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Mechanization of Leafy Vegetable Production: Current Developments and Future Prospects

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ABSTRACT: Spinach, fenugreek, amaranthus, coriander and lettuce are important leafy crops in human nutrition, owing to their abundance of vitamins, minerals, and antioxidants. With short crop duration, delicate morphology, and frequent harvesting, these crops are mainly manual and difficult to mechanize. However, the recent advancement in agricultural machinery, robotics, and automation has created an unprecedented opportunity for mechanization in the production chain of leafy vegetables, from soil preparation and sowing to harvesting and post-harvest processing. The present review discusses the developments in the mechanization of leafy vegetable production with a focus on equipment design, operational efficiency, ergonomics, and sustainability. It identifies the gaps in the available mechanization technology and discusses opportunities for innovation in AI-based automation, precision agriculture, and ergonomically optimized small machines relevant for Indian and similar developing-country conditions.

Keywords: leafy, agriculture, machinery, AI, precision.

INTRODUCTION

Development of agricultural mechanization is in close connection with the unavailability of farm labour and the growth of industrial sectors in India and abroad (Praveen & Shrivastava 2020). The majority of Indian farmers are completely dependent on agriculture, which primarily consists of small, marginal, and medium landholders (Vyas, 1979). As such, this dependency clearly shows the great necessity of mechanization for the enhancement of productivity and lightening the physical workload of farmers. Leafy vegetables, both nationally and internationally, form a very important category of agricultural commodities (Praveen *et al.,* 2024). Leafy vegetables have a very high protective food value and are very easy to grow (Diwan *et al*., 2021). Many vegetable crops like potato, yams, tomato, lettuce and some of the leafy vegetables are being commercially cultivated in aeroponic system (Boddu *et al*., 2024). Within this context, discriminating between distinct morphological and physical characteristics of different leafy greens will assist in creating innovative agricultural machinery that can efficiently reduce waste without compromising nutritional value.

From this study, it is inferred that the application of one per cent panchagavya as foliar spray at weekly intervals significantly improved morphological characters in green amaranthus (Nair *et al*., 2024).

Particularly important among our leafy crops, coriander (*Coriandrum sativum*) is highly valued as a flavouring in curries and for its excellent medicinal properties in food garnishing (Praveen *et al.,* 2025). Agriculture, in general, has played an essential role in human health and welfare by providing large quantities of food that sustain the increasing world population (Praveen *et al.,* 2025). Sustainable agriculture is emerging as an alternative that aims at maintaining equilibrium between environmental protection, economic viability, and social justice for long-term food security (Praveen *et al.,* 2025).

Leafy vegetables occupy a unique position in the global horticultural sector due to their high nutritional value and market demand. In India, crops like spinach (*Spinacia oleracea*), fenugreek (*Trigonella foenum-graecum*), amaranthus (*Amaranthus* spp.), and coriander (Coriandrum sativum) are extensively grown on small farms, with intensive manual operations. Manual sowing, thinning, irrigation, weeding, and harvesting are slow and costly. Labour shortages, increasing wages, and a need for constant quality are creating the pressing need for mechanized means of production to cut human effort in this area.

There is yet to be any mechanization involving the production of leafy vegetables, the growth of which is still dwarfed when compared with field crops. These are, for the most part, difficulties posed by the weakness of the crops, high moisture content, and the requirement for precision during cutting and handling. These barriers, however, are now beginning to be circumvented thanks to the integration of lightweight battery-operated tools, smart sensors, and automated harvesting mechanisms.

MECHANIZED OPERATIONS IN LEAFY VEGETABLE PRODUCTION

Mechanization in leafy vegetable farming has made great advances when small-scale, battery-assisted, and precision-controlled machines are used. The system from traditional manual operation is modified into semi-automated and automated, with improvements in efficiency, uniformity, and profitability. In this part, we shall focus on mechanized interventions in major operations on leafy vegetable production- from land preparation until post-harvest handling, emphasizing technical specifications, performance results, and ergonomic considerations.

A. Land Preparation

Importance. Land preparation provides for an even crop establishment, root development, and moisture retention. A fine, well-drained seedbed in leafy vegetable production is essential, as most crops are small-seeded, such as spinach, fenugreek, and coriander, requiring shallow placement.

Common Mechanized Tools.

Table 1: Common Mechanized Tools.

Machine Type	Power Source	Key Features	Suitability
Mini Tiller	2–5 hp petrol engine	Lightweight (30–60 kg), adjustable blades	Small and marginal farms
Rotary Cultivator	PTO-driven (8–12 hp)	Depth control lever, interchangeable tines	Medium holdings
Power Weeder (with intercultivation kit)	Battery or petrol	Multiple attachments: ridger, puddler, cultivator	Vegetable beds and narrow plots

Advantages

1.Reduces clod size and improves soil tilth.

