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CHEMICAL TOPPING MEDIATED MODULATION OF PLANT ARCHITECTURE AND SOURCE-SINK DYNAMICS: A REVIEW

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ABSTRACT

Chemical topping represents a strategic agronomic intervention aimed at regulating vegetative growth, optimizing reproductive development and enhancing yield stability in intensively managed cropping systems. This review critically synthesizes current knowledge on the role of chemical topping in plant growth modulation, with particular emphasis on its physiological, morphological and developmental implications. Chemical topping functions primarily through disruption of apical dominance and inhibition of gibberellin biosynthesis, thereby modifying auxin transport gradients, enhancing cytokinin-mediated lateral activity and altering endogenous hormonal equilibrium. In indeterminate crops such as chickpea, mungbean, cotton, Tabaco, mustard *etc.* these mechanisms result in reduced stem elongation, improved canopy architecture, enhanced light interception and optimized source-sink relationships. The review evaluates major classes of chemicals used for topping, including growth retardants (e.g., mepiquat chloride, chlormequat chloride, maleic hydrazide), hormonal inhibitors and desiccant/contact chemicals such as fatty alcohol formulations and maleic hydrazide with detailed discussion of their biochemical modes of action and agronomic performance. Emphasis is placed on their effects on photosynthesis, carbon partitioning, nutrient dynamics, phenological progression and harvest index. Evidence indicates that chemical topping enhances boll retention and lint yield in cotton and improves leaf yield and quality in tobacco when applied with precision. However, responses are highly genotype and environment-dependent and misapplication may lead to phytotoxicity, reduced biomass accumulation or regulatory residue concerns. The review further explores challenges associated with environmental safety, resistance management and sustainability and highlights emerging prospects including precision agriculture technologies, nano-enabled formulations and molecular breeding approaches targeting architectural traits. Overall, chemical topping is positioned not merely as a vegetative suppression tool but as a developmental optimization strategy whose effectiveness depends on integrated crop management, physiological insight and adaptive decision-making frameworks in modern agriculture.
***Keywords* :** Chemical topping, Plant growth modulation, Plant architecture.

Introduction

Apical dominance is a fundamental regulatory phenomenon in higher plants, wherein the primary shoot apex suppresses the outgrowth of axillary buds through a coordinated network of hormonal signalling pathways. This process is primarily mediated by auxin transport from the apical meristem, which indirectly inhibits lateral bud growth by modulating cytokinin biosynthesis and promoting strigulating signalling. However, recent advances have demonstrated that apical dominance is not exclusively auxin-driven but involves complex cross-talk among multiple phytohormones and metabolic signals, including sugars that act as key regulators of bud activation and shoot architecture (Barbier *et al*., 2019; Wang *et al*., 2021). The degree of apical dominance varies among plant species and is influenced by genetic, physiological and environmental factors making it a highly dynamic and adaptive trait. At the physiological level, this phenomenon is governed by the interaction of key plant growth regulators. Auxins synthesized in the shoot apex are transported downward and interact with cytokinin and strigolactones to regulate bud dormancy and activation (Omoarelojie *et al*., 2019). The balance and cross-talk among these hormones create a finely tuned regulatory system that determines whether axillary buds remain dormant or develop into lateral branches (Chen *et al*., 2023). Under non-management of apical dominance, unchecked vertical growth often suppresses lateral branching, reduces photosynthetic efficiency within the canopy and ultimately restricts biomass partitioning towards economically important plant parts.

Role of topping for managing apical dominance

Topping is an agronomic intervention that involves the physical or chemical removal of the apical meristem to disrupt apical dominance and stimulate lateral branching. This response is physiologically regulated by auxin transport from the shoot apex, which under intact conditions suppresses the growth of axillary buds and maintains their dormancy (Waldie *et al*., 2014). Removal or suppression of the apical bud reduces basipetal auxin flux, thereby relieving inhibition on axillary buds, enhancing cytokinin activity and stimulating lateral outgrowth. However, contemporary research demonstrates that branching regulation is not exclusively auxin-driven but involves complex interactions among strigolactones, cytokinin and sugar signalling pathways that collectively determine bud activation and shoot architecture (Barbier *et al*., 2019; Bertheloot *et al*., 2020; Wang & Jiao, 2022). This coordinated hormonal and metabolic reprogramming results in architectural modifications that improve canopy structure, light interception and assimilate distribution toward reproductive sinks. Agronomically, topping has long been practiced in crops such as cotton and tobacco to regulate excessive vegetative growth and synchronize reproductive development. In tobacco, topping enhances leaf expansion, biomass accumulation and alkaloid synthesis by redirecting assimilates from reproductive structures to leaves, thereby improving leaf quality and economic yield (Zhang *et al*., 2020; Willis and ED, 2017). In cotton, topping whether manual or chemical restricts indeterminate vegetative growth, improves boll retention and enhances harvest index, particularly under high nitrogen or irrigated conditions (Oosterhuis *et al*., 2021; Koutroubas & Damalas, 2020; Dhyani, 2020). These responses reflect a shift in source-sink dynamics, where assimilates are preferentially allocated to economically important organs.

The effectiveness of topping is strongly influenced by crop growth habit. Indeterminate species exhibit greater responsiveness due to continued vegetative growth after flowering, whereas determinate crops show comparatively limited responses (Bange *et al*., 2022; Oosterhuis *et al*., 2021). By restricting terminal growth, topping can accelerate reproductive development, improve canopy uniformity and reduce lodging risk under high-density planting systems (Wang *et al*., 2021). However, improper timing or excessive severity may reduce photosynthetic capacity, delay recovery and induce physiological stress, ultimately limiting yield potential (Oosterhuis *et al*., 2021; Koehler, A.K., Challis, A., 2019). At the molecular level, topping influences the expression of genes associated with axillary bud outgrowth, auxin transport and strigolactone biosynthesis. Key regulatory pathways, including the more axillary growth (max) gene network and carotenoid cleavage dioxygenases (CCD), play central roles in controlling branching through hormonal cross-talk (Wang & Jiao, 2022). In addition, sugar signalling particularly through trehalose-6-phosphate has emerged as a critical regulator linking carbon availability with bud activation and developmental transitions (Bertheloot *et al*., 2020; Hambrey, 2017). These findings demonstrate that topping is not merely a mechanical practice but a targeted physiological intervention that alters hormonal balance, metabolic signalling and plant architectural dynamics.

Manual topping

Manual topping involves the physical excision of the apical meristem, resulting in the immediate removal of the dominant auxin source that maintains apical dominance. This abrupt disruption reduces basipetal transport of indole-3-acetic acid (IAA), thereby releasing axillary buds from dormancy and enhancing cytokinin-mediated bud activation, which promotes lateral branching (Zho *et al*., 2017; Tigchelaar *et al*., 2018; Kotir, 2011). However, bud outgrowth following topping is not solely governed by auxin depletion recent studies highlight the integrative role of sugar singalling and strigolactone pathways in regulating sink strength and bud activation, indicating that branching responses are controlled by a coordinated hormonal and metabolic network (Bertheloot *et al*., 2020; Wang *et al*., 2021; Wang & Jiao, 2022). In crops such as cotton and tobacco, manual topping improves branching, boll retention or leaf expansion *and* enhances economically important yield components when applied at appropriate developmental stages (Oosterhuis *et al*., 2021). Nevertheless, manual topping is labour-intensive, often inconsistent at field scale *and* may induce mechanical injury that increases susceptibility to environmental and biological stress (Oosterhuis *et al*., 2021; Padulosi, *et al*., 2021).

