Review literature

Plant Stem Cells: Regulatory Mechanisms and Biotechnological Applications

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ABSTRACT

Plant stem cells play a central role in lifelong organogenesis, growth, and regeneration by balancing self-renewal and differentiation. These pluripotent cells reside in key meristematic regions, the shoot apical meristem (SAM), root apical meristem (RAM), and lateral meristems, each governed by intricate genetic, hormonal, and epigenetic controls. Over the past two decades, substantial progress has been made in elucidating the molecular networks that sustain stem cell identity and regulate pattern formation and organ initiation. Core pathways involving transcription factors such as WUSCHEL (WUS), CLAVATA (CLV), and PLETHORA (PLT), in conjunction with phytohormonal signaling and chromatin dynamics, orchestrate stem cell function. This review synthesizes current insights into the spatial organization and molecular control of plant stem cells, explores recent advances in genetic and imaging technologies, and examines their translational potential in biotechnology and crop improvement. Finally, it highlights current knowledge gaps and outlines future research directions to deepen our understanding of plant developmental plasticity and regenerative capacity.

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HIGHLIGHTS

- **Plant stem cells are essential for lifelong growth and organ regeneration**, maintained in specialized niches including the shoot apical meristem (SAM), root apical meristem (RAM), and lateral meristems.
- **Core regulatory networks** involve transcription factors such as **WUSCHEL (WUS), CLAVATA (CLV), PLETHORA (PLT), and SHOOT MERISTEMLESS (STM)**, which orchestrate the balance between stem cell self-renewal and differentiation.

- **Auxin and cytokinin signaling pathways** work antagonistically and synergistically to spatially and temporally regulate stem cell identity and niche maintenance.
- **Epigenetic mechanisms**, including chromatin remodeling and histone modification, provide a flexible control layer over gene expression in meristems.
- **The WUS–CLV feedback loop in SAM** and **the PLT–auxin gradient in RAM** are canonical models for stem cell niche regulation.
- **Recent technological advances,** such as live-cell imaging, single-cell transcriptomics, and chromatin profiling, have expanded understanding of meristem architecture and stem cell dynamics.
- **Applications in plant biotechnology** include crop yield enhancement, clonal propagation, somatic embryogenesis, and improved stress tolerance via targeted manipulation of stem cell regulatory pathways.
- **Future directions** aim to explore systemic signaling, niche plasticity, and cross-tissue communication to better harness stem cell systems for regenerative agriculture.

STEM CELLS DEFINITION

Plants demonstrate a unique ability for continuous growth and regeneration, a trait supported by their pluripotent stem cells. Unlike in animals, where stem cell activity is often temporary, plant stem cells stay active throughout the organism's life, driving both primary and secondary development **(Zhou et al., 2014).** Plant stem cells are primarily localized in two regions: the shoot apical meristem (SAM) and the root apical meristem (RAM), which harbor self-renewing cells capable of differentiating into a wide range of specialized tissues. In addition, lateral and vascular meristems contribute to the thickening and regeneration of tissues during secondary growth **(Zhou et al., 2014).** These regions serve as dynamic hubs where cellular behavior is tightly regulated by complex genetic networks, hormonal signaling pathways, and epigenetic modifications **(Peterson et al., 2014).** Recent advances in molecular biology, live-cell imaging, and single-cell transcriptomics have provided significant insights into the mechanisms that govern stem cell identity and maintenance. Key regulatory genes such as WUSCHEL (WUS), CLAVATA (CLV), SHOOT MERIS - TEMLESS (STM), and PLETHORA (PLT) are central to maintaining the delicate balance between stem cell proliferation and differentiation **(González-García et al., 2022; Han et al., 2021; Aida et al., 2004).** Moreover, plant hormones such as auxin and cytokinin orchestrate signaling cascades that further refine spatial and temporal control within the stem cell niche (**González-García et al., 2022).** Understanding plant stem cell biology is not only critical for developmental biology but also offers promising avenues in agriculture and biotechnology. Manipulation of stem cell pathways can enhance crop productivity, facilitate clonal propagation, and improve resistance to biotic and abiotic stress. Additionally, in vitro plant tissue culture systems, including somatic embryogenesis and organogenesis, heavily rely on the principles of stem cell reprogramming **(Toy and Dierschke, 2018).**

TYPES AND LOCALIZATION OF PLANT STEM CELLS

Plant stem cells reside in highly specialized niches known as meristems, which serve as the central source of undifferentiated, pluripotent cells responsible for plant growth and organogenesis. These meristems are classified based on their position and function into three primary types: shoot apical meristem (SAM), root apical meristem (RAM), and lateral meristems, which include the vascular cambium and cork cambium. Each of these meristems' harbors stem cells with distinct developmental roles and regulatory mechanisms (Zhou et al., 2014).

