Current Research in Agricultural Sciences
2026 Vol. 13, No. 1, pp. 1-42
ISSN(e): 2312-6418
ISSN(p): 2313-3716
DOI: 10.18488/cras.v13i1.4608

Evolution of sweet pepper (Capsicum annuum) harvesting: From traditional practices to mechanization and robotics

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Article History
Received: 29 October 2025
Revised: 15 December 2025
Accepted: 22 December 2025
Published: 24 December 2025

Keywords
Greenhouse farming
Mechanized harvesting systems
Robotic harvesting
Sustainable agriculture
Sweet pepper harvesting.

ABSTRACT

This review aims to critically examine the technological evolution of sweet pepper (*Capsicum annuum*) harvesting, highlighting the transition from labor-intensive manual practices to mechanized and robotic systems. The study synthesizes historical records, experimental studies, and recent engineering developments to compare harvesting efficiency, labor requirements, costs, and fruit quality across manual, mechanical, and robotic approaches in both open-field and protected cultivation systems. Manual harvesting traditionally required approximately 950–1000 labor hours ha^{-1}, accounting for nearly 40–50% of total production costs, whereas mechanized harvesting introduced during the mid-20th century reduced labor inputs by 80–85%, achieving capacities of up to 9,000 kg h^{-1} and decreasing operational costs from about \$1,260 ha^{-1} to \$210 ha^{-1}. However, mechanical systems were associated with higher fruit damage rates (2.3–3.9%) compared to careful hand picking (<1%). Recent robotic platforms such as SWEEPER and Harvey demonstrate selective harvesting success rates of 61–76.5% with cycle times of 15–24 seconds per fruit, indicating substantial progress toward precision and autonomy. Despite these advances, challenges related to fruit damage, destemming efficiency, perception accuracy, and cultivar variability remain significant. The findings underscore the need for integrating advanced sensing technologies, machine learning algorithms, and adaptive end-effectors to improve harvesting performance. This review provides practical insights for researchers, technology developers, and growers seeking to enhance labor efficiency, economic viability, and sustainability in sweet pepper production systems.

Contribution/Originality: This study contributes to the existing literature by providing a comprehensive, quantitative synthesis of sweet pepper harvesting evolution from manual to robotic systems. It is among the few reviews integrating historical, mechanical, and AI-driven harvesting advances, offering the first consolidated analytical comparison of efficiency, damage, cost, and sustainability across technologies.

1. INTRODUCTION

Agriculture, for a long time, has been the backbone of human civilization. It has been important for ensuring that people have enough food, supporting their livelihoods, and driving economic growth worldwide. This broad and diverse industry includes growing crops, raising animals, and various related activities that collectively help both developed and developing countries grow economically and socially. Horticulture, especially the cultivation of fruits and vegetables, is a significant part of modern agriculture within this extensive field. It not only provides nutritional value but also creates jobs and supports international trade due to its export potential. Over the past few decades, the cultivation of fruits and vegetables has become increasingly common as more people seek to consume a variety of healthy foods. Vegetables are a vital component of a healthy diet because they are rich in vitamins, minerals, antioxidants, and fiber. Capsicum annuum L., commonly known as sweet pepper or bell pepper, is one of the most valuable crops. This plant originates from Central and South America and has been cultivated since before Columbus. Following the 1500s, colonial trade routes introduced sweet peppers to Europe and Asia, where they became important crops grown in both temperate and tropical climates. Although sweet pepper is a perennial plant, in temperate regions, it is typically grown as an annual because it does not tolerate frost or cold weather [1].

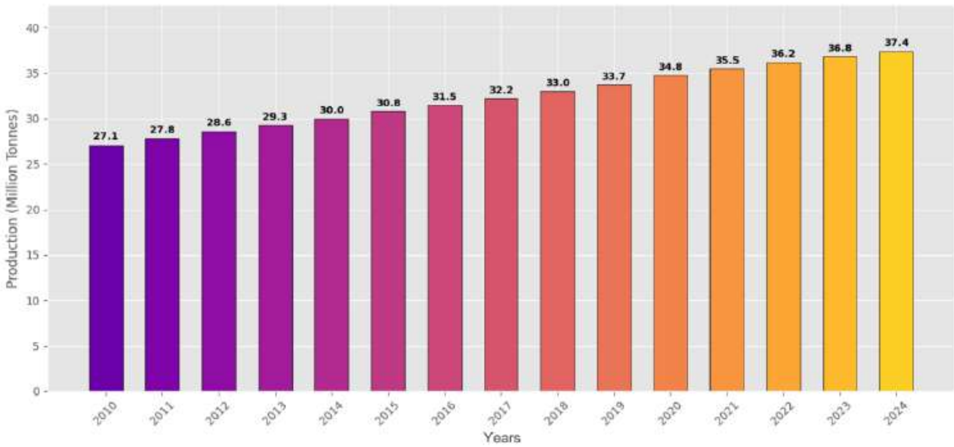


Figure 1. Global capsicum production (2010-2024) [2].

The steadily rising production of sweet pepper (*Capsicum annuum* L.) over the past ten years (Figure 1) demonstrates its increasing importance globally. By 2020, the world had produced more than 36 million tonnes of bell peppers, representing a significant increase from 2010 levels. China is now the largest producer, accounting for nearly 46% of the total global output. Mexico, Indonesia, and Turkey are also key contributors to international production, each maintaining a strong presence in the global market (Figure 2). [2]. In India, capsicum is a valuable horticultural product that is known for its high market returns. Many states, including Karnataka, Himachal Pradesh, and Maharashtra, grow it extensively, both in open fields and in protected areas. The National Horticulture Board states that India produced more than 437 thousand metric tonnes of capsicum during the 2021–22 season. This growth demonstrates the increasing importance of the crop, not only for meeting domestic demand but also for expanding its role in the export sector [3, 4].

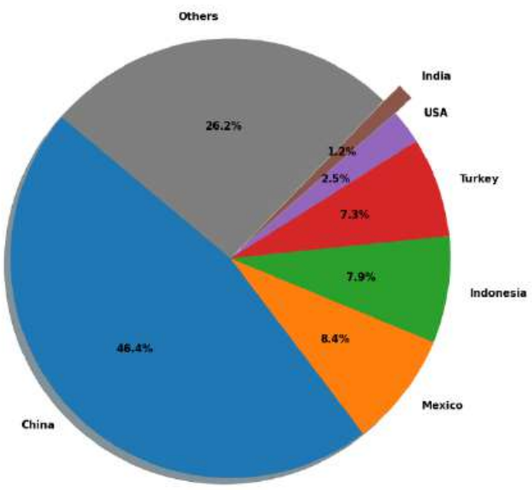


Figure 2. Country-wise share in global capsicum production (2020) [2].

From a nutritional perspective, Capsicum annuum is a highly valuable horticultural crop because it is rich in essential vitamins, minerals, and bioactive phytochemicals [5]. Red capsicum is particularly notable among capsicum varieties due to its exceptionally high vitamin C content, with some cultivars containing up to 183 mg per 100 g. This level significantly exceeds the daily recommended intake for adults and plays a crucial role in enhancing the body's antioxidant defenses. Additionally, red capsicum is an excellent source of β-carotene (provitamin A), α-tocopherol (vitamin E), and dietary fiber. These nutrients are vital for various physiological functions, including immune support, maintaining healthy vision, and promoting digestive health. Beyond these primary nutrients, capsicum contains numerous bioactive compounds such as capsaicinoids, flavonoids, and phenolic substances. These compounds have been extensively studied for their antioxidant, anti-inflammatory, and anti-cancer properties [5]. They work synergistically to neutralize reactive oxygen species (ROS), modulate inflammatory pathways, and potentially reduce the risk of chronic diseases. Table 1 shows that red capsicum usually has more important micronutrients than green capsicum, such as vitamin C, β-carotene, and vitamin E. But green capsicum has a little more vitamin K1 and calcium, which shows that both stages of maturity have their own unique and useful nutritional benefits.

Table 1. Nutrient composition of red and green capsicum (per 100 g, Raw) [5].

Nutrient / Compound	Red Capsicum	Green Capsicum	Unit
Energy	31	20	kcal
Water	92.0	93.9	g
Protein	1.0	0.9	g
Carbohydrates	6.0	4.6	g
Sugars	4.2	2.4	g
Dietary Fiber	2.1	1.7	g
Fat	0.3	0.2	g
Vitamin C (Ascorbic Acid)	127.7	80.4	mg
Vitamin A (as β-carotene)	157	18	µg RAE
Vitamin B6	0.3	0.2	mg
Folate (Vitamin B9)	46	10	µg
Vitamin E	1.58	0.37	mg
Vitamin K1	4.9	7.4	µg
Potassium	211	175	mg
Calcium	7	10	mg
Magnesium	12	10	mg
Iron	0.43	0.34	mg
Phosphorus	26	20	mg
Key Bioactive Compounds	Carotenoids (β-carotene, lutein, zeaxanthin), flavonoids, phenolic acids	Fewer carotenoids, similar flavonoids, and phenolics	—

The great nutritional value of capsicum leads to many health benefits, as shown in Figure 3, which illustrates the main physiological benefits of its bioactive compounds. The high levels of ascorbic acid and carotenoids, especially lutein and zeaxanthin, work together to lower oxidative stress, improve heart health, and protect cells from damage, which is beneficial for eye health [6]**.** Capsicum also contains phenolic acids and flavonoids, which help reduce inflammation. This may help keep joints healthy and lower the risk of metabolic disorders. Capsicum is a great choice for diets focused on losing weight and staying hydrated because it has few calories and a high water content, especially in green varieties. In addition to being beneficial, capsicum is a versatile ingredient in many cuisines worldwide because it exhibits a wide range of sensory qualities, from the sweetness of ripe red peppers to the mild pungency of some cultivars. These combined nutritional and functional benefits not only drive consumer demand but also make capsicum a key area of ongoing agricultural research. Current innovation efforts aim to improve yield potential, nutritional composition, and post-harvest shelf life using both traditional breeding methods and modern biotechnology.

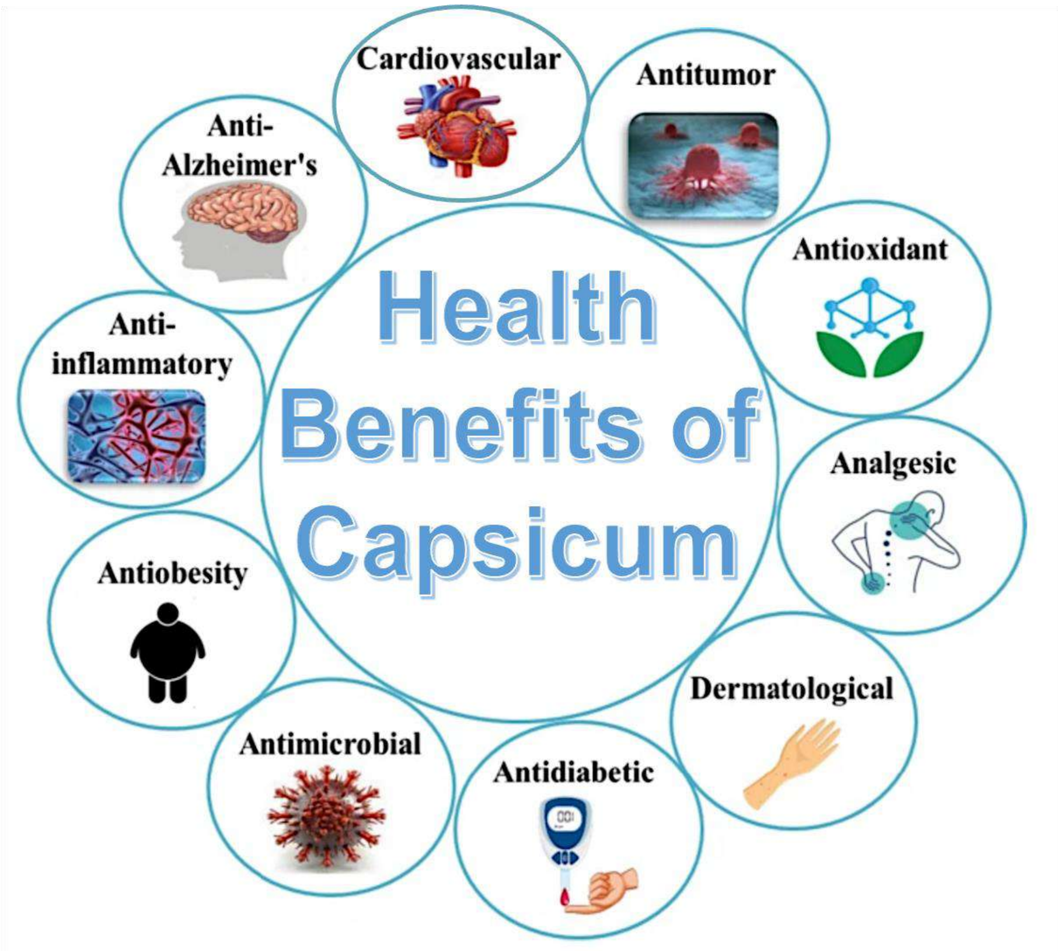


Figure 3. Health benefits of capsicum [6].

In farming, harvesting is the process of gathering fully grown crops from the field at the end of their growth cycle. It is an important step that has a direct effect on the quality, shelf life, and market value of the produce. Harvesting is often considered the most labor-intensive and time-sensitive part of crop cultivation. This is especially true in horticulture, where careful handling is necessary to maintain product integrity and reduce post-harvest losses [7]. When it comes to vegetable crops, harvesting is even more critical because they spoil quickly and are easily damaged, which can lead to rapid deterioration and financial loss.

There are unique problems with harvesting capsicum because of its shape and the fact that it ripens at different times. The fruits grow on branches that are easy to break, and the same plant may have fruits that are not all ripe at the same time, so selective harvesting is necessary [8]. Also, capsicum peduncles (fruit stems) are often hidden by leaves, which makes them harder to see and means that they need to be carefully identified and handled to avoid hurting nearby fruits or plants. Manual harvesting remains the most common method worldwide, but it involves high labor costs, ergonomic strain, and inconsistent quality [9]. With the availability of labor becoming more unpredictable and cultivation expanding in controlled environments such as greenhouses, the creation of efficient, semi- or fully-automated harvesting systems for capsicum has become a critical area of research [10].

Given the aforementioned challenges and the increasing demand for efficiency in capsicum harvesting, this study seeks to address existing knowledge deficiencies and conduct a critical analysis of the technological advancements in capsicum harvesting, focusing specifically on the shift from traditional manual techniques to semi-automated and fully robotic systems designed for precision agriculture. It aims to situate these advancements within the overarching challenges of labor efficiency, crop fragility, and structural variability of greenhouse-cultivated vegetables. This goal is pursued by addressing the following key objectives:

1. To provide a chronological review of sweet pepper harvesting methods, from traditional manual practices to modern automated systems.
2. To examine recent advancements in mechanical and robotic harvesting technologies, with an emphasis on their operational principles, sensing mechanisms, and actuation strategies.
3. To analyze global adoption trends and deployment challenges of automated harvesting systems in both open-field and greenhouse environments.
4. To evaluate the economic and environmental implications of mechanized harvesting approaches in comparison to conventional methods.
5. To identify key limitations and propose future directions for improving harvesting efficiency, selectivity, and sustainability in capsicum production.