Chemical topping

Chemical topping, in contrast, suppresses apical dominance through physiological regulation rather than physical removal. Plant growth regulators (PGRs) such as mepiquat chloride and chlormequat chloride primarily act by inhibiting gibberellin biosynthesis, thereby reducing cell elongation, limiting excessive vegetative growth and indirectly modifying source-sink relationships without removing the apical meristem. Beyond growth inhibition, these compounds influence hormonal cross-talk involving auxins, cytokinin and abscisic acid, allowing more precise modulation of plant architecture and stress responses (Rademacher, 2018; Koutroubas & Damalas, 2020). In tobacco, chemical topping and sucker control are commonly achieved using contact chemicals such as fatty alcohol formulations or maleic hydrazide, which suppress axillary bud growth and reduce the need for repeated manual interventions (Zhang *et al*., 2020). Although chemical topping may exert less abrupt suppression of apical dominance compared to manual removal, it offers greater uniformity, operational efficiency and scalability under mechanized production systems (Koutroubas & Damalas, 2020; Wolter and Puchta, 2019). Crop-specific responses illustrate distinct physiological outcomes between the two approaches. In cotton, manual topping typically induces stronger lateral branching but may temporarily disrupt canopy structure and reduce photosynthetic efficiency due to sudden loss of the apical sink. In contrast, chemical growth retardants restrict stem elongation while maintaining leaf area, thereby preserving canopy integrity and improving radiation interception (Oosterhuis *et al*., 2021; Smith *et al.,* 2018). These contrasting responses demonstrate that while both methods target apical dominance, they differ substantially in their effects on canopy structure, stress physiology and assimilate partitioning.

Despite its advantages, chemical topping requires precise optimization of dosage, timing and environmental conditions. Excessive application may overly restrict vegetative growth, reduce leaf expansion and impair recovery, ultimately leading to yield penalties (Koutroubas & Damalas, 2020). Conversely, manual topping, although simpler, often introduces variability and greater physiological stress due to inconsistent execution. Therefore, the choice between manual and chemical topping should be determined by crop growth habit, scale of production, labour availability and the desired balance between vegetative control and reproductive efficiency.

Mechanism of chemical topping

Chemical topping operates through the targeted modulation of hormonal and molecular pathways regulating apical dominance, primarily by altering auxin transport, hormonal balance and downstream signalling networks. Under normal physiological conditions, the shoot apex acts as the principal source of indole-3-acetic acid (IAA), which is transported basipetally and suppresses axillary bud outgrowth. This inhibition is not solely auxin-driven but is mediated through coordinated interactions among auxin, cytokinin and strigolactones, along with metabolic signals such as sugars that regulate bud activation and shoot architecture (Barbier *et al*., 2019; Wang & Jiao, 2022; Bertheloot *et al*., 2020). Chemical topping agents interfere with this regulatory network by weakening apical dominance through hormonal rebalancing rather than physical removal, leading to reduced auxin influence and enhanced cytokinin activity in axillary buds, thereby promoting lateral branching and modifying canopy structure. A major mechanism underlying chemical topping involves inhibition of gibberellin (GA) biosynthesis. Growth retardants such as mepiquat chloride and chlormequat chloride inhibit key enzymatic steps in the GA biosynthetic pathway, resulting in reduced cell elongation and shorter internodes. Beyond restricting vegetative growth, GA inhibition improves assimilate partitioning and enhances reproductive sink strength, particularly under intensive cropping systems (Rademacher, 2018; Koutroubas & Damalas, 2020). In cotton, such regulation has been associated with improved canopy architecture, enhanced boll retention and increased harvest index through better source-sink balance (Oosterhuis *et al*., 2021). Unlike manual topping, chemical regulation allows controlled suppression of vegetative growth while maintaining functional continuity of the apical meristem.

Certain chemical topping approaches, particularly in tobacco, rely on localized chemical injury to the apical meristem. Compounds such as fatty alcohol formulations and maleic hydrazide disrupt cellular integrity and suppress meristematic activity, effectively mimicking the effects of manual topping while enabling uniform application. These treatments also induce physiological responses including ethylene-mediated stress signalling, which contributes to suppression of apical dominance and inhibition of sucker growth (Zhang *et al*., 2020). However, the effectiveness of such treatments depends on precise dosage and timing, as excessive injury can negatively affect overall plant metabolism and productivity. At the molecular level, chemical topping influences gene regulatory networks associated with shoot branching and hormonal signalling. Key pathways include the regulation of strigolactone biosynthesis and signalling genes, such as those in the more axillary growth (max) family *and* modulation of auxin transport via PIN efflux carriers, which collectively control bud dormancy and activation (Waters *et al*., 2017; Wang *et al*., 2021). Reduction in strigolactone signalling alleviates inhibition of axillary buds, thereby promoting lateral shoot initiation. In addition, sugar signalling particularly through sucrose availability and trehalose-6-phosphate has emerged as a critical early regulator of bud outgrowth, linking carbon status with developmental responses (Fichtner *et al*., 2021; Bertheloot *et al*., 2020). These integrated hormonal, molecular and metabolic adjustments explain the effectiveness of chemical topping in reshaping plant architecture while maintaining physiological stability when applied under optimized agronomic conditions.

Table 1: Comparative analysis of manual vs chemical topping.

Parameter	Manual Topping	Chemical Topping	References
Method of action	Physical removal of apical meristem	Chemical inhibition of GA biosynthesis and hormonal regulation	Rademacher (2018)
Precision	Low, operator-dependent	High, uniform across field	Koutroubas & Damalas 2020; (Dhyani, 2020)
Labour requirement	High	Low	Oosterhuis *et al*. (2021; Willis, 2017)
Cost structure	Labour-intensive	Input-intensive	Koutroubas & Damalas 2020; Hambrey, 2017)
Effect on branching	Strong stimulation	Moderate, regulated	Wang *et al*. (2021)
Yield impact	Variable	More stable under intensive systems	Oosterhuis *et al*. (2021); Koutroubas & Damalas (2020)
Risk factors	Mechanical damage	Phytotoxicity, misapplication	Rademacher 2018; Kotir, 2011
Suitability	Small-scale farming	Large-scale mechanized systems	Koutroubas & Damalas 2020

Types of chemicals used for topping

Chemical topping utilizes a range of plant growth-modifying compounds that suppress apical dominance either through hormonal regulation or by inducing localized injury to the apical meristem (Zaytseva & Neumann, 2016; Khan & Rizvi, 2014). Plant growth regulators are broadly categorized into growth retardants, hormonal modulators (including auxin transport regulators) *and* desiccants/contact chemicals based on their mode of action and physiological effects (Ghoneim, 2018; Kumar *et al*., 2024; Rademacher, 2018) Each category differs in its mode of action, physiological effects and crop-specific suitability. The selection of these chemicals must be aligned with crop architecture, developmental stage and environmental conditions to achieve an optimal balance between vegetative growth control and reproductive efficiency (Rademacher, 2018; Koutroubas & Damalas, 2020).

Growth retardants

Growth retardants are the most widely used chemical agents for topping, particularly in indeterminate crops such as cotton. Compounds including mepiquat chloride, chlormequat chloride and daminozide act primarily by inhibiting gibberellin (GA) biosynthesis, especially at later stages responsible for the formation of bioactive Gas (Zhang *et al*., 2020). This inhibition restricts cell elongation and internode growth, resulting in a more compact plant architecture without complete suppression of the apical meristem. Beyond height control, GA inhibitors improve assimilate partitioning, optimize canopy structure and enhance reproductive sink development under intensive production systems (Rademacher, 2018; Oosterhuis *et al*., 2021). In cotton, application of mepiquat chloride is consistently associated with reduced plant height, improved canopy management and enhanced boll retention, particularly under high nitrogen and irrigated conditions. However, its effectiveness is highly dependent on application timing, dosage and environmental factors such as temperature and water availability, making precise agronomic management essential (Koutroubas & Damalas, 2020; Oosterhuis *et al*., 2021).

Hormonal modulators (auxin transport regulators)

Hormonal modulators regulate apical dominance by altering auxin transport, signalling or its interaction with other phytohormones. Reduction in basipetal movement of indole-3-acetic acid (IAA) weakens apical dominance and facilitates axillary bud activation. However, shoot branching is not regulated by auxin alone; it is controlled by a complex network involving cytokinin, strigolactones and sugar signalling pathways (Barbier *et al*., 2019; Wang & Jiao, 2022; Bertheloot *et al*., 2020). Some chemical growth regulators indirectly enhance cytokinin activity or modify hormonal sensitivity at the bud level, thereby promoting lateral bud outgrowth through altered hormonal crosstalk and signalling within axillary meristems. (Corot *et al*., 2017). These hormonal adjustments improve canopy architecture, enhance light interception and increase radiation use efficiency under high-density planting. However, their effectiveness is highly stage-dependent, as hormonal responsiveness varies across developmental stages and environmental conditions. Poorly timed applications can lead to suboptimal branching or reduced yield, which remains a common limitation in field-level adoption.

