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Application of Unmanned Ground Vehicles in Protected Cultivation

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Protected cultivation has become an important approach in Indian agriculture for achieving higher productivity, better crop quality, and year-round production of horticultural crops. However, increasing labour shortages, rising production costs, and the growing demand for precision farming have encouraged the adoption of advanced automation technologies. Among these technologies, Unmanned Ground Vehicles (UGVs) are gaining attention as efficient robotic systems capable of performing various agricultural operations inside greenhouses and polyhouses with minimal human involvement. This article discusses the concept, applications, sensing technologies, economic advantages, research developments, challenges, and future opportunities of UGVs in protected cultivation. Equipped with advanced technologies such as artificial intelligence, computer vision, LiDAR, IoT sensors, and thermal imaging systems, UGVs can perform crop monitoring, disease detection, precision spraying, harvesting, transplanting, irrigation management, and environmental monitoring with improved accuracy and efficiency. Their adoption can significantly reduce labour dependency, minimize chemical and water usage, improve crop management, and enhance overall farm productivity. The article also discusses the contribution of Indian researchers, institutions, and government initiatives in promoting agricultural robotics and smart farming technologies. Although several limitations such as high investment cost, navigation complexity, sensor-related issues, and maintenance requirements still exist, rapid advancements in robotics, automation, and digital agriculture are expected to improve the practicality and affordability of UGVs in the near future. Overall, UGVs have strong potential to transform protected cultivation into a more precise, sustainable, and technology-driven farming system in India.

Keywords: Unmanned Ground Vehicles (UGVs), greenhouse, polyhouse, protected cultivation, precision agriculture, crop monitoring.

Introduction

India is one of the world's largest producers of horticultural crops, with an annual output exceeding 352 million metric tonnes and a horticulture sector valued at over ₹3.6 lakh crore. Protected cultivation the growing of crops inside polyhouses, net houses, and climate-controlled greenhouses is a fast-growing strategy for higher productivity and year-round supply. The Indian greenhouse horticulture market was valued at USD 206.36 million in 2024 and is projected to reach USD 298.58 million by 2033 (CAGR 4.19%). Despite rapid growth, the sector faces acute labour shortages for scouting, spraying, harvesting, and data collection particularly in remote polyhouse clusters in Himachal Pradesh, Uttarakhand, Karnataka, Maharashtra, and Rajasthan. Unmanned Ground Vehicles (UGVs) autonomous, sensor-laden robotic platforms that navigate crop rows inside polyhouses are emerging as a transformative solution, carrying cameras, sprayers, robotic arms, and environmental sensors to perform diverse tasks with minimal human supervision [Raj et. al., 2023].

What is an Unmanned Ground Vehicle (UGV)?

An Unmanned Ground Vehicle (UGV) is a mobile robot that operates on land without a human physically onboard. It can be controlled remotely or work autonomously using sensors, cameras, and onboard computers to navigate and perform tasks. UGVs are equipped with technologies such as GPS, LiDAR, cameras, and artificial intelligence, which help them sense their surroundings, make decisions, and carry out operations efficiently. They are widely used in agriculture, defense, logistics, and industrial applications for tasks like monitoring, spraying, material transport, and data collection. In protected cultivation (polyhouses and greenhouses), UGVs help automate repetitive and labour-intensive activities, improving precision, reducing costs, and increasing productivity. Agricultural UGVs for Indian polyhouses are compact, low-profile platforms built for inter-row widths of 50–70 cm, powered by lithium-ion batteries for 6–14 hours per charge. Figure 1 shows the operational workflow of Unmanned Ground Vehicles in a protected cultivation.

Fig. 1. Operational workflow of Unmanned Ground Vehicles in a protected cultivation.

Key Applications of UGVs in Indian Protected Cultivation

Unmanned Ground Vehicles (UGVs) are being used for several tasks in Indian protected cultivation, making farm operations more efficient and accurate. By using sensors, AI, and automation, they help farmers manage crops better while reducing labour and input use. Figure 2 shows the major applications of UGVs in protected cultivation.

Fig. 2. Key applications of Unmanned Ground Vehicles in protected cultivation.