1.1. Systematic Review Framework

A systematic review framework was adopted to comprehensively analyze the evolution of sweet pepper (*Capsicum annuum*) harvesting from traditional manual methods to advanced mechanized and robotic systems. Relevant literature was collected from multiple scientific databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, covering the period from January 2023 to August 2024. The search utilized combinations of keywords such as *"Capsicum annuum"*, *"sweet pepper harvesting"*, *"manual harvesting"*, *"mechanized harvesting"*, *"robotic harvesting"*, and *"agricultural automation"*, linked through Boolean operators (AND, OR, NOT) to refine the queries. Publications were included if they discussed harvesting practices, mechanization, or automation specific to *Capsicum annuum*, or provided quantitative or historical insights into the evolution of horticultural machinery. Studies not in English or lacking methodological or technical details were excluded. The screened literature that met the inclusion criteria was then organized thematically and chronologically into four clusters: (i) traditional manual harvesting, (ii) early mechanization (1960–1990s), (iii) modern mechanical systems (2000–2015), and (iv) intelligent robotic harvesting (2016–present). This systematic methodology ensures that the review's historical synthesis and technological comparisons are based on transparent, reproducible, and comprehensive data collection.

2. HISTORICAL CONTEXT OF SWEET PEPPER CULTIVATION AND HARVESTING

2.1. Origins and Early Dissemination of Capsicum Annuum

Capsicum annuum, which includes sweet peppers, bell peppers, and chili peppers, has been cultivated by humans for a long time. Archaeological evidence suggests that it was domesticated as early as 7000 BCE. The Aztecs, Mayans, and Incas were some of the first societies to cultivate different types of Capsicum in their agriculture. They used them for cooking, medicine, and religious purposes. The Incas even used peppers as a form of currency, which demonstrates their significance in society [11].

Early European explorers called Capsicum "pepper" because it smelled like black pepper (*Piper nigrum*), even though the two plants are not related botanically. The name for the genus Capsicum probably comes from the Greek word *kapto*, which means "to bite," and it refers to the fruit's sharp taste. People in different parts of the world call the non-pungent types of Capsicum annuum by different names. In North America and Europe, "sweet pepper" is the most common name, while "bell pepper" is the most common name for the lobed, bell-shaped fruit. In India and Australia, on the other hand, the word "capsicum" is often used in both cooking and farming. In Hindi and Bengali, two Indian languages, the fruit is also called *Shimla mirch*, which means "Shimla chili." This name comes from the hill station Shimla, where large-scale commercial cultivation was first popularized.

The Columbian Exchange was when Capsicum annuum started to spread around the world. Christopher Columbus brought the crop to Europe in the late 15th century. It quickly spread from Spain to Africa, the Middle East, and the Indian subcontinent, thanks to good weather and established spice trade routes. By the 1st century CE, pepper had become an important part of the Roman spice trade, with Alexandria serving as a major hub for these trades. The socio-economic significance of pepper continued into the medieval era, as demonstrated by its utilization in financial dealings, including rents, dowries, and royal tributes. Historical records show that King Ethelred II of England asked German spice merchants for pepper as part of a deal [12].

2.2. Ancient and Traditional Cultivation Practices

The early cultivation of Capsicum annuum was profoundly influenced by the adaptation of agronomic practices to various climatic and edaphic conditions. Traditional farmers knew that the crop needed full sun and loose, well-drained soil that could hold some moisture. Historical horticultural records show that seeds were usually planted indoors in pots 8 to 10 weeks before the last frost. After that, the seedlings went through a hardening-off phase in which they got used to being outside before being moved outside. This method is used all over the world, and it is very similar to the way seedlings are grown in nurseries in parts of South Asia and Latin America [1, 13].

Adding things like well-aged farmyard manure and compost to the soil was an important part of growing sweet peppers the old-fashioned way. These things were usually added to a depth of 20–25 cm to make nutrients more available and improve the soil's structure. Water management was also very important. Traditional farmers stressed deep, infrequent watering (about 2.5–5 cm per week) to encourage strong root growth and keep diseases like blossom-end rot from spreading due to water stress or calcium deficiency [14]. Farmers often used their hands and eyes to check the moisture level in the soil instead of tools. This demonstrates that they possessed a deep understanding of agroecology, which had been passed down through generations.

A common method called "pinching," which involved removing apical meristems when plants were about 20 cm tall, was used to encourage lateral branching. This made the plants look bushier and may have led to more sites for fruit to grow [15]. Raised beds were common in many places, such as parts of the Indian subcontinent, because they helped with drainage, warmed the soil early, and kept weeds in check. Using organic materials like straw or dried leaves as mulch helped retain soil moisture and prevent weed growth.

In the Indian subcontinent, especially in Maharashtra, Karnataka, Himachal Pradesh, and Tamil Nadu, traditional ways of growing sweet peppers changed to work in both open fields and protected areas. Under subtropical and temperate climates, crops were often grown in the summer and rabi seasons. Indigenous knowledge systems stressed planting crops like tomatoes (*Solanum lycopersicum*) and brinjals (*Solanum melongena*) next to each other to make the best use of land and keep pests from getting into the crops [16]. Even though hybrid varieties are now the most common, smallholder farmers in hilly and semi-arid areas still grow several indigenous landraces that have unique fruit shapes and are resistant to different climates. Additionally, traditional methods such as using cow dung slurry, neem-based biopesticides, and rotating crops with legumes are still employed to maintain soil fertility and control pests [17].

2.3. Evolution of Manual Harvesting Techniques and Tools (Pre-20th Century to Present)

The manual harvesting of sweet peppers has been a key part of traditional farming for a long time. It has changed slowly from simple methods to more advanced ones to meet the needs of large-scale production and the limits of manual labor. In the past, people harvested fruit by pulling it directly from the plant (Figure 4**)**. This method was simple and common, but it had some agronomic and logistical problems. When people snapped the stem by hand, it often caused physical damage to the plant, such as bruising the fruit or breaking off immature fruits. It also often caused structural damage to the plant itself because the branches were too weak to hold up. Additionally, dense canopy cover and tired workers often meant that parts of the mature yield were missed or skipped on purpose, especially in large-scale field operations [18].

Figure 4. Direct fruit-pull harvesting of capsicum.

To address the challenges of manually detaching fruit, conventional growers gradually integrated specialized hand tools, particularly pruning shears and clippers (Figure 5), which facilitated accurate severance of the peduncle while reducing mechanical damage to both fruit and plant tissues. In some cases, a small stem stub was intentionally left on the harvested fruit to make it easier to sort, handle, and dry in the air, especially in production systems that used sun curing or long-term storage [19]. At the same time, multi-functional tools like the *hori hori* knife (Figure 6a) and sickles (Figure 6b) were used to harvest smaller-fruited plants. Machetes (Figure 6c), which were mainly used to clear vegetation, were sometimes used for high-volume harvesting in densely planted plots [19]. Furthermore, for pungent capsicum varieties with high levels of capsaicinoids, wearing protective gloves became an important safety measure to avoid skin irritation. This is still recommended in today's harvesting guidelines [19].

Figure 5. Harvesting capsicum using pruning shears or clippers.

a) Cutting action with a hori hori knife

b) Severing stems with a sickle

c) Clearing dense foliage with a machete.

Figure 6. Harvesting actions using multi-purpose hand tools applicable to capsicum cultivation.

Even though mechanized harvesting systems are becoming more popular around the world, many areas that grow sweet peppers still rely on manual labor because it has some unique benefits. Human pickers can selectively harvest by telling the difference between fruits that are at different stages of ripeness, avoiding fruits that are mechanically damaged or diseased, and moving through plants with complicated structures. However, this method has some significant problems. Fruit quality is inconsistent because harvesters make different decisions and become fatigued, which means that fruits are sometimes picked too early or too late, resulting in fruits that do not meet post-harvest grading standards [20]. Additionally, the inefficiencies of manual collection, such as having to go through the same field multiple times and relying on mobile bins, create logistical challenges that often lead to lower yields and increased operating costs [21].

From a health and safety perspective, manual harvesting exposes workers to ergonomic stress and prolonged physical activity. Workers frequently report chronic musculoskeletal disorders affecting the lower back, knees, and shoulders due to repetitive bending, squatting, and lifting [22]. Additionally, the repeated handling of capsaicin-rich varieties without proper protective measures may cause ocular, dermal, and respiratory discomfort [19]. In certain cases, inadequate harvesting techniques, such as bruising or stem damage, facilitate microbial ingress, thereby elevating the risk of post-harvest fungal or bacterial infection [23]. Hygiene-related issues, such as the unintentional introduction of foreign substances and cross-contamination via shared, unsanitized tools, exacerbate this situation [21].

The pepper cultivation industry is very uncertain economically because it still relies heavily on manual labor, especially in areas where there are fewer workers and wages are increasing. These problems have increased interest in mechanized and robotic options, as they promise accuracy, dependability, and the ability to grow. In this context, researchers are actively exploring intelligent harvesting systems as a way to reduce reliance on workers, improve product quality, and ensure that sweet pepper production can continue sustainably [21].

3. MATERIALS AND METHODS

3.1. The Dawn of Mechanization: Early Developments (Mid-20th Century to 1990s)

3.1.1. Initial Research and Experimental Harvesters

The concept of automatic harvesting systems for crops in agriculture began to develop as early as 1968. This marked the beginning of a new era of mechanization in horticulture [24]. During this period, sweet pepper (*Capsicum annuum*) became a key crop for testing automation due to its economic importance and the labor-intensive nature of its harvest. In 1967, California experienced one of the first commercial applications of mechanical harvesting specifically for Capsicum, primarily for drying purposes [25]. This important event led to more research around the world, which resulted in the creation of more than 200 different mechanical harvesting machines for sweet peppers by 1995. Patents protected these new ideas, demonstrating how quickly agricultural engineering technology has advanced in the years since [25].

Experimental harvesters were tested in a variety of agro-ecological settings in countries including Australia, Bulgaria, Canada, Hungary, Israel, Italy, Spain, the United States, and the former USSR. Each one used different mechanical principles that were suited to the crops and fields in that area [25]. In the 1970s, experimental pepper harvesters started to use modular systems that combined picking heads with units for collecting, cleaning, and moving fruit.

The goal was to increase throughput while reducing fruit damage [26]. One important example from this time is the harvester that Ernest Riggs made for Cal-Compack Foods. It was in use by 1976 and served as a model for early mechanical pepper harvesting efforts [26]. These early systems were not very effective at being selective or adapting to changes in plants, but they laid the groundwork for future improvements in robotic and precision harvesting technologies.

3.1.2. Key Mechanical Principles Explored and Early Adoption

During the second half of the 20th century, the mechanization of sweet pepper harvesting changed significantly as various mechanical ideas were experimented with. Some of the initial innovations included different methods to detach the fruit, such as spring-tine pickers, rubber-finger rakes, open double-helix rollers, and forced balanced shakers with stem-cutting heads [26]. The primary objective of these systems was to mimic manual harvesting while minimizing damage to the plants. The open double-helix and rubber-finger rake mechanisms gained popularity in the southwestern United States, particularly in California and New Mexico, during the 1970s and 1980s. Additionally, forced-balanced shakers were employed in regions where plant architecture and row spacing facilitated vibration-based harvesting techniques [26].

At the same time, complementary systems for cleaning and sorting after harvest were created to make operations more efficient. Air grading systems, counter-rotating rollers, star wheels, reflexed rubber-finger shakers, combing belts, and conveyor belts for manual or semi-automated sorting were some of the most important components [26]. These systems aimed to sort out fruit suitable for sale from trash, small pods, or peppers damaged by machines. It was particularly notable to observe shaker systems used in bell pepper harvesting trials in Florida as early as 1973. These shaker harvesters could completely detach the fruit, demonstrating nearly 100% effectiveness in fruit removal. However, they also caused significant damage, with up to 20% of harvested peppers bruised or injured by the machinery [21]. Due to the high damage rates, these systems were not suitable for one-pass harvests of unknown Capsicum varieties, which often require harvesting at different maturity stages. This limitation prompted further innovation, such as the development of combing mechanisms capable of moving through dense canopies to pick ripe fruit without causing excessive damage [21]. Table 2 shows the main events in the development of mechanical pepper harvesting, such as the first commercial harvest in 1967, the idea of automated harvesting in 1968, and the deployment of Ernest Riggs' pepper harvester in 1976 [24-26]. The table also shows how public-sector research agencies became increasingly involved initially, peaking around 1980, and then gradually lost interest by 1990 [25]. In the early 1990s, interest in mechanization increased again because processing industries exerted more pressure on it, and there was a shortage of workers. By 1995, these efforts resulted in the development of more than 200 mechanical harvesting machines worldwide, with 14 patents specifically related to sweet pepper mechanization [25]. Figure 7 shows different design configurations of mechanical pepper harvesters.

Table 2. Key milestones in sweet pepper harvesting mechanization.

Year	Event/Development	Description/Significance	Relevant Snippet ID(s)
1967	First commercial mechanical harvest	Bell peppers are mechanically harvested for dehydration in California.	Marshall [25]
1968	Concept of automatic harvesting proposed	Laid the theoretical groundwork for future robotic systems.	Li, et al. [24]
1970s	Experimental Chile harvesters developed	Integrated picking heads with collecting, cleaning, and transporting components.	Wall, et al. [26]
1973	Shaker harvesters explored in Florida	Showed 100% fruit removal but 20% damage, not practical for a once-over harvest of indeterminate plants.	Funk and Marshall [21]
1976	Ernest Riggs' pepper harvester used	A specific early mechanical harvester was deployed for Cal-Compack Foods.	Wall, et al. [26]
1980	Peak of research agency involvement	10 non-profit university, state, and federal agencies are experimenting with mechanization.	Marshall [25]
1980s	Testing of diverse picking mechanisms	Included spring-tines, rubber-finger rakes, open double-helixes, and forced balanced shakers.	Wall, et al. [26]
1990	Decline in research agency involvement	No non-profit research agencies are experimenting with mechanization.	Marshall [25]
Early 1990s	Renewed industry interest	Processing and manufacturing industries have renewed interest in mechanization.	Marshall [25]
1995	Global machine development milestone	Over 200 machines built worldwide, 14 patents issued for mechanical harvesters.	Marshall [25]

a) Peter Piper pepper harvester [26]

b) Massey jalapeño harvester [21]

c) Pik Rite pepper harvester [21]

d) Rodriguez jalapeño harvester [21]

e) Yung-Etgar/Oxbo pepper harvester [21]

Figure 7. Examples of mechanical capsicum harvesters.

3.1.3. Challenges and Fluctuations in Mechanization Interest

Early mechanical harvesting systems for Capsicum annuum were highly innovative, but the path to widespread adoption was neither straightforward nor easy in the short term. Despite significant investments in research and development during the 1970s and early 1980s, interest in mechanized pepper harvesting declined sharply by the end of that decade. The number of non-profit research institutions involved in mechanical pepper harvesting, such as universities, state, and federal agencies, decreased from 10 in 1980 to none by 1990 [25]. This retreat represented a setback for these institutions and indicated a loss of confidence in the technology's immediate effectiveness. During this period, the area of mechanically harvested sweet peppers did not exceed 400 hectares, demonstrating the limited practical application of the technology [25].