Desiccants and contact chemicals

Desiccants or contact-type chemical topping agents function through localized chemical injury to the apical meristem, leading to rapid termination of apical growth. In crops such as tobacco, fatty alcohol-based formulations and compounds like maleic hydrazide are widely used for chemical topping and sucker control (Zhao *et al*., 2017; Tigchelaar *et al*., 2018; Padulosi *et al*., 2021). These compounds disrupt cellular integrity and suppress meristematic activity, effectively mimicking mechanical topping while enabling uniform application across large areas (Zhang *et al*., 2020). Compared to manual topping, chemical desiccants provide greater uniformity, reduced labour requirements and better suitability for mechanized production systems. They ensure more consistent suppression of apical growth, which is critical for synchronized crop development and uniform maturity (Koutroubas & Damalas, 2020; Wolter *et al*., 2019). However, the extent of chemical injury must be carefully controlled, as excessive tissue damage can induce stress responses such as increased ethylene production, oxidative stress and temporary reduction in photosynthetic efficiency, ultimately affecting crop performance (Iqbal *et al*., 2021; Vermeulen *et al*., 2012; Panpatte *et al*., 2016).

Emerging and integrated chemical approaches

Recent advances in plant growth regulation emphasize integrated chemical strategies that combine multiple modes of action to optimize plant architecture and productivity. Rather than relying on single compounds, modern approaches involve the coordinated use of gibberellin inhibitors, auxin-related regulators and other plant growth regulators (PGRs) to achieve more precise control over shoot branching, canopy structure and assimilate allocation. These strategies are supported by an improved understanding of hormonal cross-talk involving auxin, cytokinin and strigolactones, which collectively regulate bud outgrowth and plant form (Barbier *et al*., 2019; Wang *et al*., 2021; Bertheloot *et al*., 2020). Such integrative regulation enables fine-tuning of vegetative and reproductive balance, particularly under high-input and high-density cropping systems. In parallel, chemical topping is increasingly being integrated with precision agriculture technologies (He *et al*., 2019). Advances in canopy analysis and crop monitoring have improved the ability to assess spatial and temporal variability in crop growth, enabling more informed application of plant growth regulators. Tools such as remote sensing, canopy modeling and decision-support systems allow stage-specific and site-specific management of crop architecture, thereby reducing the risks of over-application and improving input-use efficiency (Zhang *et al*., 2017; Chen *et al*. 2025). These developments reflect a transition from conventional growth suppression toward precision crop architecture management, where chemical topping is applied as a targeted physiological intervention rather than a generalized agronomic practice.

Hormonal chemicals (anti auxins and branching regulators)

Hormonal chemicals used in chemical topping primarily act by modulating the regulatory network controlling apical dominance, particularly through interference with auxin transport and its interaction with other phytohormones (Afsharinejad *et al*., 2016; Kwak *et al*., 2017). Under normal physiological conditions, the shoot apex produces indole-3-acetic acid (IAA), which is transported basipetally via polar auxin transport and suppresses axillary bud outgrowth. However, this suppression is not governed by auxin alone; it involves coordinated cross-talk with cytokinin and strigulates that collectively regulate branching patterns (Barbier *et al*., 2019; Wang & Jiao, 2022; Bertheloot *et al*., 2020). Chemical inhibition of auxin transport reduces this inhibitory signal, thereby releasing axillary buds from dormancy and promoting lateral branching. Auxin transport inhibitors such as N-1-naphthylphthalamic acid (NPA) have been widely used in experimental systems to mimic decapitation effects, confirming that auxin flux is central to apical control. Cytokinin-mediated regulation plays a complementary role in chemical topping responses (Ran *et al*., 2017; Miller *et al*., 2017; Kim *et al*., 2017). Following the reduction of auxin-mediated suppression, increased cytokinin biosynthesis and signalling in axillary buds stimulate cell division and meristem activation. Cytokinins act as key positive regulators of bud outgrowth, functioning antagonistically to auxin and synergistically with sugar signalling pathways (Kebrom, 2017; Barbier *et al*., 2019; Wang *et al*., 2021). Although direct cytokinin application is not commonly practiced in field-scale topping, chemical treatments that indirectly enhance cytokinin activity or sensitivity contribute significantly to improved branching and canopy development.

Strigolactones constitute another critical hormonal pathway influencing branching regulation. These carotenoid-derived hormones act as inhibitors of axillary bud outgrowth and function downstream of auxin signalling (Worrall *et al*., 2018; Verma *et al*., 2018). Suppression of apical dominance either through chemical or mechanical means reduces strigolactone signalling, thereby facilitating lateral shoot initiation. Key components of this pathway include genes of the more axillary growth (max) family and carotenoid cleavage dioxygenases (CCD), which regulate branching responses through hormonal cross-talk (Waters *et al*., 2017; Wang *et al*., 2021; Loh *et al*., 2016; Kumar *et al*., 2019). Although direct manipulation of strigolactone pathways remains largely experimental, their role provides a strong mechanistic framework for understanding the effects of chemical topping on plant architecture.

In practical crop systems such as cotton and tobacco, hormonal chemical approaches are often integrated with growth retardants to balance vegetative growth restriction and branching stimulation. Modulation of auxin transport and hormonal balance improves canopy structure, enhances fruiting branch formation and supports reproductive efficiency under intensive production systems (Koutroubas & Damalas, 2020; Oosterhuis *et al*., 2021). However, the effectiveness of these treatments is highly dependent on application timing and environmental conditions. Early application may disrupt meristem development, whereas delayed application may fail to induce significant architectural changes. In addition, environmental factors such as temperature, water availability and nutrient status strongly influence hormonal sensitivity and branching responses, necessitating precise agronomic management for consistent outcomes.

Advantages & limitations of chemical topping

Chemical topping offers significant agronomic advantages, particularly in large-scale, high-density and mechanized production systems where manual topping is labour-intensive and often inconsistent. One of the primary benefits is the relatively uniform suppression of apical dominance across plant populations, which contributes to more synchronized growth and improved crop management. Plant growth regulators such as mepiquat chloride regulate excessive vegetative growth without removing photosynthetically active tissues, thereby maintaining canopy functionality while improving reproductive efficiency (Koutroubas & Damalas, 2020; Oosterhuis *et al*., 2021). Controlled restriction of vegetative growth improves canopy architecture by reducing excessive shading and enhancing light distribution within the canopy. This contributes to improved radiation interception and more efficient photosynthetic performance under dense planting conditions. As a result, chemical growth regulation can support improved harvest index and yield stability, particularly in systems where vegetative growth is excessive due to high nitrogen availability or irrigation (Oosterhuis *et al*., 2021; Tiwari *et al*., 2012). In addition, chemical topping reduces labour requirements and enables timely crop management, which is critical under intensive production systems.

Another important advantage is improved source-sink regulation. By limiting apical growth or internode elongation, chemical topping promotes the redistribution of assimilates toward economically important sinks such as bolls or leaves. This improves partitioning efficiency and supports yield stability under favourable conditions (Oosterhuis *et al*., 2021; Koutroubas & Damalas, 2020). Additionally, moderate suppression of vegetative growth can reduce lodging risk and improve overall plant balance in vigorously growing crops. Despite these advantages, chemical topping is associated with several limitations that require precise management. Improper application either excessive dosage or incorrect timing can lead to over-suppression of vegetative growth, reduced leaf area development and delayed canopy recovery, ultimately resulting in yield penalties. Because plant sensitivity to growth regulators varies across developmental stages, poorly timed applications may negatively affect reproductive development instead of enhancing it (Koutroubas & Damalas, 2020; Oosterhuis *et al*., 2021). Environmental conditions further influence the effectiveness and safety of chemical topping. Factors such as temperature, water availability and nutrient status can modify plant responses to growth regulators, sometimes amplifying their effects and leading to physiological stress (Iqbal *et al*., 2021; Park *et al*., 2016). Contact-type desiccants, in particular, have a narrow margin of safety due to their direct mode of action. Misapplication can cause excessive tissue injury, reduced photosynthetic capacity and impaired recovery. Stress responses, including increased ethylene production and oxidative damage, may further limit crop performance if not carefully managed (Kitching *et al*., 2015; Iqbal *et al*., 2021).

