.3389/fpls.2022.841161

29. Bar-Dror T, Dermastia M, Kladnik A, Žnidarič MT, Novak MP, Meir S, et al. Programmed cell death occurs asymmetrically during abscission in tomato. The Plant Cell. 2011;23(11):4146-63. https://doi.org/10.1105/tpc.111.092494

30. Mukherjee P, Suriyakumar P, Vanchinathan S, Krishnan V, Lal MK, Jha PK, Prasad PV. Hydrogen peroxide and GA3 levels regulate the high night temperature response in pistils of wheat (*Triticum aestivum* L.). Antioxidants. 2023;12(2):342. https://doi.org/10.3390/antiox12020342

31. Iqbal M, Ul-Allah S, Naeem M, Ijaz M, Sattar A, Sher A. Response of cotton genotypes to water and heat stress: From field to genes. Euphytica. 2017;213:1-11. https://doi.org/10.1007/s10681-017-1916-2

32. Ali HM, Khan T, Khan MA, Ullah N. The multipotent thidiazuron: A mechanistic overview of its roles in callogenesis and other plant cultures *in vitro*. Biotechnol Appl Biochem. 2022;69(6):2624-40. https://doi.org/10.1002/bab.2311

33. Zhao R, Sun H, Zhao N, Jing X, Shen X, Chen S. The *Arabidopsis* Ca^{2+}-dependent protein kinase CPK27 is required for plant response to salt-stress. Gene. 2015;563(2):203-14. https://doi.org/10.1016/j.gene.2015.03.024

34. Solanki M, Shukla LI. Recent advances in auxin biosynthesis and homeostasis. 3 Biotech. 2023;13(9):290. https://doi.org/10.1007/s13205-023-03709-6

35. Hallaway M, Osborne DJ. Ethylene: A factor in defoliation induced by auxins. Science. 1969;163(3871):1067-68. https://doi.org/10.1126/science.163.3871.1067

36. Liao B, Li F, Yi F, Du M, Tian X, Li Z. Comparative physiological and transcriptomic mechanisms of defoliation in cotton in response to thidiazuron versus ethephon. Int J Mol Sci. 2023;24(8):7590. https://doi.org/10.3390/ijms24087590

37. Gujjar RS, Supaibulwatana K. The mode of cytokinin functions assisting plant adaptations to osmotic stresses. Plants. 2019;8(12):542. https://doi.org/10.3390/plants8120542

38. Xu C, Mou B. Responses of spinach to salinity and nutrient deficiency in growth, physiology and nutritional value. J Am Soc Hortic Sci. 2016;141(1):12-21. https://doi.org/10.21273/JASHS.141.1.12

39. Xu J, Chen L, Sun H, Wusiman N, Sun W, Li B, Yang X. Crosstalk between cytokinin and ethylene signaling pathways regulates leaf abscission in cotton in response to chemical defoliants. J Exp Bot. 2019;70(5):1525-38. https://doi.org/10.1093/jxb/erz036

40. Binder BM. Ethylene signaling in plants. J Biol Chem. 2020;295(22):7710-25. https://doi.org/10.1074/jbc.REV120.010854

41. Neupane J, Maja JM, Miller G, Marshall M, Cutulle M, Greene J, Barnes E. The next generation of cotton defoliation sprayer. Agri Engineering. 2023;5(1):441-59. https://doi.org/10.3390/agriengineering5010029

42. Zhan Y, Chen P, Xu W, Chen S, Han Y, Lan Y, Wang G. Influence of the downwash airflow distribution characteristics of a plant protection UAV on spray deposit distribution. Biosyst Eng. 2022;216:32-45. https://doi.org/10.1016/j.biosystemseng.2022.01.016

43. Tarazi R, Jimenez JLS, Vaslin MF. Biotechnological solutions for major cotton (*Gossypium hirsutum*) pathogens and pests. Biotechnol Res Innov. 2019;3:19-26. https://doi.org/10.1016/j.biori.2020.01.001

44. Neupane J, Maja JM, Miller G, Marshall M, Cutulle M, Luo J. Effect of controlled defoliant application on cotton fiber quality. Appl Sci. 2023;13(9):5694. https://doi.org/10.3390/app13095694

45. Patel MK, Praveen B, Sahoo HK, Patel B, Kumar A, Singh M, Rajan P. An advance air-induced air-assisted electrostatic nozzle with enhanced performance. Comput Electron Agric. 2017;135:280-88. https://doi.org/10.1016/j.compag.2017.02.010

46. Panneton BL, Bizeau A. Merging RGB and NIR imagery for mapping weeds and crop in 3D. In: Presented the Findings (paper number 141907919) at 2014 ASABE and CSBE/SCGAB Annual International Meeting; 2014 July 13-16; Montreal, Quebec Canada; 2014. p. 1-6. https://doi.org/10.13031/aim.20141907919

47. Kim J, Kim S, Ju C, Son HI. Unmanned aerial vehicles in agriculture: A review of perspective of platform, control and applications. IEEE Access. 2019;7:105100-15. https://doi.org/10.1109/ACCESS.2019.2932119

48. Han L, Yang G, Dai H, Xu B, Yang H, Feng H, Yang X. Modeling maize above-ground biomass based on machine learning approaches using UAV remote-sensing data. Plant Methods. 2019;15:1-19. https://doi.org/10.1186/s13007-019-0394-z

49. Meng Y, Song J, Lan Y, Mei G, Liang Z, Han Y. Harvest aids efficacy applied by unmanned aerial vehicles on cotton crop. Ind Crops Prod. 2019;140:111645. https://doi.org/10.1016/j.indcrop.2019.111645

50. Kong H, Yi L, Lan Y, Kong F, Han X. Exploring the operation mode of spraying cotton defoliation agent by plant protection UAV. Int J Precis Agric Aviat. 2020;3(1):43-48. https://doi.org/10.33440/j.ijpaa.20200301.65