The stagnation in adoption was largely driven by persistent technical challenges. Among the most prominent were.

(a) The inability to minimize fruit drop during mechanical detachment.

(b) Insufficient removal of foreign material (e.g., leaves, stems, and dirt).

(c) Most critically, the lack of an effective *destemming* mechanism [21].

For processing and fresh-market purposes, destemming, the clean separation of the fruit from its pedicel, is very important for getting the fruit ready for sale. Because this problem wasn't fixed, even though mechanical picking made field work easier, a lot of manual work was still needed during post-harvest processing. The labor burden didn't go down; it just moved, which made the economic case for switching from manual to mechanical systems less strong [21].

This trajectory shows a cyclical pattern in the mechanization of pepper harvesting, with technical and economic limits that slow down enthusiasm and innovation from time to time. Figure 8 shows the rise, fall, and eventual return of mechanization efforts in response to both market forces and technological readiness over time. The first growth in the 1960s and 1970s was mostly due to rising labor costs, especially in the southwestern US [26]. In this case, mechanization was a planned way to deal with rising costs of doing business. However, this first wave of new ideas was held back by technologies that weren't fully developed and performance that wasn't always reliable.

Figure 8. Mechanization roadmap for capsicum harvesting.

Although various mechanical principles were attempted, such as spring-tine, rubber-finger mechanisms, and forced-balanced shakers, these systems did not consistently meet the quality standards required for fruit destined for fresh markets [21, 26]. The issues of bruising, splitting, or incomplete harvesting resulting from these methods rendered them less cost-effective compared to manual labor. The problem was exacerbated by the fact that mechanically damaged fruit was often rejected in the market, especially when appearance was a critical factor. In many cases, mechanized solutions proved more suitable for dehydrated or processed products, which can tolerate larger surface flaws.

The inability to demonstrate immediate commercial utility led to a withdrawal of research support by 1990 [25], which is part of a larger trend of research institutions reallocating resources to areas with better returns on investment. However, in the early 1990s, renewed interest from the processing and manufacturing industries marked a turning point [25]. Several factors contributed to this resurgence: a growing shortage of workers, rising wage pressures, and incremental improvements in sensor-based and selective harvesting technologies. Additionally, niche applications such as dehydration, where surface damage is less critical, became more feasible to address with automation and machine technology.

This case demonstrates that agricultural mechanization is not a straightforward progression, but a dynamic process influenced by the intricate interaction of technological capability, market expectations, and socio-economic factors. Fundamental challenges, especially destemming and damage mitigation, remain pivotal in the modern era and continue to guide the research agenda for next-generation harvesting systems. To make sweet pepper production more sustainable, it will be very important to find a solution to these problems.

4. RESULTS

4.1. Current Global Harvesting Landscape: Manual vs. Mechanical Approaches

4.1.1. Prevalence of Manual Harvesting for Fresh Market Peppers

Manual harvesting is still the most common method used to cultivate peppers worldwide, particularly in businesses that sell fresh produce. This approach, which relies heavily on handpicking, is deeply embedded in agricultural systems because it preserves fruit quality and integrity. When harvesting bell peppers for fresh consumption, workers typically make three to four passes across the same field over a period of four to six weeks to collect fruits that have reached the appropriate ripening stage and color [27]. This staggered harvesting method is necessary because not all peppers on a single plant ripen simultaneously.

Growers who want to sell their crops fresh stress the importance of visual perfection and no physical damage, which is why manual harvesting is so effective [27, 28]. Workers can use their sense of sight and touch to avoid bruises, punctures, and other injuries. This process also allows for quality checks in the field, since harvesting and initial sorting or packing often occur simultaneously [29]. So, when peppers are picked by hand, only those that are ready for the market are picked, and those that aren't ripe or are damaged are left for later passes or thrown away. In the US, most peppers are picked by hand, including New Mexico-type green chiles, jalapeños, and serranos, which are mostly eaten when they are still green. There are two main reasons for this: (i) green fruits are more likely to sustain visible damage that the market won't accept, and (ii) a stronger detachment force is needed, which makes manual intervention more reliable [30].

However, manual harvesting has important economic and ergonomic problems, even though it has some quality-related benefits. It takes a lot of work, costing up to 20–50% of total production costs, and requires about 954 hours of work per hectare. This makes it less and less sustainable in areas where there are not enough farm workers [31]. Health problems such as musculoskeletal strain and skin and respiratory irritation caused by capsaicin make it less likely to last long-term [22]. These concerns are becoming more significant as the scale of production increases, and more people relocate to cities, making it more difficult to find seasonal farm workers.

Table 3 shows a side-by-side comparison of the pros and cons of manual and mechanical harvesting methods. As shown, manual harvesting is better at being selective and maintaining quality, but it is much worse at being efficient, completing tasks quickly, and being cost-effective. This indicates a growing need for effective automation strategies.

Table 3. Comparison of manual vs. mechanical harvesting methods for sweet peppers.

Characteristic	Manual harvesting	Mechanical harvesting	Relevant literature(s)
Primary use	Fresh market, selective picking for quality.	Processing, large-scale operations, single-pass harvest.	Western Institute for Food Safety and Security [27]
Selectivity	High (Multiple passes, fruit selected by ripeness/Color).	Low (Once-over harvest, non-selective).	Western Institute for Food Safety and Security [27]
Fruit quality	High (Minimal damage, visually perfect).	Variable (Higher potential for damage, foreign matter).	Austral Falcon [28]
Speed/Throughput	Slow, labor-intensive.	High capacity (e.g., 20,000 lbs/hr for Pik Rite).	Austral Falcon [28]
Labor requirement	High (20-50% of production costs, 954 h/ha).	Low (Significant reduction in labor utilization).	Song, et al. [31]
Cost per hectare	High (e.g., CNY 9000/ha).	Low (e.g., CNY 1500/ha, 1/6th of manual).	Han, et al. [32]
Damage rate	Low (if done carefully).	Higher potential (e.g., 2.3-3.87% reported).	Hill, et al. [30]
Destemming	Typically removed by hand during picking.	Often left on fruit, requiring post-harvest processing.	Batiha, et al. [6]
Suitability for cultivars	Flexible (Adapts to diverse plant habits).	Requires specific plant architecture (Upright, narrow angles, uniform maturity).	Funk and Marshall [21]
Adaptability to terrain	High (Operates on uneven terrain).	Limited (Less efficient on uneven terrain).	Austral Falcon [28]
Health risks	Musculoskeletal issues, capsaicin irritation.	Reduced direct contact risks.	Kang, et al. [22]

4.1.2. Mechanized Harvesting for Processing and Large-Scale Operations

On the other hand, mechanical harvesting is now the most efficient method for growing large quantities of peppers intended for processing, such as making sauces, powders, or dehydrating them, where appearance is less important [27]. Most of the time, mechanical harvesters are used in a non-selective, single-pass manner when most of the fruits on a plant are fully mature. This approach is especially common for red chili peppers and paprika varieties, which are only partially dried on the plant before being ground into powder [28].

Modern mechanical harvesting systems are highly interconnected and capable of performing multiple tasks simultaneously. They can pick fruit, move it, sort it, separate it, and place it in bins. This integration enhances operational efficiency over large land areas [32]. Some systems, such as the Pik Rite harvester, can process up to 20,000 pounds per hour, representing a significant productivity increase compared to manual labor [28].

The benefits are significant for the economy. For example, in China, mechanical harvesting costs about CNY 1500 per hectare, which is six times less than the CNY 9000 per hectare that manual harvesting costs [32]. Additionally, mechanization has been shown to reduce labor costs by 51% and total production costs by 38%, making it a more efficient option for commercial farming that aims to grow and save money [31]. But mechanization does have its problems. Damage rates are still quite high, ranging from 2.3% to 3.87% [30]. Additionally, destemming is often incomplete, which necessitates additional steps after harvest [6]. Also, mechanical systems require a certain level of uniformity in the architecture of the plants (for example, upright stems, narrow branching angles, and synchronized fruit maturity), which makes them less adaptable to different cultivars and field conditions [21]. In short, manual harvesting is still the most common way to get fresh fruit to market because it is more accurate and produces better fruit. However, mechanical harvesting is a clear way to make labor more efficient and scalable, especially for crops that will be processed in factories.

4.1.3. Geographical Distribution of Harvesting Methods

There are many different ways to harvest sweet peppers (*Capsicum annuum*) around the world. Some are traditional manual labor, some are semi-mechanized, and some are fully automated. Regional farming methods, how ready the technology is, how many workers are available, and the market (fresh vs. processed produce) all play a significant role in this diversity. A thorough analysis of geographically diverse harvesting practices reveals how local conditions and economic factors affect the implementation of advanced mechanization.

4.1.3.1. Asia – Technological Emergence with Manual Dependence

China, which produced about 46% of the world's bell peppers in 2020, is moving toward automation in large-scale operations [20]. This includes smart farming systems, smart machines for harvesting, and AI-powered sorting and packaging lines. Even with these improvements, manual harvesting remains common, especially on smallholder farms in central and southern provinces and in chili pepper farming [32]. In regions like Xinjiang, where peppers are cultivated over large areas, large machines are used for harvesting. Nonetheless, manual labor continues to be vital for tasks such as grading and handling that need to be performed before and after harvest [32].

4.1.3.2. North America – Mixed Approaches Driven by Market Type

Mexico, which grows a large quantity of bell peppers and exports many to the US, employs a variety of cultivation methods. Industrial-scale farms are gradually adopting mechanized systems, but hand-picking remains the most common method in regions with small landholdings [20]. In the US, efforts to mechanize pepper harvesting began in the 1960s and advanced significantly during the 1990s, primarily for peppers intended for drying or processing [24]. However, for fresh-market produce, especially green chile peppers, manual harvesting is still the norm because the fruit is sensitive to bruising and selective picking requires a lot of accuracy [30]. This dual-mode harvesting strategy demonstrates how labor costs, maintaining fruit quality, and investing in automation are often conflicting priorities.

4.1.3.3. Europe – Greenhouse Adoption and Mechanization Pressure

European countries are feeling increased pressure to mechanize due to rising labor costs and a shortage of workers during certain times of the year. This has resulted in higher production costs and less stable supply, leading to increased import rates and fluctuating prices [33]. High-tech greenhouses and other protected cultivation systems are very popular in countries like the Netherlands and Belgium. In these controlled environments, it is easier to automate harvesting with conveyor-based harvesting arms and vision-guided picking systems [1]. However, full autonomy in harvesting is still limited because plants need to be handled carefully and have different structures.

4.1.3.4. Asia-Pacific and Middle East – Manual Labor Transitioning to Mechanization

In South Korea, the area used to grow peppers is increasing, but the number of workers in agriculture is aging and decreasing. Manual harvesting remains the most common method, but demographic and economic pressures are driving a national shift toward mechanized solutions [31]. Simultaneously, Israel has demonstrated a long-term interest in researching mechanical harvesting technologies. Research institutions and agro-tech companies in Israel have developed several prototypes aimed at reducing reliance on manual labor and enhancing operational efficiency, particularly for crops grown in row-based systems and protected environments [32].

This analysis, based on geography, shows that even though full automation is possible with technology, it is very context-dependent. Crop type, intended use, local labor market conditions, farm size, and economic viability are all important factors that affect how crops are harvested. These factors continue to influence the speed and type of mechanization in different parts of the world.

4.1.4. The Indian Context: Traditional Practices and Emerging Mechanization

India is a major producer of Capsicum annuum, especially dry chili peppers. It is also a significant player in the agricultural economy of Asia. Recent statistics show that India was one of the top producers of chili peppers, both in terms of volume and area farmed [34]. The Malabar Coast in Kerala, which was once known as the "*King of Spices*," is an important cultural and agricultural landmark for growing pepper [35]. In these traditional settings, manual harvesting techniques have been used for a long time, and they originate from the methods employed to cultivate black pepper. Workers, especially in hilly or plantation areas, often picked pepper by hand from tall vines that could grow to be 20 to 30 feet tall. They frequently had to use handmade bamboo ladders to do this. This method, though tried and true, required significant physical effort and posed risks to workers [35].

In general, the agricultural tools in India have remained quite simple. They typically include sickles, *hori hori* knives, and machetes [35]. These tools are useful for many tasks, such as pruning, harvesting, and weeding, but they are not very effective for modern sweet pepper harvesting, especially when time and space are limited [36]. As socio-economic conditions and agronomic needs change, this old system, which requires a lot of labor, is becoming increasingly problematic.

India has made significant progress in agricultural research and production volume, but the use of mechanized solutions in sweet pepper harvesting has not kept pace. The small and scattered nature of Indian landholdings makes mechanization very difficult. About 90% of Indian farmers work on plots smaller than 2 hectares [37]. This land structure makes it impossible to use large machines for business or financial reasons. Moreover, restricted access to capital, insufficient credit facilities, and the absence of organized training in contemporary mechanization methods establish systemic obstacles to technological adoption [37].

The problem of not having enough workers, especially during busy harvest times, exacerbates these issues. This is primarily because people are migrating from rural areas to cities in search of more stable or better-paying jobs [38]. Additionally, sweet peppers spoil quickly, necessitating rapid harvesting, which can result in significant losses if the proper infrastructure is not in place. These challenges are further intensified by poor access to cold chains, inefficient transportation systems, and insufficient storage capacity, highlighting the urgent need for modernization [38].

But the Indian farming industry is still moving toward mechanized and automated solutions, thanks to both need and new ideas. Mechanized methods are becoming more popular, especially for growing a lot of peppers for processing industries [39]. These advancements are enhanced by breeding initiatives aimed at creating pepper cultivars with favorable fruit abscission traits, thereby facilitating the viability of semi-automated and fully automated harvesting systems [40].

Along with improved genetics, new technologies are also emerging. One such innovation is the development of a static automated harvesting device that utilizes image processing algorithms and mechanical scissors to locate and pick pepper fruits directly from the ground. This reduces the need for workers to climb ladders, thereby decreasing physical stress [4, 35]. Although these prototypes are still in the early stages of development, they demonstrate the potential benefits of integrating computer vision and mechatronics in agricultural applications for plant cultivation.

Indian agritech companies like KisanKraft are a significant part of this change. These companies offer a wide range of affordable farm equipment, from seeders to harvesters. They receive help from government subsidies and strong after-sales service networks [41]. The fact that these machines are now available for sale, along with state-backed support programs, is gradually making it easier for small farmers and cooperative farms to adopt mechanized farming.

In short, traditional methods are still the most common way to pick sweet peppers in India, but the industry is at a very important turning point. Precision agriculture technologies, supportive policy frameworks, and localized innovation are all coming together to make mechanized harvesting more efficient, safer, and cost-effective. To make this change happen and make Indian horticulture more resilient in the future, it will be important to keep investing in research, capacity building, and infrastructure.