Environmental and regulatory considerations also affect the adoption of chemical topping. Concerns related to chemical residues, off-target effects and environmental safety require adherence to recommended application practices and integration with broader crop management strategies. Moreover, economic returns depend on precise dose optimization and favourable environmental conditions and variability in crop response can limit predictability (Waldie *et al*-.,2014). Therefore, while chemical topping is an effective agronomic tool, its success depends on careful calibration, timing and integration with overall crop management rather than indiscriminate use.

Effect on plant morphology

Chemical topping induces significant structural modifications in crop plants by suppressing apical dominance and altering assimilate partitioning toward lateral and reproductive organs. One of the most immediate morphological responses is the reduction in stem elongation, primarily driven by inhibition of gibberellin (GA) biosynthesis and modulation of hormonal balance. Growth regulators such as mepiquat chloride reduce bioactive GA levels, leading to shorter internodes and a more compact plant architecture. This controlled reduction in plant height improves canopy stability and reduces lodging risk, particularly under high-input conditions (Rademacher, 2018; Oosterhuis *et al*., 2021). Branching pattern is another key morphological trait influenced by chemical topping. Suppression of polar auxin transport from the shoot apex weakens apical dominance and promotes axillary bud outgrowth. This response is regulated through coordinated hormonal interactions involving auxin, cytokinin and strigolactones, along with sugar signalling pathways that act as early triggers for bud activation (Barbier *et al*., 2019; Wang & Jiao, 2022; Bertheloot *et al*., 2020). In crops such as cotton, regulated chemical application can enhance the development of fruiting branches and improve distribution of reproductive sites. However, excessive suppression may reduce productive branching, indicating a strong dose-dependent response.

Leaf morphological traits are also modified following chemical topping. Reduced vegetative growth and improved canopy openness enhance light penetration, which can increase leaf thickness and chlorophyll concentration per unit area. These changes contribute to improved photosynthetic efficiency at the leaf level, although total leaf area may decline under strong growth inhibition. A moderate reduction in leaf area index (LAI) can improve light distribution within dense canopies, whereas excessive reduction may limit overall carbon assimilation and biomass production (Oosterhuis *et al*., 2021). Alterations in root-shoot balance represent another important morphological consequence. Growth retardants that restrict shoot elongation often leads to relatively greater allocation of assimilates to root systems, improving root development and resource acquisition capacity. Such changes may enhance water uptake efficiency and contribute to improved tolerance under moderate water stress conditions, although responses are strongly influenced by environmental factors (Rademacher, 2018; Oosterhuis *et al*., 2021). Reproductive structural traits are also influenced by chemical topping. Reduced vegetative growth leads to a more open canopy architecture, improving light distribution and facilitating better development and retention of reproductive structures such as bolls or pods. In cotton, this can improve fruit distribution and harvest efficiency.

Despite these advantages, morphological responses to chemical topping are highly dependent on application timing, environmental conditions and genotype. Early application may restrict the development of sufficient vegetative framework, whereas delayed application may fail to induce meaningful architectural changes. In addition, environmental stresses such as temperature extremes or nutrient limitations can alter plant sensitivity to growth regulators, resulting in variable outcomes (Koutroubas & Damalas, 2020). Therefore, chemical topping should be considered a precision canopy management tool that requires careful calibration to achieve desired morphological outcomes without compromising overall plant productivity.

Effect on physiological process

Chemical topping exerts significant effects on plant physiological processes by modifying canopy architecture, hormonal balance and assimilate distribution. These changes directly regulate photosynthetic efficiency, carbon partitioning and overall plant productivity. Plant growth regulators (PGRs) such as mepiquat chloride primarily influence endogenous hormone dynamics through inhibition of gibberellin biosynthesis, while indirectly affecting auxin-cytokinin balance. This results in controlled vegetative growth and improved coordination between source and sink activities (Rademacher, 2018; Oosterhuis *et al*., 2021). One of the major physiological effects of chemical topping is on photosynthesis and canopy function. Reduction in excessive vegetative growth leads to improved canopy structure, allowing better light penetration and distribution within the canopy. This enhances radiation interception and improves photosynthetic efficiency at the whole-plant level, particularly under high-density planting conditions (Oosterhuis *et al*., 2021). However, excessive growth suppression may reduce total leaf area, potentially limiting overall carbon assimilation, indicating that the response is highly dependent on application intensity.

Chemical topping also significantly alters source-sink relationships. By restricting apical dominance and stem elongation, assimilates are redistributed from vegetative tissues toward reproductive or economically important organs. In cotton, this results in improved boll retention and development, while in tobacco, assimilates are redirected toward leaf biomass and quality (Oosterhuis *et al*., 2021). This shift in assimilate partitioning enhances harvest index and contributes to yield stability under favourable conditions. Hormonal regulation is central to these physiological responses. Suppression of gibberellin activity reduces cell elongation, while changes in auxin transport and cytokinin activity promote better coordination of growth processes. In addition, strigolactones and sugar signalling pathways play critical roles in integrating hormonal signals with plant carbon status, thereby regulating bud activity and growth responses (Barbier *et al*., 2019; Bertheloot *et al*., 2020; Wang & Jiao, 2022). These interactions highlight that the effects of chemical topping are governed by a complex regulatory network rather than a single hormonal pathway. At the physiological level, chemical topping can also influence plant stress responses. Moderate regulation of vegetative growth may improve resource-use efficiency and plant balance, whereas excessive application can induce stress-related responses such as altered ethylene production and oxidative imbalance, potentially reduce photosynthetic efficiency and delay recovery (Iqbal *et al*., 2021). Therefore, the physiological outcomes of chemical topping depend strongly on dose, timing and environmental conditions. Overall, chemical topping functions as a targeted physiological intervention that modifies canopy function, hormonal balance and assimilate allocation. When applied under optimized conditions, these changes enhance photosynthetic efficiency, improve source-sink dynamics and support higher productivity in crops such as cotton and tobacco under intensive management systems.

Photosynthesis

One of the most consistent physiological responses to chemical topping is the modification of photosynthetic performance through changes in canopy structure and light distribution. Growth retardants such as mepiquat chloride reduce excessive vegetative growth, resulting in a more compact and open canopy. This improves light penetration into lower leaf layers and enhances the photosynthetic contribution of previously shaded leaves, thereby improving overall canopy photosynthesis (Oosterhuis *et al*., 2021). Improved canopy architecture enhances radiation interception and distribution, which supports more efficient utilization of available light under dense planting conditions. In crops such as cotton, reduction in self-shading improves intra-canopy photosynthetic balance and promotes more efficient carbon assimilation and utilization (Oosterhuis *et al*., 2021; Srinivasulu & Rao, 2012). In addition, chemical regulation of vegetative growth can increase chlorophyll concentration per unit leaf area and specific leaf weight, contributing to improved photosynthetic efficiency at the leaf level (Rademacher, 2018; Schippers *et al.*, 2015). However, the response of photosynthesis to chemical topping is strongly dose-dependent. While moderate growth regulation improves light distribution and photosynthetic efficiency, excessive suppression of vegetative growth can reduce total leaf area index (LAI), thereby limiting overall carbon fixation at the whole-plant level. This creates a trade-off between improved leaf-level efficiency and reduced canopy photosynthesis, which ultimately determines the effectiveness of chemical topping strategies (Oosterhuis *et al*., 2021). In tobacco, chemical suppression of apical growth redirects assimilatory activity toward leaf development, leading to increased leaf biomass and improved leaf quality under properly managed conditions. This shift in assimilate allocation supports sustained photosynthetic activity in economically important tissues, particularly when chemical topping is applied at appropriate developmental stages. Overall, chemical topping improves photosynthetic efficiency primarily through canopy optimization and redistribution of assimilates. However, its success depends on maintaining a balance between adequate leaf area and efficient light utilization, emphasizing the importance of precise application and crop-specific management.