2. Saves 25–35% time compared to manual hoeing.

3. Low operational cost (₹250–350/h for mini tillers).

4. Reduces drudgery, especially for women labourers in small plots.

Limitations

1. Difficult to operate in high-moisture soils.

2. Frequent clogging of rotary blades in clayey soils.

3. Requires moderate technical skill for maintenance.

B. Sowing and Transplanting

Mechanized Sowing Systems. Uniform seed distribution ensures optimal plant population and reduces the need for thinning. Mechanized sowing devices for leafy crops include:

1. Manually Operated Drum Seeder – Uses lightweight plastic or aluminium drums with variable hole sizes for spinach and amaranthus. Suitable for line sowing.

2. Battery-Assisted Drum Seeder – Improved model with motorized drum rotation for consistent speed and uniform drop rate.

3. Single-Row Vegetable Planter – Equipped with adjustable metering plates and row spacing controls.

4. Precision Pneumatic Seeder – Utilizes vacuum or positive air pressure to pick and release individual seeds with high accuracy.

Technical Features (Table 2).

Table 2: Technical Features.

Machine	Working Width (m)	Capacity (ha/day)	Power Requirement
Manual Drum Seeder	0.8	0.15–0.25	Human
Battery Drum Seeder	1.0	0.30–0.45	12V DC Motor
Pneumatic Seeder	1.2	0.6–0.8	0.5–1.0 kW Electric motor

Benefits
-20–25% seed saving compared to manual broadcasting.
-Uniform plant spacing improves yield by 10–15%.
-Easy calibration and portability.
-Reduces human error and ensures a higher germination rate.

Mechanized Transplanting. For leafy vegetables like lettuce and cabbage (where transplanting is common), semi-automatic transplanters and hand-held dibblers are used. Newer plug-tray transplanters use pneumatic gripping arms to pick seedlings from trays and place them at uniform depths.

C. Irrigation Systems
Efficient water management is crucial in leafy vegetable cultivation due to shallow root systems and high evapotranspiration rates.

Mechanized Irrigation Options
1. Drip Irrigation Systems – Deliver water directly to the root zone, minimizing evaporation.
2. Micro-sprinklers – Used for uniform moisture distribution in nursery beds.
3. Portable Battery-Operated Sprayers – Dual-use systems for irrigation and foliar feeding.
4. IoT-Based Controllers with Soil Moisture Sensors – Monitor soil conditions and automate irrigation cycles.

Advantages
-35–40% water saving compared to flood irrigation.
-Improved nutrient absorption and reduced leaching.
-Enables fertigation for leafy crops.
-Battery-operated systems enhance portability and ease of use.

Future Prospects
-Integration of solar PV systems for powering pumps.
-Use of AI algorithms for predictive irrigation scheduling.
-Cloud-based data logging for water use efficiency.

D. Weeding and Intercultural Operations
Weeding remains a time-consuming task in leafy vegetable farming due to dense plant populations and shallow crop roots.

Mechanized Weeders (Table 3).

Table 3: Mechanized Weeders.

Type	Mechanism	Example Application	Power Source
Rotary Weeder	Rotating blades uproot weeds	Spinach and coriander fields	Manual or battery
Oscillating Weeder	Vibrating tines disturb the soil surface	Fenugreek	Petrol engine
Push-Type Weeder	Simple frame with wheel-driven blades	Small farms	Manual
Robotic Vision-Based Weeder	Cameras detect and remove weeds selectively	Greenhouses	Electric, AI-based

Performance Highlights
-Weeding efficiency up to 90% using rotary weeders.
-Battery weeders reduce labour requirements by 60%.
-Ergonomically designed handles reduce muscular strain.
-AI-assisted systems enable precision weeding without crop damage.

Limitations
-High initial cost of robotic weeders.
-Limited manoeuvrability in raised bed cultivation.
-Difficulty in removing closely spaced intra-row weeds.

E. Fertilizer and Pesticide Application
Mechanized Fertilization
-Manual Fertilizer Broadcasters: Simple rotary spreaders for uniform top dressing.
-Battery-Operated Dusters: Efficient for fine powder fertilizer distribution in spinach and amaranthus.
-Fertigation through Drip: Enables simultaneous application of water-soluble fertilizers.