4.1.5. Factors Influencing Harvesting Method Selection

Choosing the best way to harvest capsicum (sweet pepper) is not just a matter of choosing between manual and mechanical methods; it is a complex decision-making process. It is a complicated trade-off that is affected by a changing mix of fruit quality, harvesting cost, labor availability, and market-specific needs. This is what we call the *Quality-Cost-Labor* paradigm. Because there are so many different types of capsicum, ways to grow them, and markets to sell it to, harvesting has to be done in a way that works for each situation. The "one-size-fits-all" rule does not always work.

For fresh market uses, the most important aspect is that the fruits look excellent and have minimal physical damage. This is because customers expect fruits that are perfect, with no bruises or signs of over-ripeness. Manual harvesting is more expensive and requires more effort, but it is superior at selecting specific fruits and handling delicate produce with care. This allows workers to check the ripeness of each fruit. This method is especially important for green capsicum, which is easily damaged and has very low market tolerance for flaws [28, 30, 42]. As a result, hand-picking remains the most common method for obtaining fresh-market-grade capsicum, especially in regions like India and Australia, where both export and domestic markets prioritize quality.

For capsicum grown for the processing industry, where the plants are turned into sauces, pastes, or frozen mixes, volume and cost-effectiveness are more important than appearance. Although this may cause a slight increase in bruising or peduncle detachment [27, 32], mechanical harvesting becomes a practical solution due to its higher throughput and significantly lower labor costs per hectare. During post-harvest processing, these minor damages can often be corrected during the cleaning, sorting, or blanching stages.

The increasing scarcity and cost of agricultural labor, especially during peak harvesting times, is a major problem that affects both market segments. Labor shortages are becoming a structural problem in many agricultural economies around the world, including India. This is forcing farmers to rethink how they do things by hand. This labor shortage has made it more appealing to invest in automation and mechanized solutions, even if that means changing the way crops are grown or accepting lower quality, especially for secondary markets [21].

This changing situation makes one important point clear: agricultural mechanization, especially when it comes to harvesting, needs to be tailored to the specific context. The most effective harvesting methods are not uniform across all regions; instead, they represent a dynamic balance influenced by regional labor economics, crop types, terrain, and consumer expectations. This has led to a co-evolutionary trend, where machine designs are being adapted to match the shape of capsicum, and breeding programs are working on developing cultivars with traits that facilitate mechanical harvesting, such as uniform maturity, reduced peduncle tenacity, fruit clustering, and easier stem detachment [21, 30]. Simultaneously, technologies for processing fruits post-harvest are being enhanced to better handle mechanically harvested produce. This integration enables system-level optimization throughout the entire production chain.

Several interdependent factors collectively influence the choice of harvesting method:

(a) Cultivar Characteristics: Different capsicum cultivars exhibit variability in maturity timing (synchronous vs. asynchronous), fruit size, moisture content, fruit shape, and stem strength, all of which influence harvestability. Breeding efforts are focused on developing varieties with traits that favor mechanization, such as reduced fruit detachment force, compact architecture, and minimal fruit breakage during harvest [21, 30].

(b) Market Orientation: The fresh produce market demands meticulous fruit selection with minimal visual defects, hence favoring manual methods. Conversely, processing markets that tolerate slight imperfections due to post-harvest handling lean toward mechanical harvesting, where cost and speed are prioritized [27, 29].

(c) Labor availability and economic constraints: Manual harvesting can constitute up to 20–50% of total production costs, depending on regional labor rates and availability [21, 30]. With labor becoming increasingly scarce and expensive in many parts of the world, the economic feasibility of mechanized harvesting becomes more attractive, particularly for large-scale operations.

(d) Plant Architecture and Agronomic Design: Capsicum plant architecture significantly impacts machine harvest efficiency. Desirable traits include upright growth, narrow branch angles, minimal basal branching, and high fruit set, which facilitate unobstructed machine access and reduce branch damage. Higher planting densities may also promote efficient mechanical harvesting by guiding fruit growth above the canopy [22, 26].

(e) Terrain and Environmental Conditions: The feasibility of mechanical harvesting is also strongly terrain-dependent. Sloped or uneven fields restrict harvester movement and compromise efficiency. On the other hand, greenhouse-grown capsicum, typically managed using indeterminate cultivars, presents both opportunities and challenges for automation, as the environment is more controlled but may require precision harvesting tools tailored for confined spaces and vertical growth structures [1, 28].

To sum up, choosing a harvesting method for capsicum is a dynamic decision based on how ready the technology is, how well it works with the crops, and how the market functions. It requires a systemic approach that combines breeding, engineering, labor economics, and market intelligence. This will help the capsicum industry make a long-term shift from manual to semi- or fully automated harvesting systems.

5. MODERN MECHANICAL HARVESTING TECHNOLOGIES

5.1. Overview of Commercial Harvester Types

Modern mechanical harvesters for sweet peppers are complex agro-engineered systems that automate a series of important tasks, such as dividing the crop, separating the fruit, collecting it, cleaning it, and moving it. These machines are designed to do more than just replicate the manual harvesting process; they also enhance efficiency, scalability, and cost-effectiveness. As noted in earlier studies [21, 32], these harvesters feature different picking mechanisms depending on the manufacturer and the intended use. Common mechanical modules include helical spiraltype, drum finger-type, long-rod comb-type, and belt-mounted comb finger-type mechanisms. Each mechanism has a unique structure aimed at minimizing fruit damage during separation.

In some models, the harvesting process involves cutting the whole plant at ground level and moving it to a forced balance shaker drum with tines or oscillating parts that shake the plant to extract the fruit [21]. This design increases throughput, especially in large operations intended for the processing industry. These harvesters often feature modular attachments for removing leaves, cleaning conveyors, and discharge elevators. This enhances the efficiency of moving the harvest from the field to the truck, reduces the need for manual labor, and ensures better operational continuity.

5.2. Operational Principles and Design Features

The Pik Rite Pepper Harvester and the Elad Etgar Bell Pepper Series 2000 are two examples of the best commercial pepper harvesting equipment. They both demonstrate different design philosophies aimed at increasing productivity and reducing fruit damage.

1. The Pik Rite Pepper Harvester is designed for high-throughput work, capable of processing approximately 20,000 pounds of bell peppers per hour. This significantly reduces labor costs [43]. Its flexible structure allows it to be used with various growing setups, such as raised beds, plastic mulch, and flat ground, making it suitable for a wide range of agricultural practices. The machine features a dual forced balance shaker system that effectively shakes the fruits loose without damaging the plants. Operators can choose between sickle bar or disc headers, enabling use in either single or twin-row configurations. A rear cleaning table and an 11-foot discharge elevator ensure smooth loading and minimal downtime during harvest. Optional upgrades, such as the Scott's Evolution Separator, facilitate easier separation and debris cleanup [32]. Figure 9 shows how mechanical harvesting works by demonstrating how the Pik Rite Pepper Harvester picks peppers.
2.

Figure 9. Capsicum harvesting using the Pik Rite pepper harvester.

3. On the other hand, the Elad Etgar Series 2000, which was made with Ardo (Belgium), Bourgoin (France), and Elad Etgar, has a new helix-based picking system with front-end parts that are better for gently picking all capsicum types, such as green, red, brown, and yellow [44]. This harvester focuses on getting a lot of work done with as little physical damage as possible. After the fruits are picked, they are sent to a built-in cleaning module, where leaves, stalks, and other debris are removed. The design is low-maintenance, reliable, and consistently produces high-quality fruit, making it the best choice for harvesting peppers in precision agriculture. Figure 10 shows how the Elad Etgar Series 2000 bell pepper harvester works to collect crops quickly and easily.
4.

Figure 10. Operation of the Elad Etgar Series 2000 bell pepper harvester.

The spring-finger roller type (Figure 11a) is another important mechanism. It has spring-loaded fingers that are mounted on a rotating drum. This system is housed in a steel frame and an upper cover. It is powered by a mechanical transmission and is designed to make things more efficient while lowering costs [45]. Biomimetic innovations, such as the pod-pepper-picking drum (Figure 11b), operate similarly. They utilize specially arranged snap fingers to imitate the natural picking process, which reduces ground drop losses and increases recovery rates [45].

a) Spring-finger roller-type mechanism. **b)** Pod-pepper-picking drum mechanism.

Figure 11. Representative mechanisms utilized in pepper harvesting.

5.3. Performance Metrics and Efficiency Improvements

The move toward mechanized pepper harvesting is primarily driven by the need to increase field productivity, reduce the reliance on manual labor, and sustain economic growth. Despite advancements, achieving optimal performance remains challenging due to trade-offs between damage rates, impurity levels, and harvesting losses. Performance evaluations, such as those conducted on crawler-type red cluster pepper harvesters, provide valuable insights into current capabilities and areas for improvement. These trials demonstrated a pure hourly productivity of 0.21 $ha{\cdot}h^{-1}$, an impurity rate of 26.7%, a damage rate of 2.3%, a loss rate of 6.1%, and a hanging rate of 4.2%. These results indicate significant progress in mechanical design but also highlight the need for further development to enhance efficiency and reduce undesirable outcomes [46].

Improving these results by optimizing operational parameters has shown significant promise. Adjustments to the drum's rotation speed, the machine's forward speed, and the spacing between the teeth can increase the picking rate from 89.73% to 95.13%, while also reducing the amount of fruit that breaks or is lost [46]. Field tests with a spring-finger roller picking header operating at 215 $r{\cdot}min^{-1}$ and traveling at 3.59 $km{\cdot}h^{-1}$ achieved an impressive picking rate of 98.47% and a breakage rate of only 3.87% [45].

Additionally, agronomic changes such as adjusting the distance between plants (for example, 40 cm spacing) have been shown to enhance harvesting performance by facilitating easier access for machines to the fruit and promoting a more uniform appearance [22]. Table 4 shows these numbers in more detail.

5.4. Persistent Challenges in Mechanical Harvesting

Despite technological advances, several persistent challenges continue to restrict the universal adoption of mechanical harvesting in sweet pepper production.

1. A primary concern is destemming, a process typically performed manually to meet fresh market standards. Mechanical harvesters tend to remove fruits without detaching stems, which adversely affects market acceptance and shifts the labor requirement to post-harvest facilities [6, 21]. Current breeding initiatives aim to develop low-detachment-force cultivars to facilitate stem-free mechanical picking [30].
2. Another limitation is foreign matter contamination, which remains problematic despite the integration of air grading systems, conveyors, and roller cleaners [26]. In high-speed harvesting scenarios, debris such as leaves, stems, and soil clumps often remain with the produce, requiring additional cleaning steps and increasing post-harvest processing costs.
3. Fruit damage is another critical concern, particularly for fresh market peppers, where appearance directly influences consumer preference. While machine designs have evolved to incorporate soft-touch components and improved gripping dynamics, bruising and breakage rates remain higher than manual harvesting. Understanding the mechanical properties of pepper fruits, tensile strength, shear resistance, and elastic limits, is essential for designing minimally invasive contact points and detachment mechanisms [47].
4. The biological trait of non-uniform maturity, common in indeterminate cultivars, further complicates mechanization, as once-over harvesting is unsuitable for plants that ripen progressively [21]. This often necessitates multiple harvesting passes or continued reliance on hand-picking for fresh consumption markets.
5. Finally, terrain variability and plant architecture present major engineering constraints. Most commercial harvesters perform optimally on flat, uniform fields, whereas many pepper-growing regions feature undulating topography or fragmented plots, limiting their applicability. Additionally, diverse plant architectures across cultivars require adaptable machinery with adjustable height, spacing, and flexibility, attributes that are expensive to integrate and difficult to generalize [21].

These ongoing challenges indicate that mechanized harvesting solutions must be embedded within a systems-wide framework. As emphasized in prior research, "no one harvest machine will be optimum" [13], highlighting the need for a co-evolutionary approach that simultaneously advances genetics, machinery, and agronomic practices.

1. First, breeding programs must be synchronized with mechanical harvesting needs, selecting for traits such as uniform maturity, reduced peduncle strength, upright growth, and minimal basal branching [21]. These traits enable smoother fruit detachment and reduce machine interference.
2. Second, farming practices must be adapted. Strategies such as optimizing plant density, ensuring proper weed control, and hilling soil around root bases can reduce lodging and support better machine operation [22, 26].
3. Third, post-harvest processing facilities must be redesigned to accommodate machine-harvested produce, which may include higher levels of foreign matter and stems. The deployment of advanced destemming systems, optical sorters, and automated cleaners is crucial for ensuring product quality while maintaining processing throughput [21].

Together, these adaptations form a holistic agricultural system, where crop biology, mechanization, and processing are co-engineered for synergy rather than retrofitted in isolation. This integrative approach is fundamental to the successful and sustainable mechanization of pepper harvesting in the future.

6. DISCUSSION

6.1. The Future of Harvesting: Robotics, Automation, and Artificial Intelligence

6.1.1. Emergence of Robotic Harvesting Systems

The introduction of robotic systems in recent years has changed the limits of agricultural automation, especially for crops that require significant labor, such as sweet peppers. Robotic harvesting is being explored as a strategic solution to address global issues like labor shortages, rising production costs, and the need for precise harvesting. The use of autonomous robotic platforms in protected cropping environments, such as greenhouses, could enable selective harvesting with less damage, and they could operate continuously. Despite decades of research, achieving consistent and commercially successful robotic harvesting of sweet peppers remains challenging due to occlusion, variations in crop shape, and the high selectivity required to maintain quality in the fresh market [48, 49].

The SWEEPER robot (Figure 12) is one of the most well-documented robotic systems designed for autonomous harvesting of sweet peppers in a greenhouse setting [48]. SWEEPER features a six degrees-of-freedom (6-DOF) industrial robotic arm (Fanuc LR Mate 200iD) equipped with a custom-made end-effector that combines a vibrating knife and a mechanism for catching fruit [50]. Its vision system utilizes an RGB-D camera and artificial lighting to detect and locate pepper fruits. The system employs algorithms based on color and shape segmentation, semantic segmentation, and edge detection to precisely identify the stem's position. The Qii-Drive Pepper AGV is a mobile platform that the robot uses for navigation. It can ascend and descend using a scissor lift and move autonomously on pipe rails or flat concrete surfaces [50].

Figure 12. SWEEPER robotic system for sweet pepper harvesting.

Field tests of SWEEPER in commercial greenhouses have shown mixed results. The time it takes to harvest a fruit is about 24 seconds, but in a lab, it can be reduced to 15 seconds [50]. However, its harvest success rate depended heavily on how the plants were set up. In optimized conditions, it could reach up to 61%, but in unmodified commercial setups, it only reached 18%. This demonstrates the importance of adapting cultivars and controlling the environment to maximize the efficiency of robotic harvesters [50].

The Harvey robotic system (Figure 13) is another important development. It was made specifically for picking sweet peppers in protected areas [49]. The 3D color vision system used by Harvey's perception pipeline can find the exact location of fruit based on a pre-trained digital model [51]. A deep convolutional neural network and 3D post-filtering work together to accurately segment the peduncle, which is necessary for finding the best cutting point [49]. The system has a suction-based gripping mechanism that keeps the fruit safe while it is being cut with a multi-tool.