Table 2: Physiological effects of chemical topping

Physiological Process	Effect of chemical Topping	Mechanism	References
Photosynthesis	Improved canopy light distribution	Reduced shading, better leaf orientation	Oosterhuis *et al*. (2021)
Hormonal balance	↓ GA, altered auxin-cytokinin ratio	Inhibition of GA biosynthesis pathways	Rademacher (2018)
Source-sink relationship	Enhanced reproductive sink strength	Assimilate reallocation	Oosterhuis *et al*. (2021)
Nitrogen use efficiency	Increased NUE	Reduced vegetative dilution effect	Oosterhuis *et al*. (2021); Rademacher (2018)
Carbon partitioning	More allocation to yield organs	Suppression of vegetative sinks	Rademacher (2018); Oosterhuis *et al*. (2021)
Canopy architecture	Compact, uniform	Internode shortening	Rademacher (2018); Oosterhuis *et al*. (2021)

Hormonal balance (auxin, cytokinin, gibberellin, ABA)

Chemical topping fundamentally alters endogenous hormonal equilibrium, which governs apical dominance, branching and assimilate allocation. Under normal conditions, basipetal transport of auxin (indole-3-acetic acid, IAA) from the shoot apex suppresses axillary bud outgrowth. Disruption of this auxin gradient through chemical topping weakens apical dominance and promotes lateral bud activation. This process is regulated through complex hormonal cross-talk involving cytokinin and strigolactones, rather than auxin alone (Barbier *et al*., 2019; Bertheloot *et al*., 2020; Wang & Jiao, 2022). Growth retardants such as mepiquat chloride primarily act by inhibiting gibberellin (GA) biosynthesis, particularly the formation of bioactive GAs, resulting in reduced cell elongation and restrained vegetative growth. This shift in hormonal balance limits excessive stem growth and improves coordination between vegetative and reproductive development (Rademacher, 2018). Reduced GA activity also contributes to a more compact canopy structure and improved assimilate utilization efficiency.

Cytokinin play a complementary role in regulating bud activation following chemical suppression of apical dominance. A reduction in auxin-mediated inhibition enhances cytokinin biosynthesis and signalling in axillary buds, promoting cell division and meristem activity. Modern studies indicate that cytokinin signalling, in coordination with sugar availability, acts as a major positive regulator of bud outgrowth and sink establishment (Kebrom, 2017; Barbier *et al*., 2019; Bertheloot *et al*., 2020).

Abscisic acid (ABA) also contributes to the hormonal response under chemical topping conditions, particularly in relation to stress regulation. Transient increases in ABA levels are often associated with stress signalling and improved resource conservation under moderate growth restriction. This may contribute to improved assimilate retention and stabilization of reproductive development under suboptimal environmental conditions (Iqbal *et al*., 2021). However, excessive hormonal imbalance or stress induction can negatively affect growth and recovery, highlighting the importance of controlled application.

In crops such as tobacco, chemical agents including fatty alcohols and growth regulators disrupt meristematic activity and auxin transport, leading to rapid termination of apical growth and reorganization of hormonal flux. Collectively, these hormonal adjustments underpin the morphological and physiological responses associated with chemical topping, particularly in relation to branching, canopy structure and yield formation.

Source-sink regulation

Chemical topping significantly modifies source-sink relationships by reducing vegetative sink strength and enhancing assimilate allocation toward reproductive or economically important organs. Suppression of apical growth decreases competition for photosynthates between actively growing vegetative meristems and developing sinks such as bolls, pods or leaves. This redistribution of assimilates improves sink strength and contributes to enhanced yield stability under favourable conditions (Oosterhuis *et al*., 2021; Rademacher, 2018).

In cotton, reduced vegetative demand increases carbohydrate availability for developing bolls, improving boll retention and yield, particularly under high nitrogen and irrigated conditions where vegetative growth is otherwise excessive (Oosterhuis *et al*., 2021). Similarly, in tobacco, removal or chemical suppression of the floral apex reduces reproductive sink competition and redirects assimilates toward leaf biomass, which is the primary economic product.

The regulation of source-sink balance is closely linked to hormonal and metabolic signalling. Reduced auxin flow from the shoot apex and changes in gibberellin activity alter assimilate partitioning patterns, while sugar signalling plays a critical role in determining sink strength and priority. Recent studies indicate that sucrose availability acts as an early regulator of bud activation and sink establishment, integrating carbon status with growth regulation (Bertheloot *et al*., 2020; Barbier *et al*., 2019). However, the response is strongly dependent on maintaining a balance between source capacity and sink demand. Excessive suppression of vegetative growth can reduce total leaf area and photosynthetic capacity, thereby limit carbon supply and offset the benefits of improved assimilate allocation. Therefore, effective chemical topping enhances source-sink balance rather than simply reducing vegetative growth, emphasizing the importance of precise timing and dosage.

Nutrient uptake and utilization

Chemical topping influences nutrient uptake and utilization through its effects on plant growth dynamics and root-shoot balance. Reduced shoot elongation often results in relatively greater allocation of assimilates to root systems, which can enhance root growth and improve nutrient acquisition efficiency under favourable conditions (Rademacher, 2018; Oosterhuis *et al*., 2021). This shift in biomass allocation may contribute to improved uptake of key nutrients such as nitrogen and potassium, particularly in systems where excessive vegetative growth would otherwise limit belowground development. Moderation of vegetative growth also reduces the dilution effect commonly observed in rapidly expanding tissues, leading to higher nutrient concentration per unit biomass. In addition, improved canopy structure and reduced plant density can enhance microclimatic conditions, indirectly supporting nutrient use efficiency by reducing stress and improving physiological functioning. However, nutrient responses to chemical topping are highly dependent on environmental factors such as soil fertility, irrigation and climate resulting in variable outcomes across production systems (Koutroubas & Damalas, 2020).

Carbon partitioning

Carbon partitioning is directly influenced by chemical topping through suppression of vegetative meristem activity and modification of assimilate allocation patterns. Growth retardants restrict cell elongation while maintaining functional photosynthetic capacity, thereby increasing the availability of carbohydrates for reproductive or economically important sinks (Rademacher, 2018; Oosterhuis *et al*., 2021).

In cotton, improved allocation of assimilates toward fruiting structures enhances boll development and yield when growth regulation is applied at appropriate developmental stages (Oosterhuis *et al*., 2021). However excessive growth suppression can reduce total biomass production and limit carbon supply, particularly under suboptimal environmental conditions. Therefore, effective carbon partitioning depends on maintaining a balance between vegetative control and sufficient photosynthetic source strength, ensuring that assimilate production matches sink demand.

Impact on growth and development

Chemical topping significantly alters growth trajectory and developmental dynamics by regulating vegetative vigour, reproductive transition and phenological progression. In indeterminate crops such as cotton and tobacco, vegetative growth often competes with reproductive development for assimilates. Application of growth regulators, particularly gibberellin inhibitors such as mepiquat chloride, restricts excessive vegetative expansion and promotes better coordination between vegetative and reproductive growth phases (Oosterhuis *et al*., 2021; Rademacher, 2018). This adjustment supports improved synchronization between flowering and assimilates availability, which is critical for reproductive success and yield formation under intensive production systems.

Vegetative growth regulation

Chemical topping suppresses vegetative meristem activity primarily through inhibition of gibberellin biosynthesis and modulation of hormonal balance. Reduced levels of bioactive gibberellins limit stem elongation and restrict excessive canopy expansion, resulting in a more compact and efficient plant architecture (Rademacher, 2018).

In crops such as cotton, moderated vegetative growth improves structural stability, reduces lodging risk and enhances canopy light distribution, particularly under high nitrogen conditions. However, excessive suppression especially under stress environments can reduce total biomass accumulation and limit growth potential. Therefore, vegetative regulation must be precisely calibrated to maintain adequate photosynthetic capacity while preventing excessive canopy development (Koutroubas & Damalas, 2020).