Crop Monitoring and Disease Scouting

UGVs with high-resolution RGB cameras and multispectral imagers systematically scan polyhouse compartments multiple times per week, with onboard CNNs and YOLO-based AI detecting early-stage infections at accuracy rates exceeding 90%, flagging anomalies on digital polyhouse maps for targeted action. Researchers have developed fine-tuned YOLOv8 models for real-time capsicum detection and growth-stage classification, achieving a mean Average Precision (mAP) of 0.967. Advanced YOLOv9 segmentation models achieved precision and recall of 0.93 and 0.86 for capsicum peduncle detection in challenging night-time conditions, directly enabling autonomous harvesting [Paul et. al., 2024].

Precision Pesticide and Fungicide Application

Conventional manual spraying in Indian polyhouses wastes chemicals, escalates costs, and increases pesticide residues on export-quality produce. UGVs with precision-spraying systems navigate to specific infected plants and apply micro-doses via targeted nozzles using variable-rate application (VRA) technology, reducing pesticide use by 40–60% while maintaining equal or better disease control. In India, low-cost robots built using Raspberry Pi have also been developed for disease detection and targeted spraying, making this technology suitable for small and medium-scale polyhouse farmers.

Automated Harvesting

Harvesting in protected cultivation is highly labour-intensive, requiring around 200–300 worker-hours per hectare per week during peak periods. To address this, researchers have developed vision-guided robotic systems with 6-DOF arms for capsicum harvesting, combining AI-based optimization with kinematic modelling, along with mobile carts for collection and storage. Innovations like pneumatic grippers for crops such as cherry and tomatoes shows advancements in soft robotics in India. Although fully autonomous harvesting is still developing, hybrid approaches where robots pick easily accessible fruits and workers handle grading and sorting provide a practical solution to reduce labour dependency.

Transplanting, Environmental Monitoring & Precision Irrigation

UGVs equipped with robotic transplanting heads can handle 1200-2000 plants per hour with consistent depth and orientation, while integrated vision systems reject weak seedlings to improve crop uniformity. As mobile measurement platforms, UGVs continuously map microclimate variations (temperature, humidity, CO_2, light) across the entire polyhouse floor, revealing hotspots that fixed sensors miss. When fitted with soil moisture probes and thermal cameras, UGVs generate real-time water-demand maps enabling zone-specific irrigation demonstrating water savings of 25–40% globally, of direct relevance to water-stressed Indian farming belts.

The Sensing Technologies Powering Indian UGVs

The effectiveness of a UGV depends on its ability to accurately perceive plants, structures, and microclimate conditions. Several complementary sensor technologies are combined on Indian research and commercial platforms.

- **RGB Cameras:** Full-colour video for fruit detection, disease recognition, and row navigation. Capsicum harvesting robot uses Intel RealSense D455 RGB-D cameras for 3D fruit localisation with errors as low as 8 mm.
- **LiDAR:** Generates precise 3D maps of polyhouse interiors for collision avoidance and accurate row navigation [Bonadies et. al., 2023].
- **Multispectral/Hyperspectral Imagers:** Capture reflectance data for early detection of nutrient stress, fungal infections, and water deficit before visible symptoms appear [Shamshiri et. al., 2023].
- **Thermal Cameras & IoT Environmental Sensors:** Detect water deficit, disease, and pest activity via leaf temperature differences; temperature, humidity, CO_2, and soil moisture sensors provide real-time microclimate data. India is among the highest-volume contributors to IoT and AI in agriculture research globally, Figure 3 shows the sensor technologies integrated into agricultural unmanned ground vehicles