A special decoupling mechanism separates the actions of gripping and cutting to make harvesting more successful [49]. In controlled settings, Harvey had a success rate of 76.5%, which shows that it was better than previous technologies [49]. This also supports the idea that robotic harvesting performance depends heavily on how well the crop design, environment, and machine learning capabilities work together.

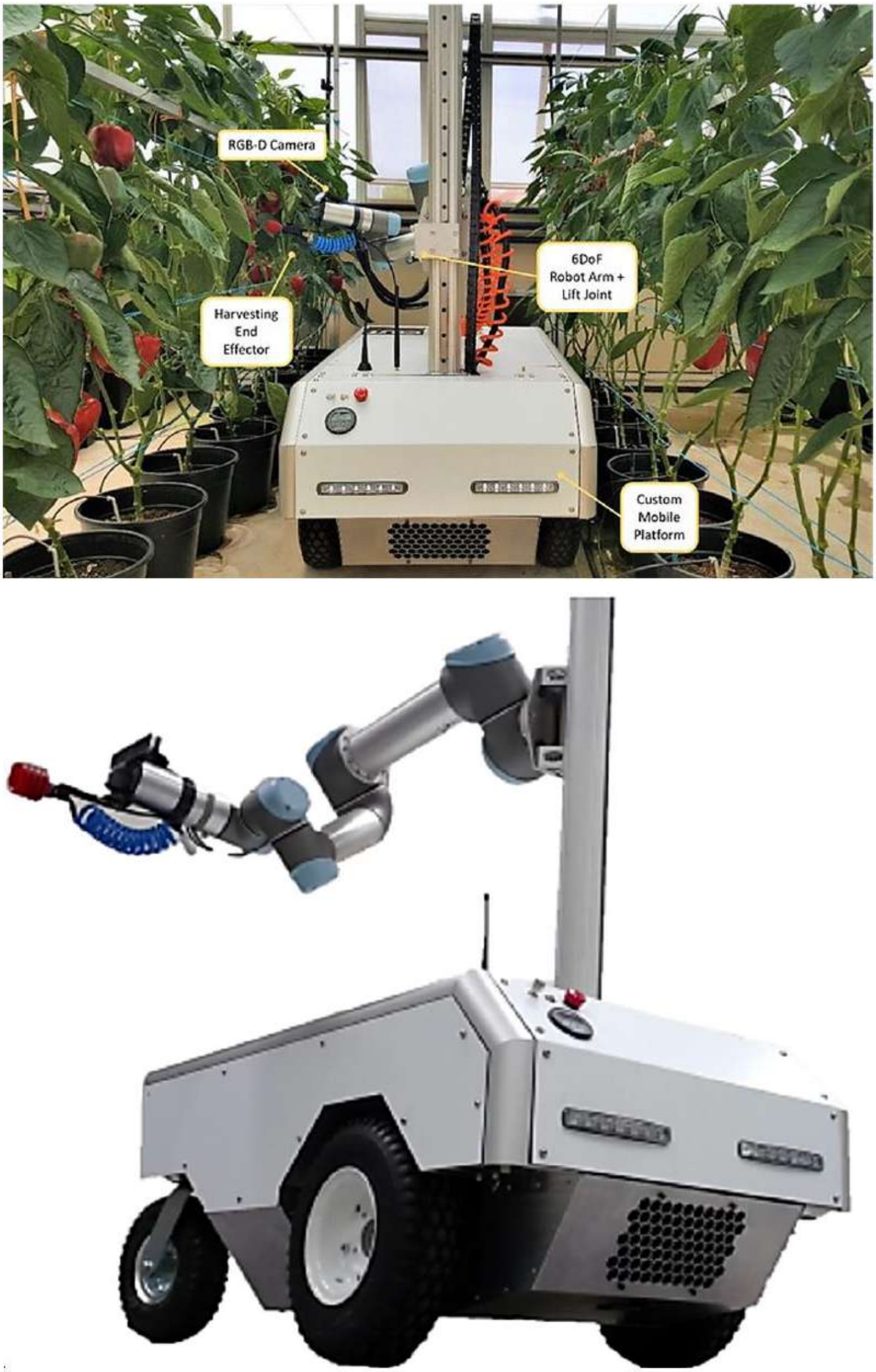


Figure 13. Harvey robot for sweet pepper harvesting.

Sweet peppers, characterized by their robust pericarp, uniform shape, and suitability for greenhouse cultivation, are increasingly regarded as an exemplary crop for the implementation of robotic harvesting technologies [51]. These case studies highlight the potential and existing constraints of robotic harvesting systems, especially in relation to their adaptability to unstructured environments and the necessity for optimized crop architecture.

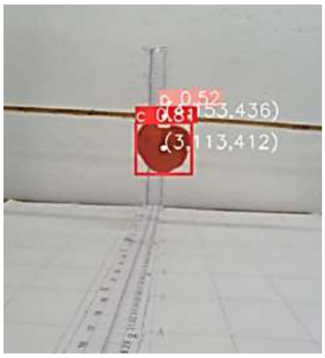
6.1.2. Key Components and Advanced Sensing Technologies

The effectiveness of robotic harvesting systems depends on the advancement of their sensory hardware and AI-based perception algorithms. Vision technologies, particularly RGB-D cameras such as the Fotonic F80 and Intel RealSense D455, are crucial to these systems because they provide essential depth and color data. These sensors are vital for accurate fruit localization and are resilient to fluctuations in greenhouse lighting [4, 50, 52]. In addition to regular web cameras, these sensors enable real-time visual feedback for tasks involving object manipulation.

Computer vision and deep learning algorithms are the main tools for finding and sorting fruits. Many people use object detection models like **YOLOv8** and **ViT** to find and sort sweet peppers in complicated scenes [4, 53]. Deep convolutional neural networks, such as Region Proposal Networks (RPNs), enable both object detection and classification in a single step, thereby increasing the speed and accuracy of robotic perception tasks [54]. To find the peduncle's position in relation to the fruit body, semantic segmentation and edge detection are used. This is important for precise detachment without damaging the fruit body [50] (Figure 14).

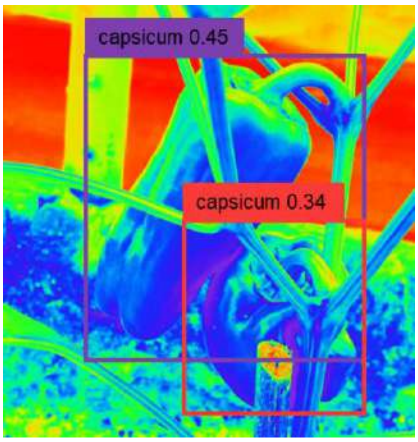
a) Capsicum detection [4]

b) Peduncle segmentation of capsicum [4]

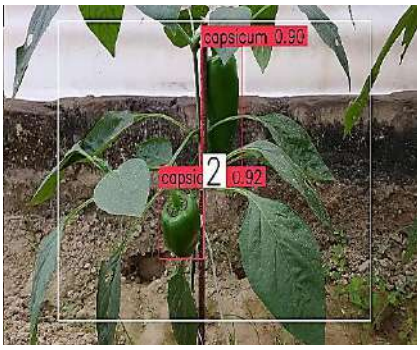


c) Peduncle localization of capsicum [4]

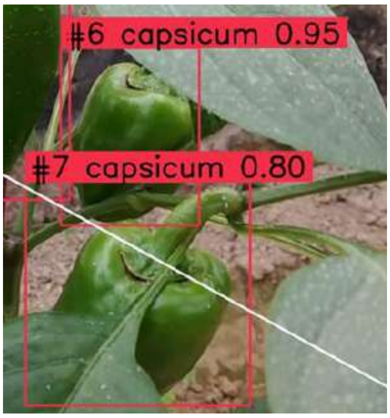
d) Peduncle segmentation in nighttime conditions



e) Capsicum detection in thermal imagery [52]



f) Frame-based capsicum counting [4]

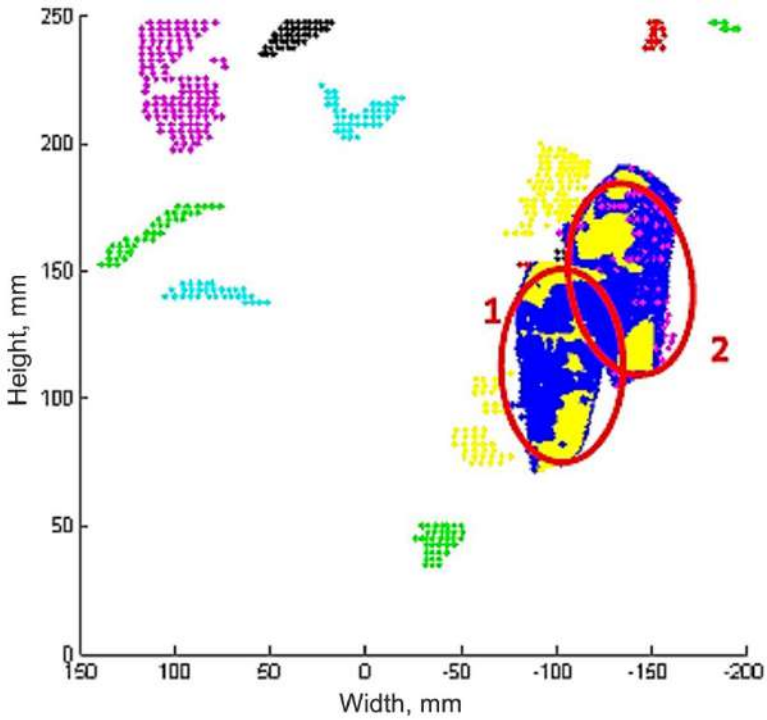


g) Capsicum counting via inclined-line crossing [4]

Figure 14. Computer vision–based tasks for automated capsicum harvesting.

LIDAR (Light Detection and Ranging) adds another level to fruit detection by creating detailed point clouds of plant surfaces used to model the shape, orientation, and position of fruit in space (Figure 15). These data sets help us determine the correct grasp pose more accurately and reduce the chance of harvest failure [55].

a) Experimental setup for LiDAR-based pose estimation



b) Point cloud acquisition and pattern matching.

Figure 15. LiDAR-based pose estimation of capsicum in a greenhouse [55].

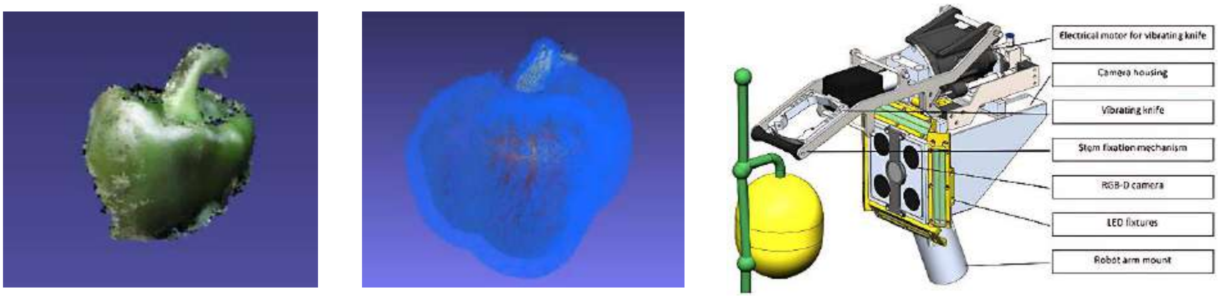
Tactile sensors become very important when visual data isn't sufficient, such as when leaves or overlapping fruits block the view. These sensors, which have sensitive contact tips, can detect when a stem is correctly positioned between cutter blades by measuring changes in resonant frequency. This allows them to distinguish stems from other plant tissues or leaves [55]. This multi-modal sensing strategy enhances the system's stability in real-world field conditions.

6.1.3. Operational Algorithms for Grasp Pose Estimation and Cutting

A set of algorithms that control how fruit interacts with robots, from getting close to detaching, is at the heart of robotic harvesting. Algorithms for grasp and cutting pose estimation look at the spatial arrangement of pepper fruits and peduncles to find the best way to approach, the best tool orientation, and the best grasp force. These calculations take into account overlapping fruits, blocked stems, and different plant shapes. They also include backup plans to avoid jamming or failing [24].

Visual servoing is an important part of these systems that ensures the end effector always maintains a stable visual reference of the target fruit while it is moving. This method allows for modifications based on real-time feedback, ensuring that cutting or grabbing is performed correctly even in environments that are constantly changing or only partially visible [50].

Figure 16 shows how the grasp pose estimation works with precise peduncle cutting to make harvesting more targeted and efficient.



a) 3D point cloud of capsicum [24] **b)** Surface normal visualization [24] **c)** End-effector cutting peduncle after pose detection [50]

Figure 16. Grasp pose estimation and peduncle cutting.

Motion planning software, such as the lazy PRM* planner and the TRAC-IK inverse kinematic solver, handles trajectory planning. These programs enable robotic arms to create precise paths that avoid obstacles. Designed to operate effectively in confined and cluttered environments typical of greenhouses, they ensure that the harvesting process proceeds smoothly and efficiently [50].

Thus, the rapid convergence of agricultural engineering, artificial intelligence, and robotics is demonstrated by improvements in robotic perception, end-effector design, sensor fusion, and algorithmic control. Although current systems still face challenges such as crop variability and environmental inconsistency, their ongoing development represents a significant step toward fully autonomous, intelligent harvesting systems for high-value horticultural crops like sweet peppers.

6.1.4. Performance of Robotic Harvesters and Comparison with Mechanical Harvesters

Even though vision-based robotic harvesting technologies have advanced significantly, there are still some performance issues that hinder the widespread use of autonomous systems in agricultural fields. The cycle time per fruit is one of the primary factors limiting the process. This impacts overall harvesting throughput and complicates the cultivation of high-density planting areas.

The SWEEPER robotic harvester, designed for greenhouses, had an average cycle time of 24 seconds per fruit when used in a commercial setting. Controlled laboratory experiments, on the other hand, showed that the cycle time could be reduced to 15 seconds per fruit, indicating potential for further hardware and algorithmic optimization through increased manipulator speed and improved crop positioning strategies [50].

Likewise, the harvest success rates for these systems vary significantly depending on crop conditions and occlusion levels.

In commercial greenhouses, the success rate for SWEEPER ranged from 18% to 61% [41]. The Harvey robot, on the other hand, used advanced 3D post-filtering and peduncle segmentation to achieve a success rate of up to 76.5% in modified experimental conditions [49].

Early prototypes of robotic harvesting, which were mostly made for research purposes, usually had success rates of about 66% and cycle times of about 33 seconds per fruit. This shows that there was a clear trade-off between how complicated the manipulation was, how well it handled occlusion, and how long it took to complete the task [50]. Recent advancements in 3D vision-based intelligent harvesting systems have yielded encouraging outcomes, with one system attaining recognition accuracies of 81.95% and 89.04% for occluded and non-occluded fruits, respectively, in addition to a harvest success rate of 86.33% and an average operational duration of 13.17 seconds per fruit [32]. These improvements demonstrate that robotic harvesters are approaching real-time efficiency as sensing technologies and decision-making algorithms improve.