Reproductive transition and flowering

Chemical topping influences reproductive development primarily by modifying source-sink relationships and reducing vegetative competition for assimilates. Suppression of apical dominance decreases the demand from actively growing vegetative tissues, thereby improving carbohydrate availability to developing reproductive organs. In cotton, this shift enhances square retention and reduces early fruit abscission, particularly under conditions where excessive vegetative growth would otherwise limit assimilate supply (Oosterhuis *et al*., 2021). Improved coordination between vegetative and reproductive growth phases can contribute to more stable reproductive development and better utilization of assimilates across the canopy. However, evidence for complete synchronization of flowering is limited; rather, the primary effect is improved retention and development of reproductive structures due to enhanced assimilate availability. In tobacco, chemical suppression or destruction of the apical meristem eliminates the reproductive sink and redirects assimilates toward leaf expansion and biochemical maturation. This shift enhances leaf biomass and quality, which are the primary determinants of economic yield in tobacco production systems. The effectiveness of chemical topping on reproductive transition is highly dependent on application timing. Early application may restrict the formation of sufficient vegetative and reproductive structures, whereas delayed application reduces the potential for assimilate redistribution and limits its impact on yield. Therefore, precise timing is essential to achieve optimal balance between vegetative growth and reproductive development.

Phenology

Chemical topping often accelerates crop maturity by reducing prolonged vegetative growth and redirecting assimilates toward reproductive or economically important organs. In crops such as cotton, application of growth regulators limits excessive vegetative growth and promotes earlier onset of “cutout” (cessation of vegetative growth), allowing more efficient utilization of assimilates for boll development and maturation (Oosterhuis *et al*., 2021; Rademacher, 2018). This can improve the uniformity of boll development and facilitate more efficient harvesting, particularly under intensive production systems. In tobacco, chemical sucker control following topping contributes to more uniform leaf development and ripening by minimizing competition from axillary shoots. This supports improved leaf quality and consistency across different stalk positions, which is critical for market grading and processin. However, phenological responses to chemical topping are highly dependent on environmental conditions. Factors such as temperature, water availability and nitrogen status strongly influence the effectiveness of growth regulators and the rate of crop development. Under suboptimal conditions, excessive growth suppression may delay recovery or reduce biomass accumulation, potentially offsetting the benefits of earlier maturity (Koutroubas & Damalas, 2020).

Developmental plasticity and environmental interaction

Plant responses to chemical topping exhibit high developmental plasticity and are strongly influenced by interactions among genotype, environment and management practices. The effectiveness of plant growth regulators depends on crop species, growth stage and prevailing environmental conditions, which together determine the magnitude and direction of physiological responses (Rademacher, 2018; Koutroubas & Damalas, 2020). Under favourable conditions, chemical regulation can improve biomass partitioning and regulate vegetative- reproductive balance, contributing to more efficient use of assimilates and improved yield stability. However, under abiotic stress conditions such as drought, temperature extremes or nutrient deficiency, excessive suppression of vegetative growth may reduce photosynthetic capacity and limit recovery, thereby negatively affecting productivity (Rademacher, 2018).

Environmental factors also influence hormone sensitivity and plant response to growth regulators. For example, temperature and water availability can alter the absorption, translocation and activity of applied chemicals, leading to variability in crop performance across different production environments (Koutroubas & Damalas, 2020). Therefore, chemical topping should be regarded as a precision developmental regulation strategy rather than a universally beneficial practice. Its successful application depends on careful integration with crop-specific management practices, environmental conditions and appropriate timing to ensure that vegetative control does not compromise overall plant productivity.

Role in yield improvement

Chemical topping is primarily employed as a yield optimization strategy that improves assimilate partitioning, enhances harvest index and stabilizes productivity under intensive cropping systems. In indeterminate crops such as cotton and tobacco, excessive vegetative growth competes with reproductive development for assimilates. The application of plant growth regulators, particularly gibberellin inhibitors such as mepiquat chloride, suppresses terminal elongation and promotes redistribution of assimilates toward economically important organs, thereby improving reproductive efficiency (Rademacher, 2018; Oosterhuis *et al*., 2021). Yield response to chemical topping is highly conditional. Benefits are most pronounced under high fertility, irrigated and high-density conditions where vegetative competition is substantial. Under suboptimal conditions, excessive growth suppression may reduce total biomass production and limit yield potential (Koutroubas & Damalas, 2020). Thus, chemical topping improves yield efficiency rather than ensuring maximum yield under all environments. In cotton production systems, chemical growth regulation enhances yield primarily through improved fruit retention and more efficient assimilate allocation to developing bolls. Reduction in vegetative sink strength increases carbohydrate availability, contributing to improved boll retention and higher lint yield under favourable conditions (Oosterhuis *et al*., 2021). Improved canopy architecture enhances light interception and reduces self-shading, which supports reproductive development and reduces square abscission. While some studies indicate stabilization of fibre quality parameters such as micronaire and fibre uniformity under regulated growth conditions, these responses are variable and strongly dependent on genotype and environmental conditions (Koutroubas & Damalas, 2020). However, excessive growth suppression particularly under drought or nutrient limitation can reduce boll size, delay development and ultimately decrease lint yield. This highlights a key point: chemical topping improves yield efficiency and stability rather than consistently increasing maximum yield. In tobacco, chemical topping directly influences yield formation by eliminating or suppressing reproductive sinks and redirecting assimilates toward leaf biomass, the primary economic product. Chemical sucker control following topping reduces competition from axillary shoots, supporting continued leaf expansion and more uniform development. This results in improved cured leaf yield, enhanced uniformity and optimized leaf quality when properly managed. However, over-application or poor timing can reduce leaf size, induce phytotoxic effects and negatively affect market grade. Therefore, the primary benefit of chemical topping in tobacco lies in yield stabilization and quality improvement rather than absolute yield increase.

Harvest index and resource use efficiency

Chemical topping can increase harvest index by reducing excessive vegetative biomass and enhancing assimilate partitioning toward harvestable organs. By limiting non-productive vegetative growth, plant growth regulators improve the proportion of total biomass allocated to economically important sinks, particularly under conditions of high nutrient availability and intensive management (Rademacher, 2018; Oosterhuis *et al*., 2021). Improved canopy structure resulting from regulated vegetative growth may enhance light distribution within the canopy, which can contribute to better radiation-use efficiency under dense planting conditions. Reduced canopy density can also improve aeration, potentially lowering the incidence of certain diseases; however, these effects are indirect and highly dependent on environmental conditions (Koutroubas & Damalas, 2020; Panpatte *et al*., 2016). Chemical topping may also influence nitrogen-use efficiency by moderating rapid vegetative expansion and reducing dilution of nutrients in newly formed tissues. This can improve the allocation of nitrogen toward reproductive organs under favourable conditions (Koutroubas & Damalas, 2020). However, these benefits are strongly context-dependent. Under low-input or rainfed systems, excessive suppression of vegetative growth may reduce total carbon assimilation and biomass production, thereby offsetting gains in partitioning efficiency. Therefore, improvements in harvest index and resource use efficiency should be viewed as conditional responses rather than universal outcomes of chemical topping.

Economic returns and yield stability

From an economic perspective, chemical topping reduces labour requirements compared to manual topping and enables more uniform crop management, particularly under large-scale production systems. The use of plant growth regulators allows timely and consistent application across fields, improving operational efficiency and reducing dependence on manual interventions (Koutroubas & Damalas, 2020). Improved control of vegetative growth can contribute to more uniform crop development and facilitate efficient harvesting, especially in mechanized systems. However, the primary economic advantage of chemical topping in many cropping systems lies in improved yield stability across seasons rather than large increases in maximum yield. Stabilizing production under variable environmental conditions is a key objective in modern agriculture, where fluctuations in climate and input availability can significantly affect productivity (Rademacher, 2018; McShane & Sunahara, 2015).

Profitability of chemical topping is highly dependent on precise management. Factors such as application timing, dosage, environmental conditions and cultivar response determine the overall effectiveness of the practice. Incorrect application may suppress growth excessively, reduce yield potential and increase input costs without corresponding benefits. Therefore, chemical topping should be considered a precision agronomic tool that requires careful optimization rather than a routine or universally beneficial practice.