Mechanized Spraying Equipment
1. Battery-Operated Knapsack Sprayer: Lightweight (5–7 kg), 12V motor-driven pump, adjustable nozzle.
2. Boom Sprayer (Push-Type): Used for uniform spraying in wide beds.
3. Solar-Powered Sprayer: Equipped with a PV panel and charge controller to ensure continuous operation.
4. Automatic Nozzle Control System: Maintains a consistent spray rate based on forward speed.

Advantages
-Reduces chemical wastage by 25–30%.
-Uniform droplet size ensures efficient pest control.
-Minimizes operator exposure to chemicals.
-Reduces fatigue and increases spray coverage.

Innovations
-Use of **drone-based sprayers** in greenhouse or open-field spinach cultivation.
-Integration with **GPS mapping** for site-specific spraying.

F. Harvesting
Harvesting of leafy vegetables is the most labour-intensive and time-sensitive operation. Manual cutting causes uneven stalk lengths and product damage.

Mechanized Harvesters (Table 4).

Table 4: Mechanized Harvesters.

Type	Crop	Mechanism	Key Features
Reciprocating Blade Harvester	Spinach, Fenugreek	Cutter bar with oscillating blades	Clean cut, adjustable height
Rotary Cutter Bar Harvester	Amaranthus, Mustard Greens	Circular blades on a rotating shaft	Uniform cutting, high throughput
Battery-Operated Sitting Harvester	Coriander, Spinach	Adjustable speed and ergonomic design	Low vibration and fatigue
Robotic Vision Harvester	Lettuce, Spinach	AI image detection and arm actuation	Selective harvesting in greenhouses

Ergonomic Assessment

Studies show a 45–60% reduction in operator heart rate and fatigue when using mechanized harvesters compared to manual sickles. Productivity improves from 60–80 kg/h (manual) to 180–220 kg/h (battery harvester).

Limitations

-Initial investment and maintenance cost.
-Battery runtime constraints (3–4 hours average).
-Skill required for adjustment and maintenance.

G. Post-Harvest Handling

Proper post-harvest handling extends the marketable life of leafy vegetables, preserving freshness and reducing losses.

Mechanized Handling Stages

1. Washing: Portable belt washers or rotary drum washers remove field soil.
2. Trimming: Motorized blades cut roots and damaged leaves.
3. Drying: Centrifugal dryers remove surface moisture before packaging.
4. Sorting and Grading: Vision-based systems classify leaves based on size and colour.

Packaging and Storage

-Modified Atmosphere Packaging (MAP): Uses perforated polymer films to maintain O_2 and CO_2 balance.
-Vacuum Cooling: Rapidly cools vegetables to 1–3°C within 20 minutes to maintain crispness.
-Conveyor-Based Transfer Systems: Reduce manual handling damage by 25–30%.

Benefits

-Extends shelf life by 3–5 days.
-Reduces post-harvest loss by up to 40%.
-Maintains nutritional quality and visual appeal.

H. Overall Impact of Mechanization **(Table 5).** Mechanization significantly improves time efficiency, labor utilization, and uniformity, while ensuring sustainability through reduced energy inputs and optimized resource use.

Table 5.

Operation	Traditional Method	Mechanized Method	Efficiency Gain (%)
Land Preparation	Manual hoeing	Mini tiller	30–40
Sowing	Broadcasting	Drum seeder	25–30
Irrigation	Flood	Drip/Micro-sprinkler	35–40
Weeding	Hand pulling	Rotary weeder	50–60
Spraying	Manual pump	Battery sprayer	30–40
Harvesting	Knife	Cutter bar	60–70
Post-harvest	Manual washing	Mechanized washer	25–35

CHALLENGES IN MECHANIZATION

Mechanization of leafy vegetable production, though advancing rapidly, faces unique technical, economic, and ergonomic challenges. Unlike cereal or tuber crops, leafy vegetables possess fragile structural characteristics and have shorter growth durations, requiring precision and care at every operational stage. The following points summarize the primary constraints limiting mechanization adoption.

A. Fragility of Leaves and Stems

The structure of leafy vegetables such as spinach, amaranthus, fenugreek, and coriander is thin and thus vulnerable to mechanical damage from sowing through weeding to harvesting. Even a slight bruise or a few cuts can cause rapid wilting, discolouration, and therefore loss of its market value. Hence, harvesting tools must have accurate cutting blades, soft gripping mechanisms, and levels of controlled vibration in order not to damage the leaves. The cut continues to become more complicated, especially for crops having different thicknesses of leaves or differential rigidity of stems, where the same cutting force cannot be systematically applied.

