



Soft Grippers in Farm Robotics

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Soft grippers in farm robotics are emerging as an advanced solution for safe and efficient handling of delicate crops and food products. Unlike conventional rigid grippers, soft grippers are developed using flexible and compliant materials that can adapt to irregular crop shapes without causing damage. Their applications in agricultural robotics include harvesting, sorting, packaging, and post-harvest handling. Soft robotic grippers improve harvesting efficiency, reduce crop losses, and support automation in modern agriculture. With the integration of intelligent sensing and adaptive grasping technologies, soft grippers play an important role in sustainable and precision farming systems. This article synthesizes findings from recent research studies to provide a comprehensive overview of soft grippers in farm robotics, focusing on their working principles, harvesting applications, food product handling capabilities, technological innovations and future research directions. The discussion highlights how soft grippers are becoming a critical component of Agriculture 4.0, where robotics, artificial intelligence, and smart sensing technologies converge to create resilient and efficient food production systems.

Keywords: Soft robotics; agricultural robotics; fruit harvesting; food handling; pneumatic actuation; Agriculture 4.0.

Introduction

Current agriculture is rapidly adopting robotics and automation technologies to improve productivity, reduce labor shortages, and increase farming efficiency. Automated systems are now used for harvesting, sorting, spraying, monitoring, and packaging operations. Precision agriculture further enhances modern farming by using sensors, artificial intelligence, robotics, and data-driven technologies for accurate crop management and sustainable production. In this advanced agricultural system, soft robotic grippers have become an important innovation for farm robotics. Unlike rigid grippers, soft grippers are made from flexible materials that can safely adapt to the shape and texture of delicate crops. Their gentle handling ability makes them suitable for harvesting, packaging, and post-harvest operations while reducing crop damage and improving efficiency in smart farming applications.

Fundamentals of Soft Grippers in Farm Robotics

Soft grippers are robotic end-effectors fabricated from flexible polymers such as silicone elastomers, thermoplastic polyurethane, and other compliant materials. Unlike rigid metal claws, these grippers deform when interacting with objects, distributing pressure evenly across the surface of the crop. This characteristic significantly reduces the risk of mechanical damage and allows the robot to operate safely in close proximity to plants and human workers. The agricultural environment presents unique challenges due to variability in crop size, shape, orientation, and ripeness. Soft grippers are uniquely suited to this environment because their inherent compliance enables passive adaptation without requiring complex control algorithms. As a result, they are capable of handling a wide range of agricultural products, from soft fruits to packaged food items.

Working Principle of Soft Grippers

The working principle of soft grippers is based on the coordinated interaction between compliant materials, actuation systems, and intelligent control. The process begins when machine vision detects and locates the target crop, after which the robotic arm positions the soft gripper around the object and activates the actuation mechanism to achieve a gentle and adaptive grasp.

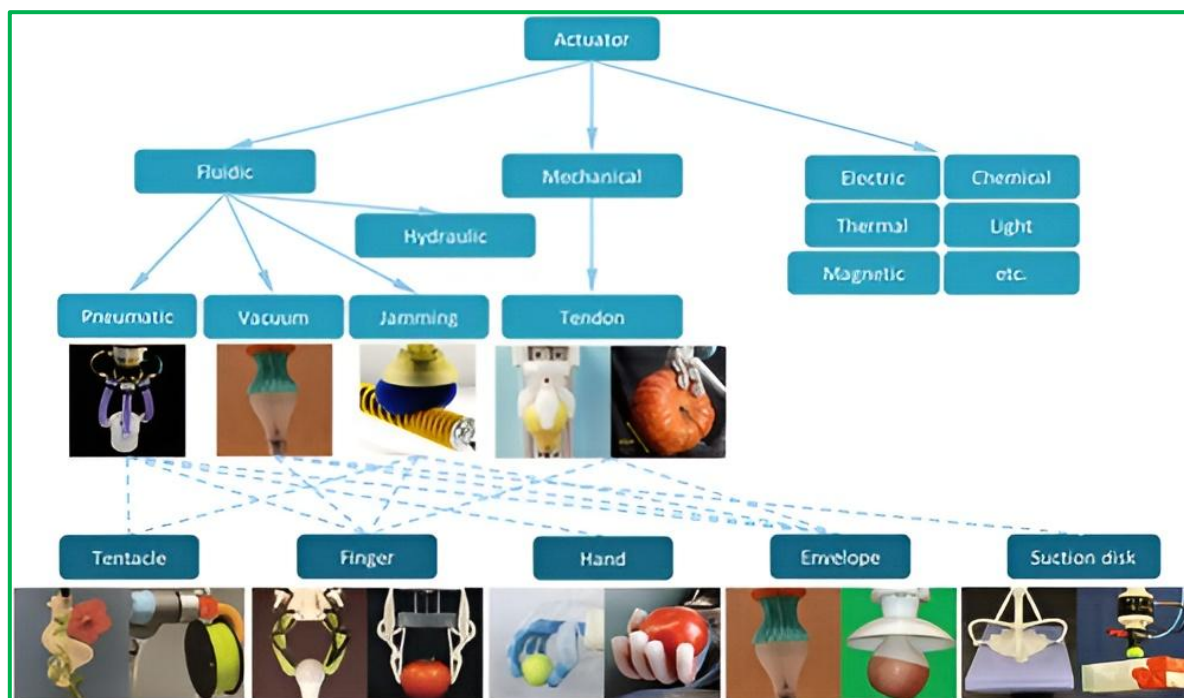


Fig.1 The diagram for diversified soft robotic actuators for agricultural product harvesting, especially with four actuation mechanisms (Source: Liu et al., 2023)

Pneumatic actuation is the most widely used mechanism in agricultural soft grippers. In this approach, compressed air inflates internal chambers embedded within flexible fingers, causing them to bend and wrap around the fruit or vegetable. The resulting conformal contact distributes pressure evenly across the surface of the produce, significantly reducing bruising and mechanical damage during harvesting and handling.