Synthesis

Chemical topping improves crop productivity primarily by optimizing assimilate partitioning, enhancing harvest index and regulating the balance between vegetative and reproductive growth. By limiting excessive vegetative development, it promotes more efficient allocation of resources toward economically important organs, contributing to improved yield stability and crop uniformity under intensive production systems. However, its effectiveness is strongly dependent on environmental conditions, crop genotype and management precision. The benefits of chemical topping are most evident under high-input systems where vegetative competition is substantial, whereas under suboptimal conditions, excessive growth suppression may limit biomass accumulation and reduce yield potential. Importantly, the primary advantage of chemical topping lies in stabilizing yield across seasons rather than consistently increasing maximum yield. Therefore, it should be applied as a targeted growth regulation strategy based on crop-specific requirements, with careful attention to application timing, dosage and environmental conditions to avoid adverse effects and ensure optimal performance (Rademacher, 2015; Oosterhuis & Snider, 2019; Taiz *et al*., 2015).

Challenges & limitations of chemical topping

Chemical topping represents a critical canopy management strategy in intensive cropping systems, particularly were excessive vegetative growth compromises reproductive efficiency. One of its primary advantages lies in the precise and uniform suppression of apical dominance compared to manual topping. In crops such as *Gossypium hirsutum*, plant growth regulators (PGRs) like mepiquat chloride and chlormequat chloride effectively inhibit gibberellin biosynthesis, resulting in reduced internode elongation, compact canopy architecture and improved light interception (Rademacher, 2015; Oosterhuis & Snider, 2019). Improved canopy structure enhances spray penetration, reduces lodging susceptibility *and* facilitates mechanical harvesting under high-density planting systems. In *Nicotiana tabacum*, chemical sucker control following topping—commonly using maleic hydrazide or fatty alcohol-based formulations—significantly reduces labour requirements and ensures uniform suppression of axillary buds, thereby improving leaf yield and chemical composition. (Singh *et al*., 2020). The scalability and compatibility of chemical topping with mechanized agriculture make it economically advantageous in commercial production systems. Another important benefit is the optimization of source-sink relationships and harvest index. By suppressing vegetative sinks, chemical topping redirects assimilates toward reproductive organs or economically valuable tissues. In cotton, this results in improved boll retention, synchronized boll maturation and enhanced picking efficiency (Oosterhuis & Snider, 2019). Growth regulation has also been associated with improved radiation-use efficiency through reduced canopy shading and better leaf area distribution. Furthermore, moderated vegetative growth can enhance nitrogen-use efficiency by minimizing dilution effects in rapidly expanding tissues and improving partitioning toward reproductive sinks (Taiz *et al*., 2015; Fichtner *et al.*, 2021). Importantly, chemical topping contributes more to yield stability across variable environmental conditions than to absolute yield maximization, especially under intensive cultivation.

Despite these advantages, chemical topping presents significant limitations. Crop response to PGRs is highly genotype-specific and strongly influenced by environmental conditions, leading to variability in effectiveness across cultivars and agroecological zones (Rademacher, 2015). Under abiotic stress conditions such as drought or nutrient deficiency, excessive suppression of vegetative growth can reduce total biomass accumulation and ultimately limit yield potential. In tobacco systems, improper application of maleic hydrazide or related compounds can result in phytotoxic effects, including leaf chlorosis, deformation and undesirable residue accumulation, adversely affecting cured leaf quality and market acceptability (Singh *et al*., 2020; Wang *et al*., 2022). These risks highlight the necessity for precise timing, correct dosage and crop-specific calibration rather than routine or blanket application. Environmental and regulatory concerns further constrain the use of chemical topping. Although many modern PGRs are considered relatively low-risk compared to traditional agrochemicals, repeated or excessive use raises concerns regarding environmental persistence, off-target effects and potential contamination of soil and water systems (Carvalho., 2015). In export-oriented crops such as tobacco and cotton, strict maximum residue limits (MRLs) necessitate careful adherence to pre-harvest intervals and regulatory guidelines. Additionally, environmental factors such as rainfall, temperature fluctuations and humidity can significantly influence the efficacy of applied chemicals, particularly for contact-based formulations, thereby increasing variability in field outcomes.

Economic dependency on chemical inputs also represents a critical limitation. While chemical topping reduces labour costs, it increases reliance on external inputs, including chemical availability, formulation quality *and* application technology. Misapplication or suboptimal timing can lead to yield penalties that outweigh potential economic benefits. (Koutroubas & Damalas, 2020). Moreover, excessive reliance on chemical growth regulation may obscure fundamental agronomic issues such as imbalanced nutrient management, particularly excessive nitrogen fertilization or improper plant density. Therefore, chemical topping should not be viewed as a standalone solution but as an integrated component of a broader crop management strategy. Its long-term sustainability depends on balancing agronomic benefits with environmental safety, economic viability and precise management practices.

Future prospects

The future of chemical topping is shifting from generalized growth suppression toward precision-regulated plant development driven by physiological modelling, data-driven decision support systems and environmentally sustainable formulations. As agricultural systems intensify under climate variability and resource constraints, growth regulation strategies must evolve beyond conventional gibberellin-inhibiting compounds toward integrated crop management frameworks. In high-value crops such as *Gossypium hirsutum* and *Nicotiana tabacum*, emerging research emphasizes optimization of dose response relationships and application timing through genotype × environment × management (G×E×M) interactions and crop simulation modelling approaches (Basso & Antle, 2020). Advancements in precision agriculture technologies including remote sensing, UAV-based canopy monitoring and variable-rate application systems are enabling real-time assessment of crop growth dynamics and site-specific regulation of plant growth regulators. These tools facilitate dynamic adjustment of chemical topping practices based on canopy structure, biomass accumulation and stress conditions, thereby improving input-use efficiency and minimizing environmental risks (Sishodia *et al*., 2020). Integration of such technologies is expected to transform chemical topping from a static agronomic intervention into a responsive, data-driven management strategy.

Future developments also focus on environmentally safer and more targeted formulations, including reduced-dose growth regulators, controlled-release systems and bio-based alternatives that minimize off-target effects and residue concerns. In parallel, advances in plant physiology and molecular biology are improving understanding of hormonal cross-talk and regulatory networks governing plant architecture, which may enable the development of more precise growth modulation strategies (Rademacher, 2015;). Additionally, the integration of chemical topping with improved nutrient management, optimized planting density and stress-resilient cultivars will be critical for achieving sustainable productivity gains. Despite these advancements, the successful adoption of next-generation chemical topping strategies will depend on accessibility of precision technologies, farmer awareness and economic feasibility, particularly in developing agricultural systems. Therefore, future research should focus on developing cost-effective, scalable and environmentally sustainable approaches that integrate chemical regulation with holistic crop management practices.

Recent studies indicate that chemical topping not only modifies plant architecture but also enhances canopy structure, light interception *and* assimilate partitioning, suggesting its potential role in optimizing resource use efficiency under changing climatic conditions (Shi *et al.,* 2022). Moreover, the rapid development of novel PGRs and formulations, including targeted and environmentally safer compounds, is expected to improve the precision and effectiveness of chemical topping practices. Integration with advanced technologies such as gene editing and smart agriculture tools may further enable crop-specific and stage-specific regulation of plant growth processes (Liu *et al*, 2025). Additionally, emerging research on hormonal and molecular mechanisms, such as cytokinin regulation and gene expression pathways involved in branching, provides new opportunities to refine chemical topping strategies for enhanced productivity (Anonymous 2025)