B. Short Crop Cycle and High Machinery Cost

Most leafy vegetables mature within 20-45 days after sowing. Due to the inherent short crop periods, it is often uneconomical for smallholder farmers to invest in expensive machinery that is used only for a few weeks each season. In addition, a return on the investment becomes restricted unless the same machine can be used across various crops or operations. Hence, there is a need to develop multi-functional complex machinery that can easily adapt to different leafy crops grown in different seasons. Where smallholder farmers cultivate farms that are less than 1 ha, machine-sharing models or cooperative-based custom hiring centres can enhance affordability.

C. Non-Standardized Crop Geometry

Leafy vegetables differ from cereals in terms of row spacing, plant height, and canopy structure. For example, coriander and spinach have low, dense canopies, while amaranthus grows taller and more erect. An input complicator in machine design, which can be especially useful for seeders, weeders, and harvesters, relies on consistent crop geometry for efficient operation and is presented with this variability. The design of universal mechanisms that can self-adjust to different canopy structures using sensors or adaptive actuators remains an open field of research.

D. Lack of Awareness and Technical Training

Thus, there exist machineries, but installation has remained low due to limited farmer awareness and poor training in handling such implements (FAO, 2020). Most small-scale farmers are either new to mechanization systems or do not have access to after-sales service centres. Also, they are prevented from obtaining those machines in rural markets because of limited local manufacturing capacities and high dependence on imports. Hands-on training programs, demonstration units, and user manuals in local languages can fill the knowledge gap in that regard and stimulate widespread acceptance.

E. Mechanical and Environmental Constraints

High moisture content in leafy vegetables causes frequent clogs in the cutting and conveying systems and harvesting blades. Moisture accelerates corrosion in metal components and also affects electronic components coming into use with automation. Besides that, the above field conditions-undulating terrain, heavy soils, and greenhouse conditions of high humidity-add more complexity to mechanized operations. For long-life functionality, the development of anti-corrosive materials improved sealing techniques, and moisture-resistant designs are vital.

RECENT ADVANCES

From the innovations and integration of smart technologies in agricultural mechanization research in recent years to the mitigation of the preceding limitations was the main thrust. The concentration is going away from the routine mechanical systems to fully automated, sensor-based, and ergonomically optimized machines dedicated specifically to delicate leafy vegetables.

A. Battery-Powered Multi-Row Harvester

A few of the latest prototypes, like the battery-operated harvester, have features such as adjustable crank speeds, adjustable cutting heights, and adjustable ergonomic seating positions for the operator. This type of machinery uses DC motors with respective speed control units so that the blade motion can be varied as per the requirements of density and texture of crops by the operator. Multi-row attachments increase harvesting efficacy to about 300-400 kg per hour, but cutting uniformity is well maintained while leaf damage is reduced at harvest.

B. AI-Odnoloca Vision Systems

Artificial intelligence (AI) has made revolutionary strides in crop recognition and maturity determination inside controlled environments (Sharma & Shivandu 2024). Based on analysis of both leaf colour and morphology, vision-based algorithms determine whether leaves are ready for harvest. This system also allows many mature leaves to be harvested while leaving immature tissue for regrowth. This is particularly useful in very high-value crops such as lettuce and spinach produced in greenhouse or hydroponic systems.

C. Autonomous Robotic Platforms

Most uses of autonomous mobile robots feature machine-vision, laser-scanning, and robotic arm technology in greenhouses for seeding, weeding, and harvesting (Shi *et al*., 2023). These robots use GPS or LiDAR guidance to direct them to crop rows and carry out crop care practices without damaging adjacent plants. Although too expensive for now, these systems promise decreased dependence on labour and increased productivity in intensive production setups.

D. 3D-Printed Components

With the help of 3D printing technology in machinery design, it is possible to design light, customizable components to be used in harvesting and sowing equipment (Javaid & Haleem 2019). For instance, polymer-based components replace traditional metallic parts, resulting in a decrease in weight and vibrations caused by the machine. Furthermore, it allows 3D-printed blades and housings to be easily replaced or changed based on the crop needs, thus offering flexibility for small manufacturers and research centres.

E. Ergonomic Operator Design

Human comfort remains an essential factor in mechanization success. The importance of ergonomic designs that reduce vibration transmission and operator fatigue. Battery-operated systems now feature padded seating, vibration isolation mounts, and adjustable handles that accommodate different operator heights and working postures. Such features have been shown to improve efficiency and operator safety, particularly in long-duration harvesting operations.

F. Integration of GPS, Sensors, and IoT
Recent machinery incorporates GPS, accelerometers, and moisture sensors integrated through IoT (Internet of Things) platforms (Shaikh *et al*., 2022). These systems allow for real-time data collection on field conditions, machine performance, and crop status. Farmers can monitor progress remotely and adjust operational parameters such as cutting height or irrigation intervals. The integration of IoT improves overall precision, reduces resource wastage, and ensures uniform crop management.