But when compared to traditional mechanical harvesters, robotic systems still fall short in terms of overall productivity and durability. Table 4 shows a comparison of some mechanical pepper harvesters, including important performance metrics like picking rate, breakage rate, and loss rate. The spring-finger roller-type mechanical harvester, for instance, had a picking rate of 98.47% and a breakage rate of 3.87% at a roller speed of 215 rpm and a travel speed of 3.59 km/h [33].

The drum of the elastic tooth type harvester, when used under optimal conditions, had a picking rate of 95.13%, with only 2.66% breakage and 3.95% fruit loss [29].

Biomimetic pod-pepper picking drums are another efficient design. During field tests, they lost 7.85% of their ground drop, which demonstrates how biologically inspired mechanisms can influence performance [45]. In contrast, crawler-type mechanical harvesters designed for red cluster peppers had a pure hourly productivity of 0.21 $ha \cdot h^{-1}$, but they also exhibited an impurity rate of 26.7% and a loss rate of 6.1%, which may not be acceptable for yields suitable for export [46].

Robotic harvesters are better at accuracy and adaptability, especially in structured environments like greenhouses. However, mechanical harvesters are clearly better at raw throughput and efficiency in uniform field conditions.

Consequently, contemporary research initiatives ought to emphasize the mitigation of this performance disparity by concentrating on real-time perception in occluded environments, manipulator path optimization, and hardware-software co-design to enhance the harvest success rate and diminish the average cycle time per fruit.

Additionally, hybrid methodologies that combine mechanical principles with intelligent perception (for instance, smart grippers or semi-automated arms directed by vision models) may develop as a viable transitional solution towards complete autonomy.

The metrics in Table 4 are a standard for judging future robotic systems and show how important it is to design robotic harvesters that can optimize for more than one goal.

Table 4. Performance metrics of representative pepper harvesters.

Harvester Type/Mechanism	Key performance metric	Value/Range	Optimal Parameters (if applicable)	Relevant Snippet ID(s)
Crawler-type red cluster	Pure hourly productivity	0.21 ha·h⁻¹	v_m = 1.75 m·s⁻¹, n = 181 r·min⁻¹	Yang, et al. [46]
Crawler-type red cluster	Impurity rate	26.7%	v_m = 1.75 m·s⁻¹, n = 181 r·min⁻¹	Yang, et al. [46]
Crawler-type red cluster	Damage rate	2.3%	v_m = 1.75 m·s⁻¹, n = 181 r·min⁻¹	Yang, et al. [46]
Crawler-type red cluster	Loss rate	6.1%	v_m = 1.75 m·s⁻¹, n = 181 r·min⁻¹	Yang, et al. [46]
Crawler-type red cluster	Hanging rate	4.2%	v_m = 1.75 m·s⁻¹, n = 181 r·min⁻¹	Yang, et al. [46]
Drum of elastic tooth type (Optimized)	Picking Rate	95.13%	Drum rotational speed: 182 r/min, Operating speed: 0.42 m/s, Tooth spacing: 40 mm	Yang, et al. [46]
Drum of elastic tooth type (Optimized)	Breakage Rate	2.66%	Drum rotational speed: 182 r/min, Operating speed: 0.42 m/s, Tooth spacing: 40 mm	Yang, et al. [46]
Drum of elastic tooth type (Optimized)	Loss Rate	3.95%	Drum rotational speed: 182 r/min, Operating speed: 0.42 m/s, Tooth spacing: 40 mm	Yang, et al. [46]
Spring-finger roller type	Picking Rate	98.47%	Roller rotation speed: 215 r·min⁻¹, Travel speed: 3.59 km·h⁻¹	Kim, et al. [45]
Spring-finger roller type	Breakage Rate	3.87%	Roller rotation speed: 215 r·min⁻¹, Travel speed: 3.59 km·h⁻¹	Kim, et al. [45]
Biomimetic pod-pepper picking drum	Ground Drop Loss Rate (Field Test)	7.85%	Picking drum speed: 210 rpm, Pepper-feeding speed: 1100 mm·s⁻¹, Bending angle of spring tooth: 162°	Kim, et al. [45]
Robotic harvester (SWEEPER)	Average Cycle Time per Fruit	24 s (commercial); 15 s (lab)	Optimized crop conditions, higher manipulator speed	Arad, et al. [50]
Robotic harvester (SWEEPER)	Harvest Success Rate	18-61% (commercial conditions)	Best-fit crop conditions (modified) yield higher success	Arad, et al. [50]
Robotic harvester (Harvey)	Harvest Success Rate	76.5% (modified scenario)	Novel peduncle segmentation, 3D post-filtering	Lehnert, et al. [49]
Intelligent Harvesting System (3D Point Cloud)	Recognition Accuracy (Occluded)	81.95%	-	Han, et al. [32]
Intelligent Harvesting System (3D Point Cloud)	Recognition Accuracy (Non-occluded)	89.04%	-	Han, et al. [32]
Intelligent Harvesting System (3D Point Cloud)	Harvesting Success Rate	86.33%	-	Han, et al. [32]
Intelligent Harvesting System (3D Point Cloud)	Single Harvesting Operation Time	13.17 s	-	Han, et al. [32]

6.1.5. Limitations and Challenges in Robotic Harvesting Systems

Although robotic harvesting technologies have advanced significantly, certain challenges hinder their widespread adoption in commercial agriculture. One of the primary issues is the requirement for "best-fit crop conditions," which often necessitates pre-harvest preparations. These preparations include selectively trimming leaves that obstruct the view and strategically thinning fruit clusters to facilitate robot access and visibility [50]. Such modifications are generally unnecessary during manual harvesting, leading to additional labor and costs, which somewhat offset the advantages of automation.

Furthermore, the precise identification of peduncles in three-dimensional space continues to pose a considerable technical challenge. This is especially difficult for sweet pepper types that have curved or uneven peduncles, or when the color of the peduncle is the same as the fruit body or the leaves around it [24]. These situations confuse visual perception algorithms, even the most advanced deep learning architectures, which means that more research is needed on multi-sensor fusion and robust perception models.

The shift from traditional mechanical harvesters to smart robotic systems represents more than just a technological advancement; it signifies a fundamental change in agricultural practices toward cognitive automation. For many years, traditional mechanical systems have faced issues with non-selective harvesting, which often results in fruit damage, incomplete harvesting, and destemming problems that compromise fruit quality after harvest [21]. Robotic systems, however, utilize precision actuators and adaptive end-effectors capable of gripping and cutting with minimal damage to the fruit [41]. Real-time feedback loops made possible by visual, tactile, and force sensors that mimic human dexterity make these systems even better.

One of the best aspects of modern robotic harvesters is their use of advanced sensors such as RGB-D cameras, LIDAR, and tactile feedback systems. When combined with deep learning-based AI models like YOLOv8, these sensors can be highly selective and interpret the context in a manner previously achievable only by skilled human workers [24]. This capability allows robotic systems to distinguish between ripe and unripe fruit, prevent damage to adjacent crops, and adapt dynamically to environmental fluctuations, essential prerequisites for harvesting fresh market produce.

Additionally, the emphasis on utilizing robotic harvesters in greenhouse settings is a deliberate strategic design choice. Controlled environments naturally make lighting, background clutter, and occlusions less unpredictable. These are significant challenges for perception systems in unstructured outdoor fields [24, 48]. This makes detection and actuation algorithms more reliable, which facilitates smoother harvesting cycles. Furthermore, greenhouses often feature vertical farming structures and straight rows of crops, which are easier for robots to navigate and work within. All of these benefits make greenhouse farming an ideal setting to test robotic harvesting technologies on a large scale for the first time [56].

The integration of this technology has effects that go beyond just automating physical tasks. Robotic systems now allow for real-time feedback loops for post-harvest quality assessment, yield estimation, and harvest planning through data-driven insights. The use of computer vision and machine learning changes harvesting into an information-centric process, where sensor-generated data can be stored and analyzed to improve the process over time [57]. This not only makes the process more efficient and less wasteful, but it also fits with the "smart farming" model that is the basis of modern precision agriculture [58].

In the end, this evolution suggests a future in which smart robotic harvesters are closely linked to crop genetics, farming methods, and systems for controlling the environment. This kind of integration will probably change the roles of human workers from picking things up by hand to supervising and making decisions. This will help address global concerns about labor shortages, food safety, and product quality consistency [48]. However, for this vision to become a reality in business, significant work is needed to improve robots' ability to see in crowded or obstructed areas, handle deformable crops effectively, and harvest crops quickly and cost-effectively. Addressing these challenges will be crucial in determining the scalability and widespread adoption of robotic harvesting systems in both greenhouses and open fields. Figure 17 shows that the severity of different limitations varies a lot depending on the robotic harvesting feature.

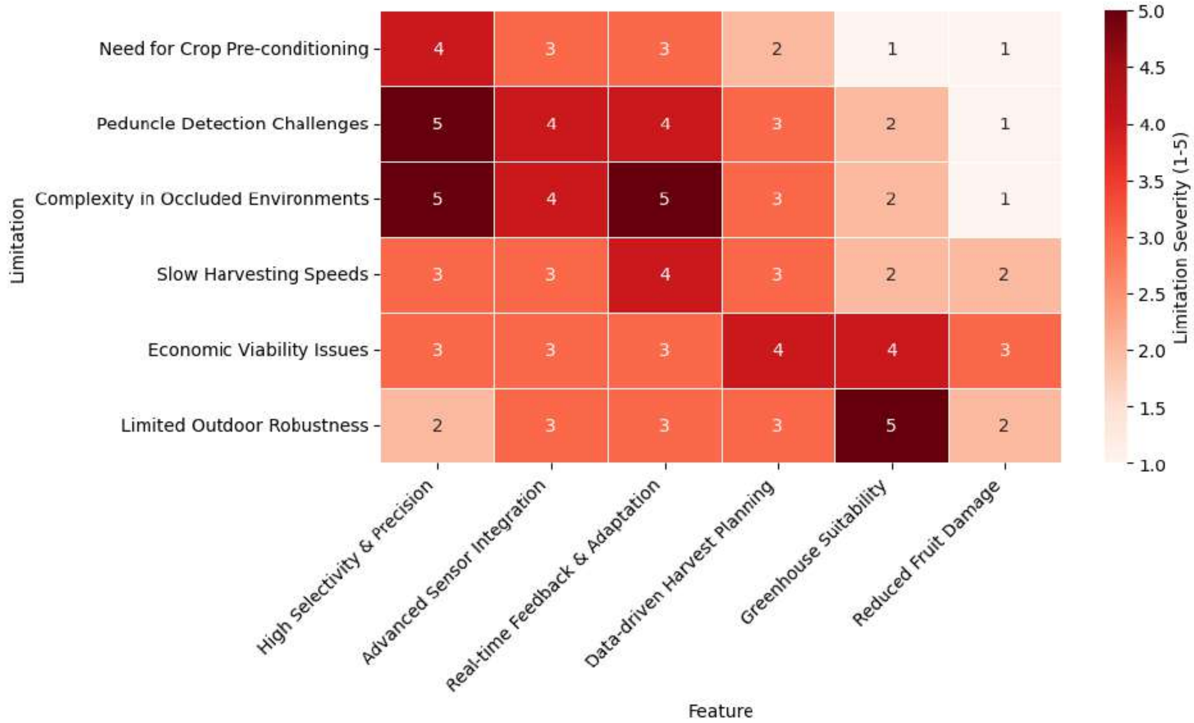


Figure 17. Heatmap showing limitation severity across robotic harvesting features.

6.1.6. AI-Driven Grading and Sorting in Post-Harvest Processing

Adding artificial intelligence (AI) to post-harvest processing is a significant change in the agricultural value chain. It brings the benefits of automation not only to field-level tasks but also to processing and packaging. Automation, powered by AI technologies, is becoming increasingly important from harvest to final distribution. Conveyor-based systems, advanced imaging, and machine learning algorithms are transforming the way horticultural products like bell peppers *(Capsicum annuum)*, also known as "capsicum" in India and Australia, are graded and sorted. These systems work together to ensure high throughput and consistent quality.

Post-harvest AI systems are designed to accelerate and enhance the accuracy of processing, as well as to increase profitability by reducing human error and maximizing the value of each unit of produce. For example, the Elisam GranTorino and TOMRA's equipment are both engineered for rapid and precise grading of bell peppers [57]. These industrial-grade machines incorporate both mechanical and AI components to perform 360° precision grading. They achieve this by utilizing specialized rotating carriers that capture up to 40 high-resolution images of each bell pepper from various angles. This comprehensive image acquisition enables detailed surface analysis, including the detection of visual defects, shape irregularities, and the presence of doubles, two peppers stuck together in the same holding cup [57].

Volumetric weighing, which is done in real time through built-in computer vision modules, makes these systems even more accurate. These modules use cutting-edge cameras and software to keep track of the average weight and throughput of products, often at speeds that humans can't reach [57]. At the same time, ultrafine color separation software allows you to dynamically profile changes in the color of bell peppers. These tools make it easy to quickly create or fine-tune color grading profiles based on live camera data. This helps packhouses maintain their quality and aesthetic standards. Intuitive dashboards that show real-time graphs of important metrics, such as the percentage of rejected peppers, the amount of waste generated, and the distribution of quality grades across each batch, usually support the operational interface [57].

Optical sorters are also very important for keeping products safe and in line with the law. These machines use a combination of sensors and AI algorithms to detect and eliminate a wide range of foreign materials, such as plastic pieces, stones, wood, and glass, as well as internal and external defects, such as rot, stem remnants, calyxes, cores, and unwanted color patches [59]. Importantly, these systems can handle large quantities of produce at an industrial scale while maintaining product quality and reducing the number of false positives.

AI-integrated post-harvest systems have the added benefit of being able to trace everything from start to finish. Automated labeling connects packages to digital records that show where each bell pepper came from and which field it was harvested from [57]. This traceability not only facilitates inventory management and logistics but also enhances food safety by enabling quick responses in cases of contamination or recalls.

One of the most important benefits of AI in post-harvest processing is that it helps ensure that the quality is maintained, especially when harvesting is done mechanically. Mechanical harvesting is cheaper, but it often causes more physical damage and impurities in the harvested material [32]. AI-enabled sorters act as a corrective layer by quickly identifying and removing faulty items. This compensates for the problems associated with automation at the field level [59]. This filtering after the fact ensures that only high-quality produce enters the supply chain. This allows for mechanical harvesting without compromising the quality of the final product.

Also, using AI systems for grading and sorting makes consistency and market value much better. AI systems give standardized, objective assessments of quality [28], unlike manual sorting, which is always different because workers get tired, have different opinions, and don't always do things the same way. These machines guarantee "consistent quality" [57] across batches by having features like 360° scanning, volumetric analysis, and fine color grading. This is a feature that is highly sought after in both domestic and international markets. Better consistency in the look and quality of products also means fewer rejections after packaging, less waste, and better pricing strategies.

These smart systems also help make the production pipeline more sustainable by reducing the need for unskilled manual labor and providing workers with opportunities to learn new skills. As people transition from manual graders to system operators and maintenance technicians, the entire value chain becomes more technology-driven, robust, and efficient.