Precision agriculture and sensor-based application

Advancements in precision agriculture technologies, including remote sensing, UAV-based imaging and canopy spectral diagnostics, are enabling real-time assessment of vegetative vigour and canopy structure. These tools facilitate quantitative monitoring of crop growth dynamics through vegetation indices and canopy reflectance patterns, allowing informed and threshold-based application of plant growth regulators to maintain optimal canopy architecture while minimizing unnecessary chemical inputs (Sishodia *et al*., 2020). Variable-rate application technologies, integrated with geographic information systems (GIS) and sensor-based decision support systems, enable spatial optimization of input delivery across heterogeneous fields. This site-specific management approach improves input-use efficiency and reduces environmental impact by aligning chemical application with actual crop requirements rather than uniform field-level practices (Zhang *et al*., 2017; Bongiovanni & Lowenberg-Deboer, 2018). Furthermore, the integration of crop simulation models with real-time field data offers significant potential for predictive and adaptive management of plant growth regulation. By combining physiological crop models with sensor-derived canopy parameters, it becomes possible to dynamically adjust growth regulator application based on crop status and environmental conditions, thereby enhancing precision, efficiency and sustainability of chemical topping practices (Basso & Antle, 2020). The adoption of precision agriculture and sensor-based technologies is enhancing the efficiency and sustainability of chemical topping by enabling site-specific and time-optimized application of plant growth regulators (PGRs). Remote sensing tools such as UAVs and satellite imagery, particularly through vegetation indices like NDVI, facilitate real-time assessment of crop vigor and spatial variability, allowing variable-rate application of topping agents (Mulla, 2013; Sishodia *et al*., 2020). In addition, proximal sensors including chlorophyll meters, thermal imaging *and* LiDAR provide accurate information on canopy structure, biomass and plant stress, which are critical for determining the optimal stage for chemical topping (Sankaran *et al*., 2015). The integration of these technologies with GPS-guided sprayers and AI-based decision support systems improves application precision, reduces chemical wastage and minimizes environmental impact (Zhang *et al*., 2017; Shamshiri *et al*., 2018). Thus, precision agriculture offers a transformative approach for improving the effectiveness and sustainability of chemical topping practices.

Nano-formulations and controlled release systems

There is growing interest in developing bio-based growth regulators derived from plant extracts, algae and microbial metabolites that modulate endogenous hormonal pathways with reduced environmental persistence. Research on plant bio stimulants and natural signalling compounds indicates their potential to regulate plant architecture indirectly through improved nutrient uptake, stress tolerance and hormonal balance (du Jardin, 2015; Rouphael & Colla, 2020; Yakhin *et al*., 2017). Compounds influencing auxin transport, cytokinin biosynthesis and gibberellin metabolism from biological sources may offer safer alternatives to synthetic retardants. However, variability in efficacy and lack of standardized formulations remain key limitations. Nano-formulations and controlled release systems are emerging as innovative approaches to improve the efficiency and environmental safety of chemical topping agents. Encapsulation of plant growth regulators (PGRs) in nanocarriers such as polymeric nanoparticles, nano emulsions *and* nanoclays enables slow and targeted release, enhancing uptake and reducing volatilization and leaching losses (Kah *et al*., 2018; Liu & Lal, 2015). These systems can provide sustained delivery of active ingredients, maintaining optimal concentrations at the target site and minimizing the frequency of application. Studies have shown that nano-enabled agrochemicals improve bioavailability and efficacy while lowering required doses, thereby reducing phytotoxicity and environmental contamination (Servin *et al*., 2015).

Furthermore, controlled release formulations responsive to environmental triggers such as pH, temperature *and* moisture are being developed to achieve precise regulation of plant growth processes (Chen & Yada, 2011; Nuruzzaman *et al*., 2016). Such advancements hold significant potential for refining chemical topping practices by ensuring uniform and efficient delivery of growth regulators under field conditions. However, further research is needed to address concerns related to cost, scalability and long-term environmental impacts of nanomaterials. Overall, nano-formulations represent a promising frontier for sustainable and precision-based crop management.

Molecular and genetic approaches

Advances in plant molecular biology and functional genomics are redefining growth regulation strategies at the genetic level. Identification of genes controlling apical dominance, branching patterns and hormone biosynthesis such as auxin transporters (PIN proteins), gibberellin biosynthetic enzymes and cytokinin signalling regulators provides opportunities for breeding or gene-editing approaches to optimize plant architecture intrinsically (Wang & Jiao, 2018; Leyser, 2021). Genome editing technologies, particularly CRISPR/Cas systems, enable targeted modification of architectural traits, potentially reducing reliance on external chemical regulators (Bortesi & Fischer, 2015). However, regulatory restrictions, biosafety concerns and public acceptance continue to limit widespread deployment. Advances in molecular biology and genetics are providing new insights into the mechanisms underlying chemical topping by elucidating the regulation of apical dominance and branching at the gene level. Key hormonal pathways involving auxin, cytokinin and strigolactones are controlled by genes such as TB1 (teosinte branched1), BRC1 (branched1) and pin-formed (pin) auxin transporters, which regulate bud outgrowth and plant architecture (Wang *et al*., 2019). Chemical topping agents are known to influence these hormonal pathways, suggesting a close interaction between exogenous growth regulators and endogenous gene expression. Recent transcriptomic and gene expression studies in crops like cotton have demonstrated that chemical topping alters the expression of genes associated with hormone biosynthesis, signalling and assimilate partitioning (Li *et al*., 2020).

Furthermore, emerging technologies such as CRISPR/Cas-mediated gene editing offer opportunities to develop crop varieties with optimized branching patterns and reduced dependence on chemical topping (Saini *et al*., 2023); Martín-Trillo *et al*., 2011). The integration of molecular breeding with agronomic practices could enable precise manipulation of plant architecture, enhance yield potential while minimize chemical inputs. Thus, molecular and genetic approaches hold significant promise for refining and potentially replacing conventional chemical topping strategies in sustainable crop production systems.

Sustainability and regulatory considerations

Future chemical topping strategies must align with global sustainability goals, including reduced chemical residues, improved environmental safety and enhanced climate resilience. Increasingly stringent regulatory frameworks governing pesticide use, maximum residue limits (MRLs) and environmental risk assessments are driving the development of low-residue and biodegradable formulations (Carvalho *et al*., 2015). Integrated crop management approaches combining optimized plant density, balanced nutrient management and cultivar selection with minimal chemical intervention are likely to define next-generation systems (Taiz *et al*., 2015). Overall, the paradigm of chemical topping is evolving from simple vegetative growth suppression toward precision developmental regulation, supported by digital agriculture, advanced formulations and molecular-level understanding of plant growth processes. Its future sustainability will depend on the successful integration of these technologies into economically viable and environmentally responsible production systems.

Table 3: Future innovations in chemical topping.

Innovation Area	Description	Advantage	References
Precision agriculture	Sensor + UAV-based application	Reduced chemical use	Sishodia *et al*. (2020)
Variable rate technology	Site-specific PGR application	Improved efficiency	Bongiovanni & Lowenberg-Deboer (2018)
Nano-formulations	Controlled release systems	Lower dose, higher efficiency	Kah *et al*. (2018); Shang *et al*. (2019)
Biostimulants	Natural growth regulators	Eco-friendly alternative	Rouphael & Colla (2020); du Jardin (2015)
CRISPR/genetic control	Modify plant architecture genes	Reduced chemical dependency	Rouphael & Colla (2020); du Jardin (2015)
Decision support systems	Model-based application timing	Precision management	Leyser (2021); Bortesi & Fischer (2015)

Conclusion

Chemical topping represents a strategically engineered intervention in plant developmental regulation, functioning through targeted modulation of apical dominance, hormonal equilibrium and source sink dynamics to optimize crop productivity. By inhibiting gibberellin biosynthesis, altering auxin transport gradients *and* indirectly enhancing cytokinin-mediated lateral activation, chemical growth regulators restructure canopy architecture, stabilize vegetative reproductive balance and improve assimilate partitioning toward economically important organs in crops such as *Gossypium hirsutum* and *Nicotiana tabacum*. When precisely timed and appropriately dosed, these interventions enhance radiation use efficiency, harvest index, maturity synchronization and yield stability, particularly under high-input production systems. However, chemical topping is inherently context-dependent, with outcomes strongly influenced by genotype × environment × management interactions excessive suppression may constrain total biomass production, disrupt physiological homeostasis or compromise quality attributes. Furthermore, emerging regulatory, environmental and sustainability considerations necessitate refinement of conventional growth retardant strategies toward precision-guided, residue-minimized and biologically informed approaches. Future integration of molecular genetics, sensor-based decision tools and advanced formulation technologies will likely transform chemical topping from a reactive vegetative control measure into a predictive developmental optimization system embedded within sustainable crop management frameworks.

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