# Gravitropism and plant growth in extraterrestrial space

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**Abstract**. Gravitropism is a vital biological mechanism that enables plants to orient their roots downward and shoots upward in response to gravity, ensuring survival and optimal resource acquisition. However, in microgravity environments, such as space, this natural growth orientation is disrupted, resulting in disorganized root and shoot growth. This paper explores the mechanisms underlying gravitropism, focusing on statocytes and auxin-mediated responses, and examines how plants adapt to the absence of gravity. Strategies for mitigating microgravity effects, including clinostat-based simulations, artificial gravity, and genetic modifications, are discussed, highlighting their significance for sustaining plant growth in extraterrestrial environments. These insights are essential for advancing space agriculture and supporting long-term human space exploration by enabling sustainable life support systems.
**Key words**: auxin signaling, gravitropism, microgravity, plant adaptation, space agriculture,

**Introduction**. Gravitropism, also known as geotropism, is a fundamental biological process that governs plant growth in response to gravity. This process enables plants to orient their roots downward and their shoots upward, ensuring that they grow in directions conducive to survival. However, in the absence of gravity, such as in space, this natural orientation mechanism is disrupted, posing significant challenges to plant growth. As humanity looks toward long-term space exploration, understanding the effects of microgravity on gravitropism and plant growth is crucial for developing sustainable life support systems. This paper examines the phenomenon of gravitropism, the challenges posed by microgravity, and the adaptations plants undergo in extraterrestrial environments.

**Gravitropism**: **a mechanism for growth orientation**. Gravitropism is an adaptive response to gravity that ensures plants grow in a manner that supports their survival. The process involves specialized cells known as statocytes (Kume et al 2021), located in the root cap and shoot tip. These cells contain statoliths - dense starch-filled organelles that settle at the bottom of the cells under the influence of gravity (Kume et al 2021). The positioning of statoliths within these cells sends signals to other parts of the plant, triggering differential growth rates. In roots, this results in growth toward gravity (positive gravitropism) (Concepcion 2023), while in shoots, it causes growth against gravity (negative gravitropism) (Kohler et al 2024). These responses are essential for ensuring that roots can anchor the plant and absorb water and nutrients from the soil, while shoots can grow towards light to facilitate photosynthesis.

**Challenges in microgravity**. In microgravity environments, such as those experienced aboard spacecraft and space stations, the force of gravity is negligible, and gravitropism is largely disrupted. As a result, plants grown in space do not experience the directional cues provided by gravity. Early space experiments revealed that, in the absence of gravity, plant roots exhibit disorganized growth, often growing in multiple directions, and shoots may grow in a random or tangled pattern (Chebli & Geitmann 2011; Herranz & Medina 2014; Boucheron-Dubuisson et al 2016).

This phenomenon occurs because the plant's auxin distribution, a hormone responsible for regulating growth, becomes unbalanced (Li et al 2022). In normal gravity, auxin accumulates on the lower side of the plant's tissues, promoting growth on that side and causing the plant to orient itself in the correct direction. In microgravity, however, the lack of gravitational force prevents the settling of statoliths, and the plant struggles to establish a coherent growth pattern (Sathasivam et al 2021).

**Adaptations in space**. To address these challenges, researchers have conducted a variety of experiments to observe and understand how plants adapt to microgravity. Some species of plants, such as *Arabidopsis thaliana*, a model organism in plant biology, have been shown to adapt to altered gravitropic cues by using other environmental signals, such as light (phototropism) and touch (thigmotropism), to guide growth (Villacampa Calvo 2021).

Space agencies like NASA have utilized clinostats and rotating bioreactors to simulate gravity in space by continuously rotating the plant samples (Zhang et al 2022). This technique ensures that plants experience a uniform distribution of stimuli, promoting the natural growth of roots and shoots. However, while clinostats help mitigate some of the gravitational effects, they do not completely replace gravity, and plants continue to exhibit altered growth patterns.

Moreover, the application of artificial gravity, by rotating spacecraft or specific habitats, has been proposed as a solution to help overcome these challenges. By creating centrifugal forces that mimic gravitational forces, plants would be able to respond to the directional cues necessary for proper growth (Zhang et al 2022).