A. Shoot Apical Meristem (SAM)

The shoot apical meristem is located at the tip of the plant shoot and is responsible for generating aerial organs such as leaves, stems, and flowers. SAM consists of a central zone (CZ), which houses slowly dividing stem cells, surrounded by a peripheral zone (PZ) where cells begin to differentiate and contribute to organ formation. Below the CZ lies the rib meristem (RM), which gives rise to internal stem tissues **(Han et al., 2021).** SAM maintenance is governed by a feedback loop involving the WUSCHEL (WUS) trans-cription factor and the CLAVATA (CLV) signaling pathway. WUS, expressed in the organizing center, promotes stem cell fate in the overlying cells, while CLV3, a small peptide produced by stem cells, restricts WUS activity to prevent over proliferation. This balance ensures stem cell homeostasis and precise control of shoot development **(Zhou et al., 2014; Schlegel et al., 2021).**

B. Root Apical Meristem (RAM)

Located at the tip of the root, the root apical meristem mirrors the organization of SAM but functions in root elongation and development. RAM contains a quiescent center (QC), a group of slowly dividing cells that act as a reservoir to replenish damaged or differentiated cells in the surrounding stem cell niche. Surrounding the QC are initial cells that give rise to specific root tissues such as the epidermis, cortex, endodermis, and vascular tissues **(Aida et al., 2004; Mähönen et al., 2014).** The PLETHORA (PLT) gene family plays a key role in maintaining stem cell identity in RAM. PLT proteins work in conjunction with auxin gradients to establish the root stem cell niche and guide patterning during root development. Additional factors, such as SHORT ROOT (SHR) and SCARECROW (SCR), regulate radial patterning and cell layer specification (**Shimotohno et al., 2018; Xiong et al., 2020).**

C. Lateral and Vascular Meristems

Unlike apical meristems that contribute to primary growth (lengthening), lateral meristems are responsible for secondary growth, which increases the girth of the plant. These include vascular cambium, which generates secondary xylem (wood) and phloem, and cork cambium, which produces protective outer layers like bark **(Zhou et al., 2014).** Stem cells in lateral meristems are less well characterized but are known to maintain a dynamic balance between xylem and phloem differentiation. Transcription factors such as WOX4 and HD-ZIP III are implicated in regulating stem cell activity in the vascular cambium. These meristems are essential for the structural integrity of woody plants and for efficient water and nutrient transport **(Zhou et al., 2014).**

MOLECULAR REGULATION OF STEM CELLS

The regulation of plant stem cell identity and behavior is orchestrated by an intricate network of transcription factors, hormonal signals, and epigenetic mechanisms. These regulatory systems ensure the continuous self-renewal of stem cells and the timely differentiation required for organogenesis. Among the most well-characterized regulatory modules are the *WUSCHEL–CLAVATA* feedback loop in the shoot apical meristem, the *PLETHORA–auxin* gradient in the root apical meristem, and chromatin remodeling complexes that modulate gene accessibility in meristematic tissues.

TRANSCRIPTIONAL REGULATORS

- ***WUSCHEL (WUS)* and *CLAVATA (CLV)***

  In the shoot apical meristem (SAM), *WUSCHEL (WUS)*, a homeodomain transcription factor, plays a central role in maintaining stem cell identity. WUS is expressed in the organizing center and promotes the expression of stem cell fate in the overlying central zone **(Zhou et al., 2014).** In a tightly controlled negative feedback loop, *CLAVATA3 (CLV3)*, a small peptide secreted by stem cells, restricts WUS expression via the CLV1/CLV2 receptor complex, maintaining meristem size and stem cell number **(Han et al., 2021; Schlegel et al., 2021**).