In conclusion, the increasing use of AI in post-harvest grading and sorting processes represents a fundamental transformation in contemporary horticultural supply chains. Even if upstream field operations are only partially automated or limited by problems that are specific to a certain crop, smart downstream processing can greatly improve the overall efficiency, quality assurance, and traceability of the system. So, AI-powered post-harvest solutions not only make bell pepper production more profitable and easier to scale, but they also fit in with bigger goals like food safety, reducing waste, and making the supply chain more resilient.

7. ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

7.1. Labor Costs and Economic Benefits of Mechanization

Labor is still a major cost of growing and picking sweet peppers. It usually makes up a large part of the total production costs, between 20% and 50% [30]. For instance, in Southwest Florida, the costs of picking, packing, and hauling together make up about 61% of the total costs of harvesting and marketing, which comes to $2,640 per acre [60]. In South Korea, on the other hand, it takes 954 hours of work to harvest sweet peppers from one hectare, which is 39.2% of the total work needed to grow them [61]. These numbers demonstrate how labor-intensive and resource-consuming manual harvesting is. This problem is exacerbated by a lack of workers and higher wage expectations in both developed and developing agricultural economies [28].

Mechanization is a very effective way to address economic problems. Using mechanical harvesting tools instead of manual labor can save on high costs. For example, in China, mechanical harvesting costs CNY 1500 per hectare, which is only one-sixth the cost of manual harvesting (CNY 9000/ha) [32]. Using machines to harvest can reduce labor costs by as much as 51% and total production costs by as much as 38% [31]. Also, data show that mechanized farming always makes more money than traditional methods. For example, in 2020, it made an extra USD 16.61 per acre, and in 2021, it made an extra USD 27.10 per acre [62]. These gains are due to both lower labor costs and better operational consistency and efficiency.

Adding digital mechanization, such as the Internet of Things (IoT), artificial intelligence (AI), and autonomous systems, enhances the economy. Smart farming solutions have reduced labor costs by 65%, overall operating costs by 74%, electricity consumption by 20%, and water usage by 30% in technologically advanced greenhouse operations [63]. These efficiencies result in quicker equipment cost recovery, improved environmental sustainability, and increased profit margins, even for smallholder farmers. Table 5 presents the net economic benefits, comparing the primary cost and benefit metrics for manual versus mechanical/automated harvesting systems.

7.2. Investment, Return on Investment (ROI), and Profitability Analysis

Even though mechanized harvesting has clear long-term benefits, the switch requires a lot of money up front, especially for high-value protected cultivation systems [28]. When it comes to shade-grown sweet peppers, fixed costs such as infrastructure, machinery, and long-lasting equipment can exceed $60,000 per acre, not including depreciation, interest, and taxes [64]. These kinds of numbers can make it difficult for small and medium-sized producers to get started. However, mechanization should not only be evaluated based on initial costs. It should also be considered in terms of return on investment (ROI), operational lifespan, and the ability to replace workers.

Economic research shows that mechanized pepper production is a profitable method for generating income. For instance, in Ghana, pepper growers earn an average of GH₵1.98 for every GH₵1.00 invested, indicating that their capital nearly doubles within a single production cycle [65]. Digital mechanization, which encompasses more than just machinery and includes decision-support systems and real-time monitoring, reduces payback periods by increasing yield predictability, minimizing input waste, and enhancing labor efficiency [63]. These systems are particularly advantageous in controlled-environment agriculture, where consistency and high throughput are essential for maintaining competitiveness in the market.

As labor costs increase and availability decreases worldwide, the need for capital-intensive mechanized solutions becomes even more important [21]. Manual labor systems are adaptable and require minimal initial investment (e.g., hand tools); however, they are progressively becoming economically unviable in the long term [28]. On the other hand, mechanization not only saves money on operations but also makes performance more predictable, reduces the need for human labor, and lowers the risk of labor-related problems [63]. Research indicates that digitally enhanced greenhouses can achieve reductions of up to 65% in labor costs and 74% in overall operating expenses [63]. Also, using less fertilizer, pesticides, and water saves money over time and encourages responsible resource use.

Not only do balance sheets show how profitable mechanization is, but they also help lower risk. Mechanized systems provide an "assurance premium" by ensuring that crops are harvested on time, preventing spoilage, and maintaining consistent product quality [66]. These indirect economic benefits are especially significant for high-value crops and large-scale operations that supply competitive markets, even though they are more difficult to quantify. Mechanical and robotic solutions are vital for processing industries and export markets where throughput and uniformity are essential [32]. In areas with high labor costs or older agricultural workers, mechanization is no longer a choice; it is a necessity [30].

Lastly, mechanization is likely to change the structure of the sweet pepper industry. Larger agribusinesses and cooperatives may be able to gain an edge over their competitors by utilizing economies of scale to invest in and operate machinery. This could lead to increased consolidation within the industry, which would alter land use, ownership patterns, and employment dynamics.

In conclusion, economic analysis strongly supports the use of mechanical and digital technologies in the production of sweet peppers. The initial investment is high, but the long-term benefits for the economy and operations, such as ROI, cost-effectiveness, reduced labor, and lower risk, are substantial and well-supported by data, as shown in Table 5. The mechanization of agriculture constitutes a feasible approach to developing resilient, profitable, and sustainable food production systems.

Table 5. Economic comparison: manual vs. mechanical/Automated harvesting costs and benefits.

Cost/Benefit category	Manual harvesting (Typical)	Mechanical/Automated harvesting (Typical)	Value/Range	Relevant Snippet ID(s)
Labor cost per hectare	CNY 9000/ha	CNY 1500/ha	1/6th of the manual cost	Han, et al. [32]
% of production cost (Harvesting)	20-50%	Significantly reduced	-	Hill, et al. [30]
% of harvest & marketing costs (Picking, Packing, Hauling)	61% (Southwest Florida)	Significantly reduced	$2,640/acre (manual)	AgroReview [33]
Labor Hours per Hectare (Harvesting)	954 h/ha (Korea)	Significantly reduced	-	Choi, et al. [61]
Labor Utilization Reduction	-	Up to 51%	-	Song, et al. [31]
Total Cost Reduction	-	Up to 38%	-	Song, et al. [31]
Net Profit Increase	-	USD 16.61/Acre (2020), USD 27.10/Acre (2021)	-	Ahmed and Miller [62]
ROI (Ghana pepper production)	-	1.98 (GH₵ 1.98 gained for every GH₵ 1 invested)	-	Akolgo [65]
Labor cost reduction (Digital greenhouse)	-	65%	-	Işitan and Kutlubay [63]
General operational expense reduction (Digital greenhouse)	-	74%	-	Işitan and Kutlubay [63]
Initial investment cost	Low (Hand tools)	High (Machinery, infrastructure)	>$60,000/acre for fixed costs (shade-grown)	Austral Falcon [28]
Payback period	Shorter (Due to lower initial investment)	Shorter (Due to significant cost savings)	-	Işitan and Kutlubay [63]

7.3. Energy Consumption and Greenhouse Gas Emissions in Pepper Production

As the global agricultural sector places greater importance on sustainability, energy consumption and greenhouse gas (GHG) emissions have emerged as essential metrics for assessing the environmental sustainability of crop production systems. Sweet peppers are a high-value horticultural crop, but they have a relatively high carbon footprint. Recent studies indicate that their average emissions are approximately 0.73 kg CO_2-equivalent (CO_2e) per pound of produce, making them one of the vegetables with the highest lifecycle emissions [67]. A standard in the UK sets this even higher, at 1.65 kg CO_2e per kilogram, which includes emissions from farming, processing, packaging, transportation, and storage [68]. This data underscores the importance of adopting low-carbon methods when cultivating sweet peppers, especially as mechanization and controlled-environment agriculture become more prevalent.

The growing stage is responsible for the majority of emissions, accounting for approximately 80% of the total carbon footprint, or about 0.59 kg CO_2e per pound of produce [67]. This disproportionately high contribution results from several factors, including the extended growing season, significant land use, and the intensive application of high-energy inputs such as synthetic fertilizers and pesticides [67]. Furthermore, emissions are not confined to field-level activities; upstream processes like the production, transportation, and application of agrochemicals increase the carbon intensity of this phase. The embedded energy and emissions profile also encompasses the use of diesel-powered machinery, electricity for irrigation, and plastic mulching.

The post-harvest stages, which include harvesting, processing, and packaging, make up 13.68% of the total footprint (about 0.10 kg CO_2e per pound) [67]. This is mostly because plastic packaging materials use a lot of energy and cleaning, cooling, and sorting operations use a lot of electricity. The transportation phase, on the other hand, makes up 6.71% (about 0.05 kg CO_2e per pound), and international supply chains can have a big effect on this. For example, peppers brought into the U.S. from Mexico often need refrigerated trucks. These trucks use a lot of energy and release more nitrogen oxides and particulate matter than regular trucks [67].

Sweet pepper production can consume significant energy overall. A study on cultivation in a typical field environment found that it used 18,442.29 MJ per hectare, which included both direct and indirect energy inputs [69]. Human labor, diesel fuel, electricity, and irrigation water are examples of direct energy inputs. Machinery, fertilizers, pesticides, and seeds are examples of indirect energy inputs [69]. For instance, using machinery alone adds 156.14 MJ per hectare, accounting for 0.85% of the total energy input. The greenhouse gas (GHG) emissions from these machines amount to 11.09 kg CO_2e per hectare, representing 0.36% of the total emissions [69]. Although this fraction may seem small, it becomes significant in mechanized or large-scale operations where diesel-powered equipment is extensively used or where irrigation loads are substantial.

Greenhouse production provides productivity enhancements and quality uniformity, yet it constitutes a complicated trade-off regarding energy consumption and emissions. Controlled environments often require additional lighting, heating, and CO_2 enrichment. If these are not powered by renewable energy, they can significantly increase operational emissions [67]. However, new facilities are beginning to address this issue by utilizing recycled industrial heat, low-energy LED lights, and systems that capture and reuse CO_2. Nonetheless, not all businesses have adopted these technologies yet, and many commercial greenhouses still rely heavily on fossil fuels.

The environmental effects of growing peppers extend beyond cultivation. Plastic packaging, which is essential for maintaining freshness and marketability, significantly contributes to post-harvest emissions [67]. Additionally, refrigerated transport systems used for long-distance distribution remain a major source of emissions that require further attention [67]. Even stages that do not directly emit large quantities of greenhouse gases, such as processing and storage, can still contribute to overall emissions through electricity consumption, refrigerant leaks, and logistical inefficiencies [68]. These broader life cycle considerations underscore the importance of adopting a systems-oriented approach to sustainability, which involves comprehensive emissions tracking from seed to shelf.

The environmental trade-offs of mechanization and more intensive farming practices are clear: they have significant energy costs, but they also provide economic benefits and facilitate workers' tasks (as discussed in Sections 7.1 and 7.2). Diesel-powered harvesters, electrically powered greenhouse systems, and synthetic agrochemical inputs all contribute to the carbon footprint, particularly during the growing phase [67, 69]. As shown in Table 6, a stage-by-stage breakdown of carbon emissions along the sweet pepper production chain shows that growing remains the most significant environmental issue, followed by packaging and transportation. Figure 18 illustrates that the carbon footprint of capsicum varies considerably depending on the stage of production in the UK benchmark.

So, the way to make sweet peppers in a way that is good for the environment and the economy must be balanced. While mechanization and controlled-environment systems hold promise for yield and profitability, they necessitate a thorough life cycle assessment to pinpoint carbon-intensive hotspots, particularly during the cultivation phase and post-harvest processes. Future improvements must focus on machinery that uses less energy, greenhouses that run on renewable energy, low-carbon packaging, and better transportation logistics. The sweet pepper industry can align itself with bigger climate and sustainability goals while still being productive and competitive in the market by taking these environmental costs into account and changing its production systems.

Table 6. Carbon footprint breakdown of bell pepper production stages.

Production stage	Carbon footprint (CO_2e)	Percentage of total footprint	Key contributing factors	Relevant snippet ID(s)
Overall	0.73 kg (1.6 lbs) CO_2e/lb	100%	Growing, harvesting, processing, packaging, and transporting.	Howarth [67]
Overall (UK Benchmark)	1.65 kg CO2e/kg	100%	Agriculture, transport, processing, packaging, storage	CarbonCloud [68]
Growing	0.59 kg (1.3 lbs) CO_2e/lb	79.61%	Land usage, long growing period, high maintenance, pesticide/fertilizer use	Howarth [67]
Harvesting, Processing, Packaging	0.1 kg (0.23 lbs) CO_2e/lb	13.68%	Plastic packaging, processing energy	Howarth [67]
Transporting	0.05 kg (0.11 lbs) CO_2e/lb	6.71%	Imports (e.g., US from Mexico), refrigerated trucks (higher emissions)	Howarth [67]
Agriculture (General)	80% (of 1.65 kg CO_2e/kg)	-	Biological processes, input production/use (fertilizer, pesticides), machinery energy	CarbonCloud [68]
Transport (General)	6% (of 1.65 kg CO_2e/kg)	-	Movement from field to factory to consumer, various modes and fuels	CarbonCloud [68]
Packaging (General)	14% (of 1.65 kg CO_2e/kg)	-	Energy and raw materials for packaging	CarbonCloud [68]
Processing (General)	≈0% (of 1.65 kg CO_2e/kg)	-	Cleaning, heating, cooling, drying, mixing, sterilization, fermentation, chemicals	CarbonCloud [68]
Storage (General)	0% (of 1.65 kg CO_2e/kg)	-	Lighting, heating, chilling, ventilation, and refrigerant leakage	CarbonCloud [68]

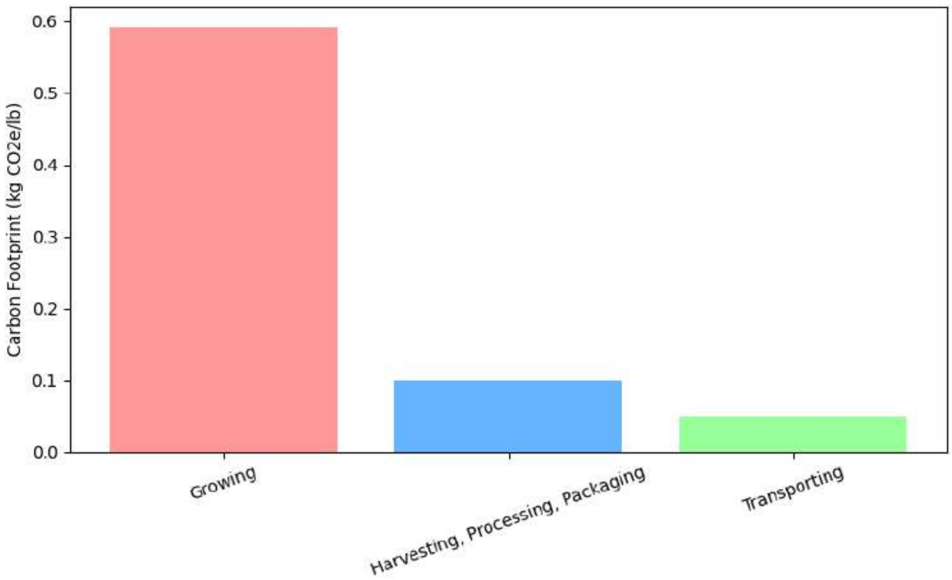


Figure 18. Carbon footprint of capsicum across production stages in the UK benchmark.