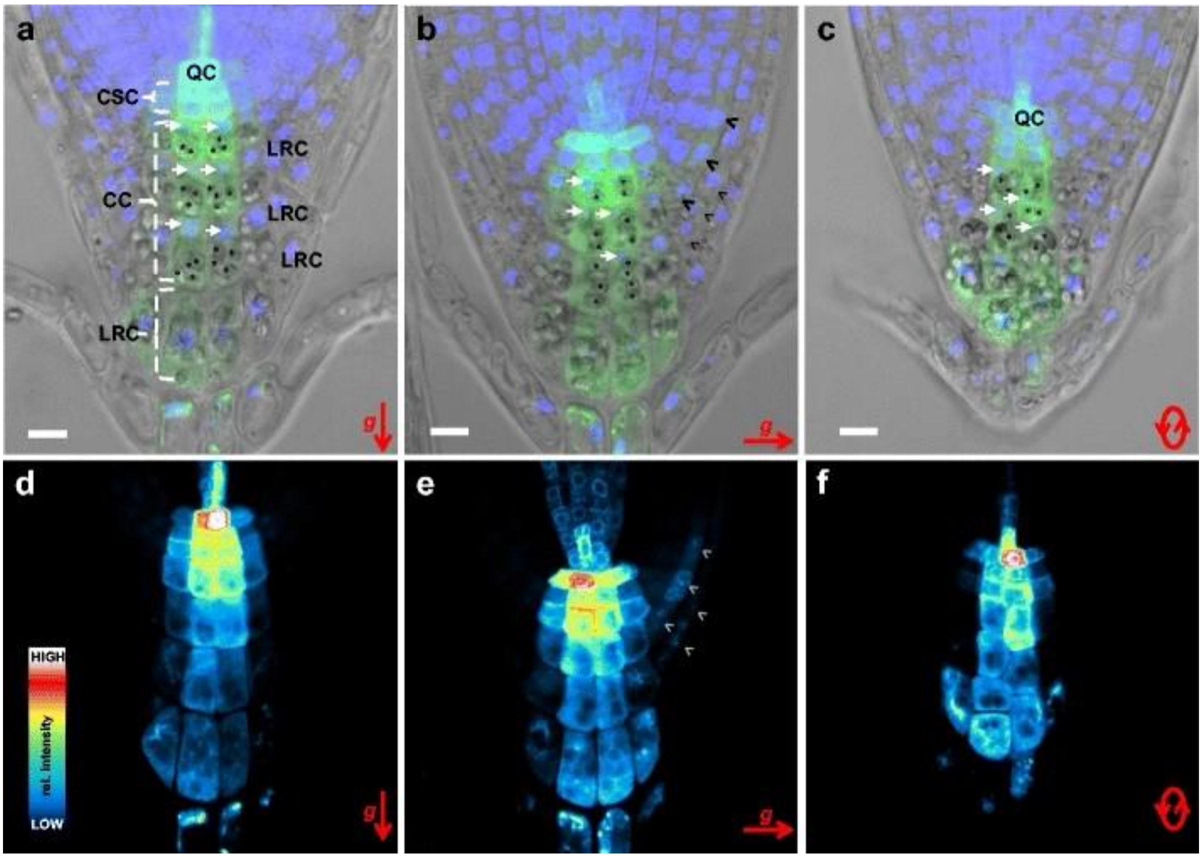


Figure 1. A figure published by Wang et al (2016) highlights structural changes and the distribution of specific molecular factors (fluorescent markers or proteins of interest) in *Arabidopsis* roots exposed to normal gravity (control) and simulated microgravity using a 2D clinostat.

***Notations in the Figure 1***
QC (Quiescent Center): a quiescent center is a specialized region in the root where cells remain largely undivided, acting as a "control hub" for root meristem organization.
CSC (Columella Stem Cells): columella stem cells are responsible for regenerating columella cells, which play a role in gravity perception.
CC (Columella Cells): columella cells contain amyloplasts (organelles that function as gravity sensors).
LRC (Lateral Root Cap): a protective layer of cells located at the root's margins, shielding the root tip during growth.
g↓ and g→ red arrows indicate the direction of gravity:
g↓ = normal vertical gravity.
g→ = simulated microgravity induced by rotation.

***Panel descriptions***
Panels a, b, c. Combined images (confocal microscopy + transmitted light) showing root structure:
a (Control under normal gravity, g↓): displays the typical organization of root zones. Fluorescent markers highlight the normal distribution of proteins or substances of interest.
b (Simulated microgravity, g→): redistribution of fluorescent substances (indicated by arrows). Alterations in the orientation of columella cells.
c (Recovery after simulated microgravity): partial restoration of normal structure following the cessation of microgravity conditions.
Panels d, e, f. Visualization of fluorescence intensity distribution in cells (color-coded):
d (Control): high fluorescence concentrated in QC and CSC, indicating normal status.
e (Simulated microgravity): fluorescence appears dispersed, suggesting changes in molecular factors in response to microgravity.
f (Recovery): fluorescence distribution starts returning to normal.

***Explanation for Figure 1***. The figure illustrates the impact of simulated microgravity on the architecture and molecular dynamics of *Arabidopsis* roots. Changes in fluorescence distribution and root structure suggest that microgravity disrupts gravity sensors (such as amyloplasts) and reorganizes the dynamics of proteins involved in gravity response. Recovery after simulated microgravity demonstrates that these changes are largely reversible.

**Implications for long-term space exploration**. Understanding how plants grow in space is not only essential for basic biological research but also for the future of space exploration. Plants play a crucial role in life support systems, providing oxygen, food, and psychological benefits to astronauts. Therefore, ensuring that plants can grow efficiently in microgravity is vital for the sustainability of long-term space missions, such as those planned for Mars or lunar bases.

Researchers are exploring genetic modifications to improve plant adaptability to microgravity (Haveman et al 2021). Some studies have shown that the expression of certain genes related to gravity-sensing mechanisms can be altered to improve plant responses to microgravity. Additionally, controlled environments, such as the Veggie experiment aboard the International Space Station (ISS), have provided valuable insights into how plants can be cultivated in space, influencing future agricultural practices in extraterrestrial habitats (Carillo et al 2020).

**Conclusions**. Gravitropism is a vital biological process that allows plants to orient themselves in response to gravity. In extraterrestrial environments where gravity is absent, this process is disrupted, causing plants to exhibit abnormal growth patterns. While current techniques such as clinostats and artificial gravity help mitigate these effects, understanding the underlying mechanisms of gravitropism in space remains crucial for the success of long-term space exploration. Future advancements in space agriculture, genetic modifications, and habitat design will be essential for cultivating plants in space, enabling sustainable life support systems and facilitating the growth of food in extraterrestrial environments.

**Conflict of interests**. The authors declare that there is no conflict of interest.

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