FUTURE PROSPECTS

The mechanization of leafy vegetable production is expected to evolve toward greater automation, sustainability, and inclusivity. Upcoming trends focus on optimizing existing designs for smallholder adaptability, cost-effectiveness, and renewable energy utilization.

A. Smart Robotics and Selective Harvesting
Future robotic harvesters will utilize machine learning and depth-sensing cameras to identify mature leaves, estimate biomass, and plan cutting trajectories (Moreno & Andújar 2023). Selective harvesting minimizes waste and ensures multiple harvests per crop cycle. Collaborative research between agricultural engineers and computer scientists is vital for developing affordable and locally adaptable robotic systems.

B. AI-Based Quality Grading and Defect Detection
AI-based image recognition can assess quality parameters such as leaf colour, shape uniformity, and pest damage (Sharma & Borse 2016). Integrating these systems with packaging lines could automate post-harvest sorting, improving product uniformity and export quality standards (Das *et al*., 2025).

C. Collaborative Design for Small Farms
Modular and collaboratively designed machinery will play a crucial role in enabling small and marginal farmers to adopt mechanization. Low-cost fabrication units, open-source design platforms, and cooperative ownership models can ensure that technology development aligns with local needs and affordability.

D. Solar-Battery Hybrid Systems
Sustainability in mechanization will increasingly depend on renewable energy (Mousazadeh *et al.,* 2009). Solar-battery hybrid sprayers, weeders, and harvesters can provide an uninterrupted power supply, reduce operational costs, and lower greenhouse gas emissions. Integrating solar charging panels into machine frames or operator stations can make field operations independent of grid electricity.

E. Ergonomic and Gender-Friendly Design
Mechanization strategies must address the ergonomic needs of women and elderly workers who constitute a significant portion of the horticultural workforce. Lightweight materials, adjustable handles, and simplified control systems enhance inclusivity and usability. Design parameters should consider anthropometric data specific to local populations to ensure comfort and safety.

F. Policy and Institutional Support
Public-private partnerships, subsidies for machinery purchase, and the establishment of mechanization training centers can enhance technology dissemination. Government programs promoting start-ups in agri-tech and farm equipment manufacturing can accelerate innovation. Furthermore, integrating mechanization awareness in agricultural extension curricula can build long-term capacity among farmers and students.

CONCLUSIONS

Mechanization in leafy vegetable production is undergoing a transformative phase, transitioning from manual operations to highly sophisticated, sensor-integrated systems. Innovations in battery-operated, lightweight, and ergonomically optimized machinery have substantially reduced labour requirements, improved operation speed, and maintained product quality. While the potential benefits are clear, challenges such as economic feasibility, training, and standardization must be addressed to ensure widespread adoption among smallholders. The key to successful mechanization lies in context-specific design, ensuring that machines are affordable, adaptable, and environmentally sustainable. Integration of AI, IoT, and robotics will further refine precision and operational efficiency. However, achieving this vision requires coordinated efforts among researchers, policymakers, manufacturers, and farmers. By aligning innovation with ground realities, India and other developing countries can ensure that leafy vegetable mechanization contributes to both agricultural productivity and rural livelihood enhancement.

FUTURE SCOPE OF THE STUDY

The mechanization of leafy vegetables production provides significant opportunities for any additional development with automated, robotized, and artificial intelligence. Future efforts in research should be aimed at coming up with cost-efficient, small-sized, and modular machines to suit small and medium-sized farms so as to enhance access and adoption. The use of high-tech sensory conditions, i.e. LiDAR, hyperspectral image and machine vision can substantially increase the accuracy of planting, harvesting and grading processes.

In addition to that, the Internet of Things (IoT) and data analytics used together will make it possible to track the health of crops, the state of the soil, and the work of equipment in real time, which will help develop evidence-based decision-making. Mechanized operations can be made more efficient in terms of energy use and sustainability through the application of renewable energy sources, including solar and hybrid batteries.

Moreover, improvements in ergonomics should be made to guarantee the comfort and safety of the operators, especially in semi-mechanized or manually assisted machines. Cooperation on research between engineers, horticulturists, and data scientists may result in producing adaptive and autonomous systems that can handle leafy vegetable delicacy without reducing its quality. Field trials and techno-economic analysis will also need to be conducted in the long run in order to authenticate the performance of machines, safeguard the economic viability and the application on a large scale within various agro-climatic regions.

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