7.4. Impact of Agricultural Machinery on Soil Health

Modern agriculture's greater reliance on machines has led to a number of unintended ecological effects. One of the most serious is soil compaction, which is a type of soil degradation. Soil compaction occurs when soil becomes denser due to external mechanical pressure, usually from heavy farm equipment. This phenomenon is characterized by a decrease in soil porosity and an increase in bulk density, which together make it more difficult for the soil to retain and transmit air, water, and nutrients essential for plant growth [70].

Soil compaction often occurs without any obvious signs on the surface, making it difficult to notice and is frequently ignored in field management. Nevertheless, its effects are profound and long-lasting. Compaction impedes root penetration into the ground, restricts air movement within the root zone, hampers water infiltration into the soil, and reduces the ability of crops to absorb nutrients [70]. Even in the absence of visible crop problems, this deterioration of soil structure can lead to reduced yields. Consequently, it becomes more challenging to assess the true costs associated with mechanization-driven intensification.

The increasing weight and size of modern farm equipment are among the primary reasons for worsening soil compaction. When large tractors, combines, and harvesters are used in fields with low moisture levels, they can cause deep subsoil compaction. Such damage to the subsoil is particularly difficult to repair and can persist for decades [71]. In compacted soils, reduced biological activity exacerbates the problem because the disrupted microenvironment harms microbial populations and root growth, both of which are essential for nutrient cycling and soil health [71].

A certain amount of soil compaction is an unavoidable side effect of mechanized farming, but it is very important to actively manage and lessen these effects. Common remediation techniques include subsoiling, which involves deep tillage to break up compacted layers. However, these methods use a lot of energy, cost a lot of money, and only work for a short time unless they are used with other management strategies [71]. Also, if these kinds of interventions are done when the soil is too wet or without following controlled traffic patterns, re-compaction can happen quickly, cancelling out the benefits of the first time.

Soils that lack significant organic matter are more susceptible to compaction because they do not withstand mechanical pressure well. Conversely, soils rich in organic matter are better able to maintain their structure and endure stresses from machinery [71]. Cover cropping, organic amendments, and crop residues not only improve soil quality but also promote biological activity, providing a biologically sustainable method to prevent compaction.

Additionally, the belief that compaction is solely a mechanical issue has been contested by recent studies indicating that it is fundamentally a biological concern, one that compromises the ecological basis of soil functionality [71]. By limiting root growth and microbial communities, compaction interferes with the processes that keep soil healthy and allow it to recover. This acknowledgment necessitates a transformative shift in mechanized agricultural methodologies: transitioning from reactive mechanical interventions to proactive, biologically-informed management.

To mitigate long-term risks, sustainable agricultural mechanization must embed strategies that reduce the likelihood and impact of compaction. These include.

1. Controlled Traffic Farming (CTF): Restricting machinery movement to predefined lanes minimizes the total compacted area.
2. Reduction in axle loads and machinery weight: Use of lighter equipment or distributed loads can reduce pressure on the soil.
3. Optimized Field Timing: Avoid field operations during wet conditions when the soil is most susceptible to compaction.
4. Enhancement of soil organic matter: Through compost application, residue retention, and crop rotations with deep-rooting species to improve structural resilience.

If not addressed, soil compaction could diminish the long-term benefits of using machinery in farming by necessitating increased inputs, such as irrigation and fertilizers, to maintain yields. This would elevate both economic costs and environmental footprints [70]. Consequently, integrating mechanization with soil-conserving agronomic practices is not only advantageous but also essential to ensure the resilience and sustainability of modern agricultural systems.

7.5. Water Use Efficiency in Harvesting Systems

The literature does not specifically outline the direct correlation between sweet pepper harvesting machinery and water use efficiency; however, a comprehensive analysis of mechanized agricultural systems indicates substantial indirect consequences for water management. Understanding this relationship is very important because sustainable water use is a key part of climate-smart agriculture and systems for growing crops that use resources efficiently.

It is important to know that harvesting machines are not designed to use water. However, integrating them into the production pipeline requires certain agronomic adjustments that affect the system's water balance. For example, the successful use of harvesting automation often depends on having uniform crop stands and optimal soil texture, both of which require good farming practices. When the soil is consistent and not clumpy, machine-based harvesting functions more effectively. This is often achieved by preparing raised beds and employing fine tillage [21]. Additionally, using plastic or organic mulch, which is commonly used to prevent weed growth and maintain ground level for machine movement, not only enhances harvesting efficiency but also significantly improves the soil's moisture retention capacity [72]. This means that the need for frequent irrigation cycles can be reduced, which helps save water indirectly.

Also, the trend toward mechanized agriculture that uses computers is increasing, which benefits the optimal use of water. Precision irrigation management is achievable with advanced IoT-enabled field sensors and AI-based analytics [63]. These tools can be seamlessly integrated into larger greenhouse monitoring systems or open-field automation platforms. This integration allows for real-time data on the water status of plants, soil moisture levels, and rates of evapotranspiration. Consequently, it becomes easier to apply water more accurately to specific areas [73]. Although these technologies are not physically part of the harvester, they are components of the mechanized system's infrastructure that optimize resource utilization as a whole.

There is proof from real life that these benefits are true. For example, controlled studies in digital greenhouses have shown that adding AI-based irrigation scheduling to automated cultivation routines can reduce water use by up to 30% without compromising crop quality or yield [63]. This represents a significant improvement in water efficiency, which is particularly important in regions where water resources are scarce.

On the other hand, mechanization can also cause problems that make water use less efficient. When heavy machinery is used to prepare the soil and harvest crops, it often causes soil compaction, which is a physical process that makes soil less porous and permeable [70]. Compacted soils have lower infiltration rates and less ability to hold water, so crops need to be watered more often to keep the water available. This goes against the potential water savings that could be achieved through better scheduling and mulching, demonstrating how mechanization can have both positive and negative effects on water resources.

So, even though the harvesting machine doesn't directly use water, it is an important part of a complicated system where water use is affected in many ways. Some of these are ways to prepare land before harvest, patterns for mechanical traffic, and the use of digital sensing and analytics platforms. When looking at how efficiently mechanized sweet pepper harvesting systems use water, you need to think about how machine design, farming practices, and the environment all affect each other.

Consequently, forthcoming research must embrace a systems-level approach in examining the water footprint of agricultural mechanization. This means figuring out how much water precision tools save indirectly, looking at how soil compaction affects irrigation needs over time, and making harvester parts that put less pressure on the ground. Creating lightweight harvesting machines with built-in sensors that are optimized for both environmental sustainability and operational efficiency could make a significant difference in the water-smart farming movement in horticulture.

8. SOCIO-ECONOMIC IMPACT AND THE FUTURE OF HARVESTING

This section examines how the transition from manual to mechanized and AI-driven harvesting technologies has transformed the cultivation of sweet peppers (*Capsicum annuum*) worldwide. It emphasizes changes in labor practices, market adaptations, and the integration of intelligent sensing systems.

8.1. The Socio-Economic Transformation of the Sweet Pepper Workforce

The mechanization of sweet pepper harvesting has greatly changed the agricultural workforce, shifting from low-skill, labor-intensive jobs to specialized technical and analytical positions [74]. In large producing areas such as California and New Mexico, early mechanized systems like spring-tine and shaker harvesters resulted in many seasonal workers losing their jobs [75]. But with the rise of smart robotics and precision farming, this change in jobs has turned into a change in the way people work, with skilled operators, technicians, and data analysts needed to run complex automation systems [76].

The Netherlands, Japan, and the United States are all high-income countries that have benefited from this change. More automation means less reliance on temporary workers, higher average wages, and safer working conditions [77]. Robotic systems have also helped address common ergonomic problems, such as repetitive strain and musculoskeletal injuries resulting from manual harvesting [78]. From an economic point of view, mechanization lowers the risk of labor shortages and changing wages, which stabilizes production costs and makes it possible to invest in protected cultivation and sensor infrastructure for the long term [79].

8.2. Case Studies and Global Comparisons

The adoption of mechanization and AI technologies varies widely by market focus, economic context, and labor conditions. Table 7 compares greenhouse, protected, and open-field sweet pepper harvesting technologies, showing that robotic systems address labor shortages and enable selective fresh-market harvesting, while semi-mechanized approaches primarily reduce labor costs in processing systems despite higher fruit damage rates.

Table 7. Performance and socio-economic impacts of robotic and semi-mechanized sweet pepper harvesting systems across production environments.

Scenario	Technology focus & project	Performance & socio-economic impact	Reference
Greenhouse fresh market (EU)	**SWEEPER robot** (AI-powered, selective harvesting)	**Goal**: Market readiness. Proven technical viability in the *CROPS* project. **Economic Driver:** Solve chronic labor capacity problems and reduce operational costs by overcoming the 94-second cycle time barrier reported in earlier prototypes.	WURGreenhouseHorticulture [48] and Arad, et al. [50]
Protected cropping (Australia)	**Harvey robot** (Autonomous, vision-based harvesting)	**Performance**: Achieved a **58% harvest success rate** in modified crop environments during initial field trials. **Economic Driver:** The combination of effective vision algorithms and novel end-effector design targets the high-value fresh produce market, where high success rates justify the capital investment.	Lehnert, et al. [49]
Open-field processing (USA/Chile)	**Semi-mechanized harvesters**	**Economic Context**: Labor costs can account for up to 50% of the total production cost for Chile pepper. Mechanization or robotics can reduce this by approximately 10%. **Limitation:** Damage rate is high (6.9% reported in robotic prototypes), making selective harvesting essential for fresh market crops, but less critical for processing crops.	Masood and Haghshenas-Jaryani [80]

These regional examples illustrate that the socio-economic viability of automation depends not only on cost-benefit analysis but also on market segmentation, policy support, and the alignment of technology with cultivar characteristics.

9. CONCLUSION AND FUTURE OUTLOOK

9.1. Summary of Key Developments and Current State of Sweet Pepper Harvesting

The way sweet peppers (*Capsicum annuum*) are harvested has changed significantly. It used to be done manually with simple tools and by people, but now there are more advanced semi- and fully-automated methods. In the past, harvesting was performed solely by workers who picked mature fruits by hand to avoid damage and maintain high quality. This method ensured that fruits were handled and sorted carefully based on their ripeness, size, and external appearance. However, it required considerable effort, time, and skill from farm workers.

In the middle of the 20th century, people started trying to mechanize sweet pepper harvesting. This was because they needed to make harvesting more efficient and deal with a growing lack of workers. But these early mechanical systems often didn't work as well as human pickers and had trouble with crop variability, damage rates, and destemming problems. This made people less interested in mechanization for a while in the late 20th century. However, research and development in this area have seen a big comeback in the last 20 years. This is mostly because of economic reasons, like rising labor costs, fewer workers, and the need for year-round production in controlled greenhouse environments.

Today, manual harvesting remains the most common method for growing crops for sale, especially in the fresh vegetable market, where quality is paramount. Factors such as appearance, texture, and minimal bruising are critical. Manual techniques enable precise handling and selective harvesting based on the maturity stages of the crops. This is particularly important for crops like capsicum, where uniform ripening is not always guaranteed. Conversely, mechanical harvesting is increasingly popular for processing-grade sweet peppers and large-scale operations. Mechanical harvesters utilize various tools, including shaker systems, helix rotors, and finger-type pickers. These machines are equipped with built-in cleaning, conveying, and collecting units. They can process large quantities of fruit rapidly and efficiently; however, they often struggle with delicate fruit, leading to issues such as stem breakage, bruising, and contamination by foreign matter. Despite improvements in hardware and system design over time, ensuring effective destemming and minimizing physical damage remains challenging.

Because of these problems, the cutting edge of harvesting technology is now characterized by the use of smart robots, machine vision, and artificial intelligence (AI). The SWEEPER and Harvey research projects are good examples of this trend. These robotic platforms use multi-modal sensory inputs, advanced computer vision algorithms, and robotic manipulators to find, locate, and pick sweet peppers on their own in greenhouses. They work well in structured environments, especially when they have deep learning-based fruit detection modules and precise end-effectors for cutting and grasping. AI is used not only for harvesting but also for handling operations after harvesting, such as grading, sorting, and packaging. This ensures that the quality of the products is always consistent, improves traceability, and makes the value chain more efficient. Therefore, robotics and AI are not only addressing the problems that mechanical harvesters have always faced but are also transforming the way automation functions in horticulture.

9.2. Addressing Remaining Challenges and Opportunities for Innovation

Even though there has been significant progress, there are still some technical, economic, and environmental problems that need to be addressed before automated sweet pepper harvesting can reach its full potential. These issues also present opportunities for ongoing innovation:

1. Labor Transformation: The adoption of automation is expected to significantly reduce reliance on manual labor, transforming the agricultural workforce. Future roles will likely shift toward managing and maintaining

robotic systems, data infrastructure, and AI models. This transformation can mitigate labor shortages while also elevating the skill set and working conditions of the agricultural labor force [22].

2. Economic Viability: One of the primary barriers to the adoption of advanced robotic harvesters is the high capital expenditure associated with procurement and deployment. However, once implemented, these systems can deliver substantial long-term savings by reducing operational costs, enabling round-the-clock harvesting, and improving harvest efficiency. This cost-benefit tradeoff is crucial for maintaining competitiveness in global markets, particularly as input costs continue to rise [32].
3. Environmental Footprint: Sustainability is a growing concern in capsicum production systems. The environmental burden, especially carbon emissions, is primarily associated with the crop growth phase. However, harvesting machinery also contributes through fuel use, soil compaction, and operational energy demands. To minimize environmental impact, future harvesting systems must prioritize energy efficiency, adopt electrification where feasible, and integrate with sustainable greenhouse management practices [67, 70].
4. Resource Optimization: The integration of precision agriculture technologies, such as multispectral imaging, LiDAR-based canopy mapping, and AI-driven decision-making, allows for targeted application of irrigation, fertilizers, and pesticides. These practices help reduce resource wastage and promote environmental sustainability while maintaining or improving yield and quality. This resource-efficient approach is crucial in high-input greenhouse environments [63].
5. Food Security and Quality Assurance: Advanced harvesting and post-harvest processing technologies contribute to minimizing losses, reducing variability in product quality, and enhancing the shelf life of sweet peppers. Such improvements directly support global food security goals by ensuring a reliable supply of nutritious produce while reducing wastage and inefficiencies throughout the value chain [57].

In summary, although substantial advancements have been made in the automation of sweet pepper harvesting, additional interdisciplinary research is required to address existing constraints and to create scalable, economical, and sustainable systems. Future endeavors must focus on enhancing robotic perception systems in occluded environments, creating adaptive grippers, facilitating integration with Internet of Things (IoT) networks, and conducting field validation in authentic greenhouse and open-field settings.

Funding: This research was supported by the Indian Institute of Technology, Kharagpur, West Bengal (Grant number: PMRF 2402325).
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: Both authors contributed equally to the conception and design of the study. Both authors have read and agreed to the published version of the manuscript.

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