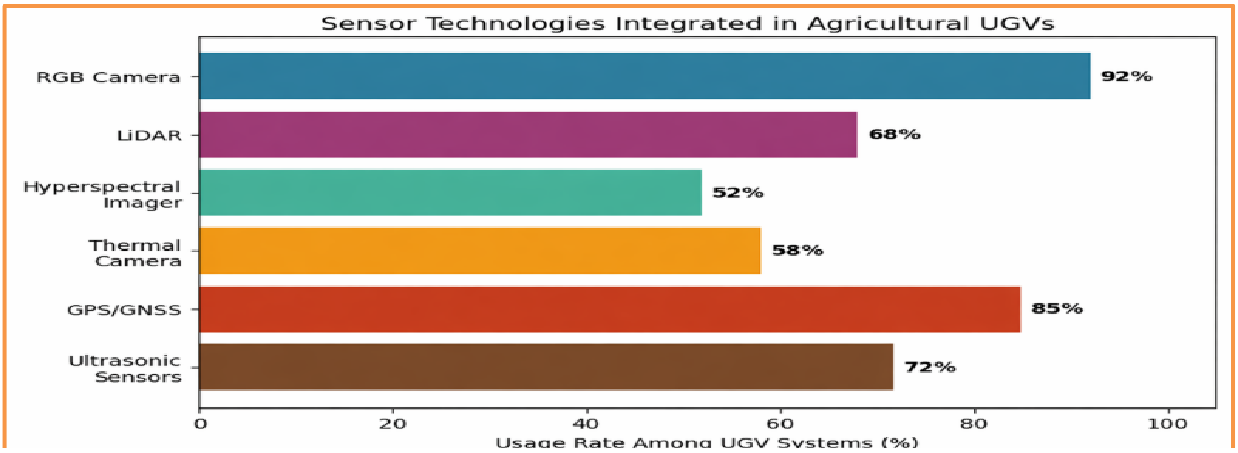

Fig. 3. Sensor technologies and their integration in agricultural UGV platforms

Economic Benefits and Return on Investment

Unmanned Ground Vehicles (UGVs) in protected cultivation systems present a strong economic case through input savings, productivity gains, and improved market access. By automating monitoring and spraying, UGVs reduce labour, water, and chemical use critical in high value crops like capsicum and cherry tomato, where labour constitutes a substantial share of costs. In India, relatively lower system costs (₹15–50 lakh) enable a payback period of about 3–5 years for a one-hectare unit. Figure 4 shows how different economic benefits are distributed with the adoption of UGVs in greenhouse operations. Labour savings account for the largest share at 45%, showing that reduced dependence on manual work, followed by chemical savings at 20% and water savings at 15%, indicating significant reductions in input costs. Yield improvement contributes 12%, reflecting better crop performance due to precise management, while premium pricing makes up the smallest share at 8%, suggesting limited but valuable gains from improved produce quality.

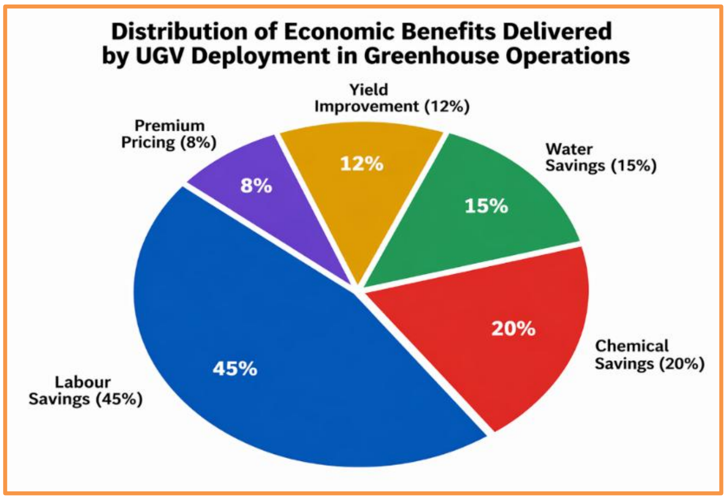

Fig. 4. Distribution of economic benefits delivered by UGV deployment in greenhouse operations

India's Research Ecosystem: Building the Foundation

India's academic institutions are steadily building the intellectual infrastructure for indigenous agricultural UGV development. Indian researchers published internationally recognized studies on vision-guided robotic systems, including a 6-DOF robotic arm for capsicum harvesting (YOLO-based computer vision with kinematic modelling), a peduncle-holding end-effector for robotic mango harvesting, and a low-cost Raspberry Pi-based disease detection and spraying robot designed for Indian farming contexts. India has emerged as one of the world's most prolific contributors to IoT and AI in agriculture research, with publication output growing sharply from 2023 to 2025. Government programmes the Digital Agriculture Mission, the National AI Strategy for Agriculture, ICAR's Precision Farming Development Centres, and Bharat Electronics Limited's Atmanirbhar Bharat UGV initiatives provide institutional support and public funding to translate prototypes into farm-ready systems [García-Mateos et. al., 2025]. Figure 5 shows the adoption levels of different UGV applications in protected cultivation. It indicates that crop monitoring and data collection have the highest adoption, while pesticide spraying and irrigation management have moderate adoption levels. In contrast, harvesting and transplanting show comparatively lower adoption, reflecting the challenges and slower adoption of automation in these operations