- ***Shoot Meristemless (STM)***

  STM is essential for the initiation and maintenance of the SAM. It prevents premature differentiation of stem cells by repressing genes associated with differentiation and maintaining cytokinin signaling **(Peterson et al., 2014)**. STM also interacts with WUS to reinforce the undifferentiated state in the meristem.

- ***PLETHORA (PLT)***

  In the root apical meristem (RAM), *PLETHORA (PLT)* transcription factors establish the stem cell niche. PLT proteins form a gradient that determines cell fate along the root longitudinal axis. High PLT concentration near the quiescent center (QC) maintains stem cell identity, while lower concentrations promote differentiation (**Aida et al., 2004; Mähönen et al., 2014).** PLT function is closely tied to auxin distribution and chromatin accessibility **(Shimotohno et al., 2018).**

HORMONAL REGULATION

- **Auxin**
  Auxin is a critical regulator of stem cell identity, particularly in the RAM. Localized auxin maxima established by PIN-FORMED (PIN) auxin transporters initiate PLT expression and support the formation of the QC and stem cell initials. Auxin also influences gene expression via the AUXIN RESPONSE FACTOR (ARF) family of transcription factors **(Xiong et al., 2020).**

- **Cytokinin**
  Cytokinin plays an opposing but complementary role to auxin, particularly in the SAM. It promotes stem cell proliferation by activating WUS expression through the ARR (Arabidopsis Response Regulator) pathway. A balance between cytokinin and auxin signaling is essential for maintaining stem cell niches and coordinating organogenesis **(González-García et al., 2022).**

EPIGENETIC REGULATION

Stem cell function is also regulated at the chromatin level. Histone modifications, DNA methylation, and chromatin remodeling contribute to the transcriptional plasticity required in meristems. For instance, the Polycomb Repressive Complex 2 (PRC2) is known to silence differentiation-related genes in stem cells, maintaining their pluripotent state **(Peterson et al., 2014).** Recent studies have shown that chromatin accessibility is modulated in response to hormone signaling and environmental cues, suggesting a dynamic interplay between epigenetic state and stem cell behavior.

SIGNALING PATHWAYS IN STEM CELL MAINTENANCE

Plant stem cell maintenance depends on precise signaling pathways that integrate spatial cues, hormonal signals, and feedback mechanisms to preserve the identity and organization of meristematic cells. Among the most studied regulatory circuits are the WUSCHEL–CLAVATA (WUS –CLV) feedback loop in the shoot apical meristem (SAM), and the PLETHORA–auxin signaling gradient in the root apical meristem (RAM). These pathways define the stem cell niche, a micro-environment where undifferentiated cells are kept in a proliferative and undifferentiated state, while their progeny undergo differentiation upon displacement.

THE CLAVATA–WUSCHEL FEEDBACK LOOP

The CLV–WUS pathway is a classic example of a negative feedback loop that maintains the stem cell pool in the SAM. WUSCHEL (WUS), a homeobox transcription factor, is expressed in the organizing center (OC) and promotes stem cell fate in overlying cells by activating downstream targets and indirectly inducing the expression of CLAVATA3 (CLV3) **(Zhou et al., 2014; Han et al., 2021).** CLV3 encodes a small signaling peptide that is secreted by stem cells and perceived by the CLV1/CLV2 receptor-like kinase complex. CLV signaling acts to repress WUS expression, thereby restricting the size of the stem cell niche **(Schlegel et al., 2021).** The balance between WUS-promoted stemness and CLV-mediated repression creates a dynamic homeostatic loop that allows the SAM to sustain a constant pool of stem cells while supplying new cells for organ formation. Recent studies have expanded this model by identifying additional components, such as HAM transcription factors that modulate WUS activity and CLE40, a related peptide ligand that operates in peripheral zones **(Zhou et al., 2014).** These findings underscore the spatial complexity of signaling inputs in meristem patterning.