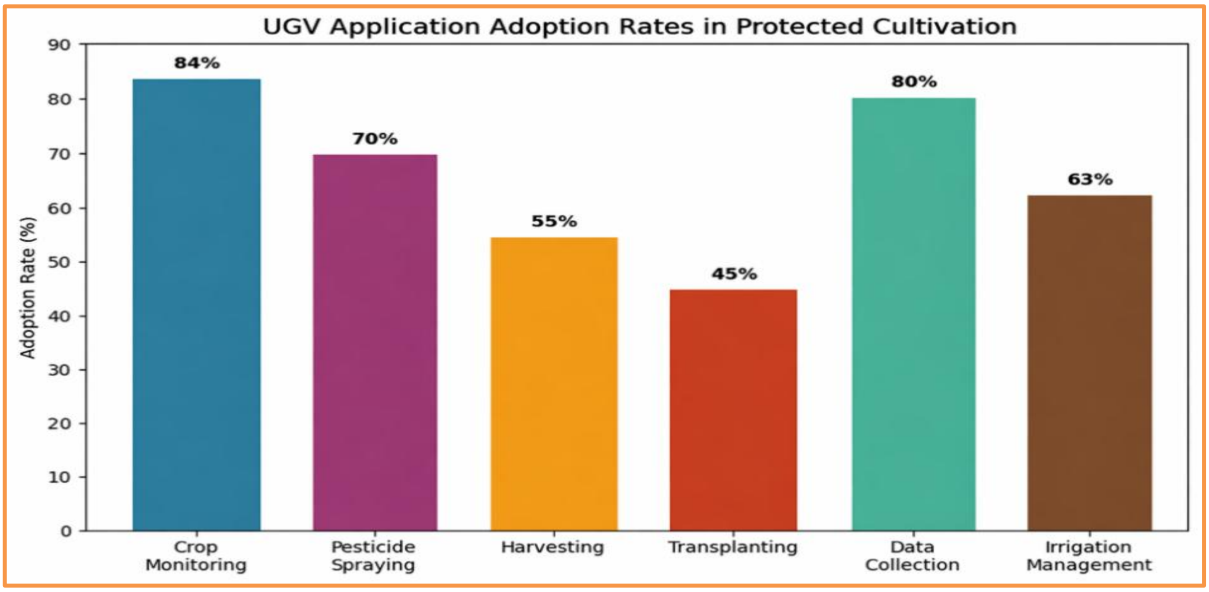

Fig. 5. Adoption rates of UGV applications in protected cultivation operations in India

Challenges and Limitations

Unmanned Ground Vehicles (UGVs) in protected cultivation face several challenges that limit their widespread adoption. Navigation inside greenhouses and polyhouses is difficult due to narrow pathways, dense crops, poor GPS signals, and obstacles such as pipes and support structures. UGVs also require expensive sensors, cameras, batteries, and AI systems, making the initial investment cost very high for small and medium farmers. Limited battery life and frequent charging reduce working efficiency, while wet, muddy, or uneven surfaces inside protected structures can affect vehicle movement and stability. UGVs may sometimes damage crops because of close plant spacing and inaccurate movement. Their sensors and cameras can also be affected by dust, humidity, water droplets, and changing light conditions, reducing operational accuracy. Communication problems caused by poor wireless signals inside greenhouses may interrupt remote monitoring and control. In addition, UGVs require skilled operators and regular maintenance, which may not be easily available to all farmers. Variations in greenhouse designs, crop types, and row spacing further reduce the adaptability of UGVs. Despite these limitations, continuous advancements in robotics, artificial intelligence, and automation technologies are expected to improve the performance and adoption of UGVs in protected cultivation in the future. Figure 6 shows the challenges and limitations of UGVs in protected cultivation.

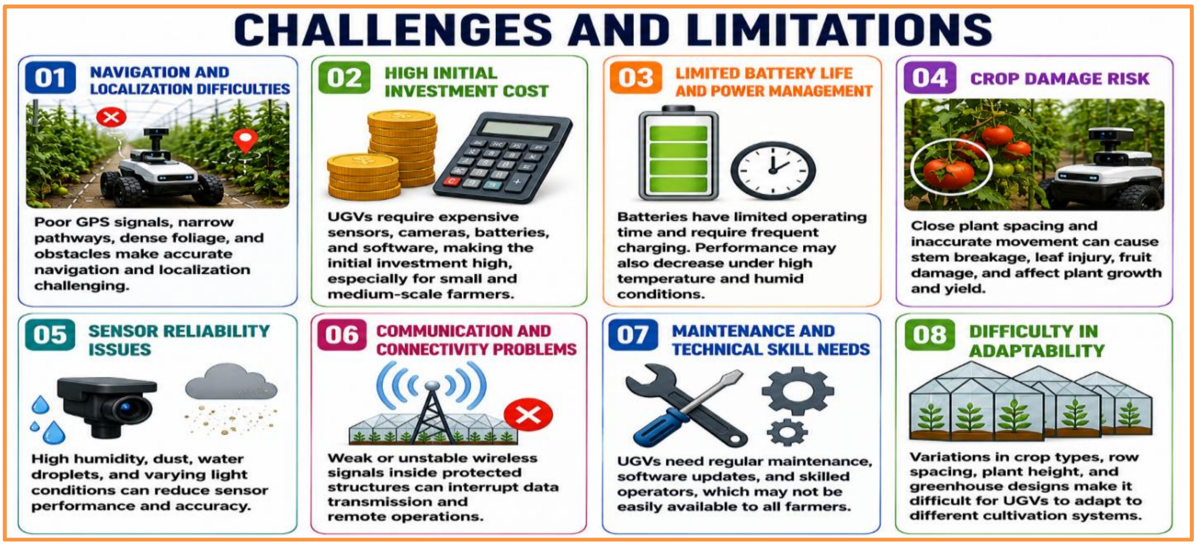

Fig. 6. Challenges and limitations of UGVs in protected cultivation

Future Prospects for India

The convergence of affordable AI hardware, indigenous chip design under the India Semiconductor Mission, 5G rollout in agricultural regions, and India's deepening robotics research ecosystem is rapidly narrowing the gap with the global protected cultivation robotics frontier. Key trends likely to define the next generation of Indian agricultural UGVs include.

- **Indigenous Low-Cost Platforms:** Indian startups and research groups are designing UGV platforms specifically for the dimensions, crop types, and budget constraints of Indian polyhouses.
- **Edge AI for Bandwidth-Limited Farms:** Onboard AI models on affordable devices (NVIDIA Jetson, Coral TPU) enable real-time detection and navigation without cloud or cellular dependence.
- **UAV–UGV Collaboration:** Aerial drones providing wide-area crop surveillance combined with UGVs performing targeted ground-level interventions creates a powerful multi-tier precision agriculture architecture.
- **Multi-Crop Adaptability & Digital Twins:** Modular platforms with interchangeable tool heads will cut capital cost per function, while UGV sensor data feeding real-time 3D digital models enables predictive management of climate, disease risk, and yield aligned with India's Digital Agriculture Mission.

Conclusion

Unmanned Ground Vehicles represent a genuine and timely technological opportunity for India's rapidly growing protected cultivation sector. By automating disease scouting, precision spraying, harvesting, transplanting, and environmental monitoring, UGVs offer Indian growers a clear pathway to higher productivity, lower input costs, better product quality, and improved competitiveness in premium domestic and export markets. As hardware costs decline, indigenous platforms emerge, and edge AI matures, UGVs are set to become as commonplace in the Indian modern polyhouse as drip irrigation and shade netting making the era of the autonomous Indian greenhouse not a distant vision, but a reality already taking root.

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