TRANSCRIPTION FACTORS IN NICHE IDENTITY

Transcription factors play a key role in establishing and maintaining stem cell niches. In addition to WUS and CLV3, SHOOT MERISTEMLESS (STM) is crucial for preventing stem cell differentiation and promoting cytokinin activity in the SAM **(Peterson et al., 2014).** STM works synergistically with WUS to maintain meristem identity. In the RAM, PLETHORA (PLT) transcription factors form a graded distribution controlled by auxin levels. This gradient determines cell fate: high PLT expression sustains stemness near the quiescent center (QC), while lower levels drive differentiation as cells move outward **(Aida et al., 2004; Mähönen et al., 2014).** The SHORT ROOT (SHR) and SCARECROW (SCR) transcription factors further contribute to radial patterning and niche maintenance in the root **(Shimotohno et al., 2018).**

STEM CELL NICHE ARCHITECTURE AND INTERCELLULAR SIGNALING

The stem cell niche is not defined solely by intrinsic factors but also by intercellular signaling from surrounding support cells. In the SAM, the organizing center acts as a source of WUS, while in the RAM, the QC serves a similar function by maintaining surrounding stem cells in an undifferentiated state **(Han et al., 2021).** Signals from differentiated tissues such as the endodermis and vascular initials also feedback to reinforce stem cell behavior, suggesting a modular and plastic regulatory network **(Xiong et al., 2020).** Hormones such as cytokinin and auxin further refine this system by differentially activating transcriptional networks in a tissue-specific and developmentally responsive manner **(González-García et al., 2022).**

BIOTECHNOLOGICAL APPLICATIONS

Manipulating stem cell pathways presents opportunities for:

- **Crop yield improvement** via modification of WUS–CLV pathways **(Toy & Dierschke, 2018).**
- **Clonal propagation** through enhanced tissue culture and somatic embryogenesis.
- **Stress tolerance** by engineering hormone and transcription factor responses in stem cell niches.

CONCLUSION

Plant stem cells are regulated by multilayered networks of transcriptional, hormonal, and epigenetic signals.

Core circuits such as WUS–CLV and PLT–auxin illustrate how local feedback sustains stemness. Advances in single-cell omics, live imaging, and genome editing will further illuminate niche dynamics and support innovative crop breeding strategies.

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مراجعة أدبية

الخلايا الجذعية النباتية: الآليات التنظيمية والتطبيقات في التكنولوجيا الحيوية

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الملخص العربي

تلعب الخلايا الجذعية النباتية دورًا محوريًا في التكوين المستمر للأعضاء، والنمو، والتجدد على مدار حياة النبات، من خلال تحقيق التوازن بين التجديد الذاتي والتمايز. وتوجد هذه الخلايا متعددة القدرات في مناطق رئيسية من النسيج الإنشائي، وهي القمة النامية للساق(SAM) ، والقمة النامية للجذر(RAM) ، والأنسجة الإنشائية الجانبية، وكل منها يخضع لتنظيم دقيق على المستويات الجينية والهرمونية والوراثية فوق الجينية. وخلال العقدين الماضيين، أُحرز تقدم كبير في فهم الشبكات الجزيئية التي تحافظ على هوية الخلايا الجذعية وتُنظِّم تكوُّن الأنماط وبدء تكوين الأعضاء. وتشمل المسارات المحورية في هذا التنظيم مجموعة من عوامل النسخ مثل ***WUSCHEL (WUS)****، و* ***CLAVATA (CLV)****، و* ***PLETHORA (PLT)****، بالتوازي مع الإشارات الهرمونية النباتية وديناميكية الكروماتين، مما ينسق عمل الخلايا الجذعية. يستعرض هذا المقال الفهم الحالي للتنظيم المكاني والجزيئي للخلايا الجذعية النباتية، ويستكشف التطورات الحديثة في تقنيات الجينات والتصوير، ويُقيّم إمكاناتها التطبيقية في التكنولوجيا الحيوية وتحسين المحاصيل. كما يُسلط الضوء على الفجوات المعرفية الحالية ويقترح اتجاهات مستقبلية للبحث لتعميق فهمنا لمرونة النمو النباتي وقدراته التجديدية.*

الكلمات المفتاحية :*القمة النامية للساق، القمة النامية للجذر، الأنسجة الإنشائية الجانبية، عوامل النسخ، وظيفة الخلايا الجذعية.*