Vacuum-based gripping is another important method, particularly for smooth-surfaced fruits and packaged food products. Vacuum suction cups create negative pressure to securely attach to the object, enabling stable lifting and placement while maintaining gentle contact.

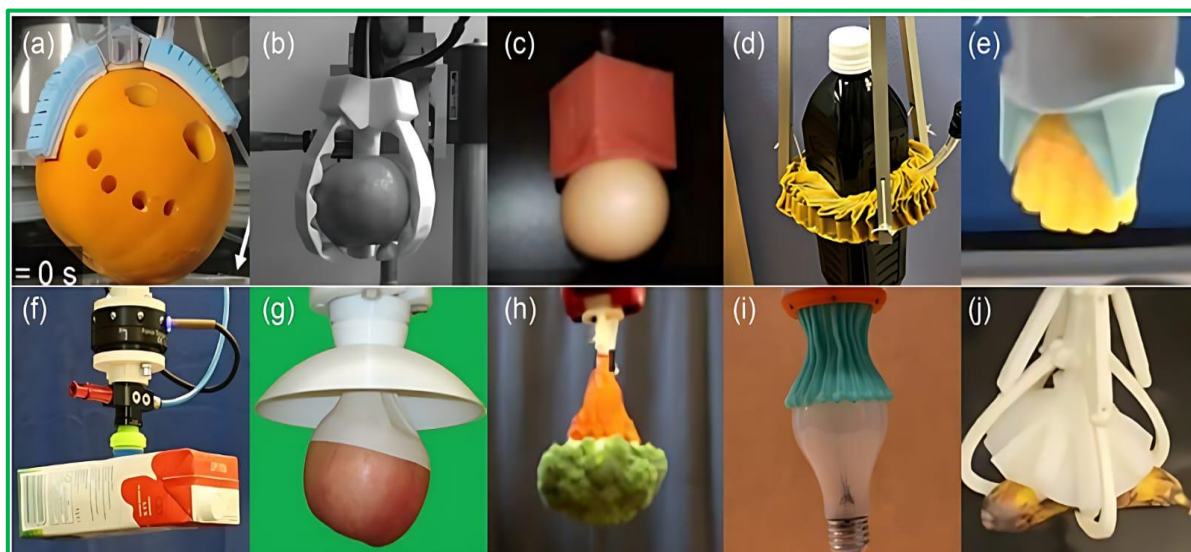


Fig.2 Vacuum-driven soft grippers (Source: Liu et al., 2023)

Tendon-driven actuation systems mimic biological muscles by using cables or artificial tendons to pull flexible fingers inward. This mechanism allows precise control of finger movement and improves grasp stability when handling irregularly shaped crops.

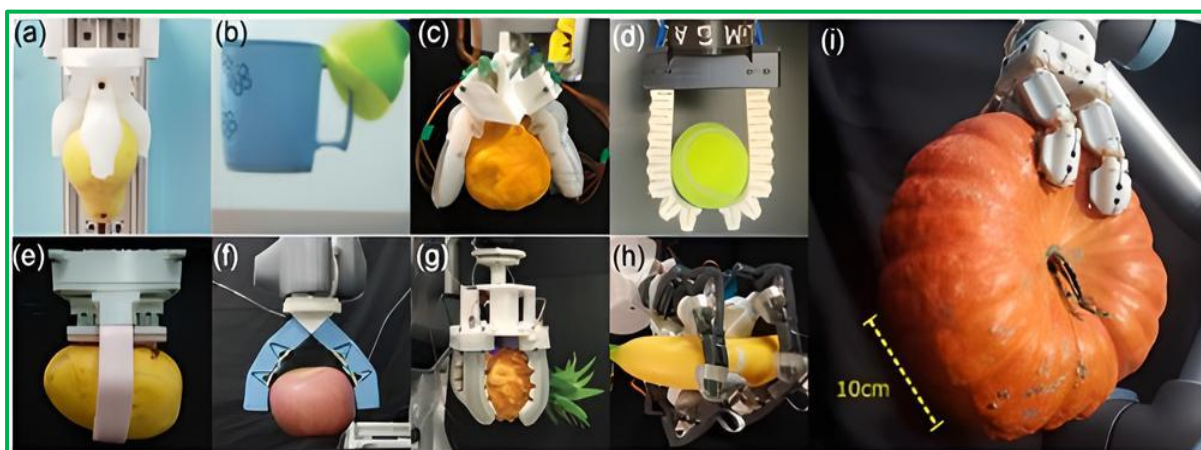


Fig.3 Tendon-driven soft grippers (Source: Liu et al., 2023)

Jamming-based mechanisms introduce variable stiffness by using granular or layer jamming structures that can switch between soft and rigid states. When vacuum pressure is applied, the internal particles lock together, increasing stiffness and allowing the gripper to carry heavier loads while preserving adaptability.

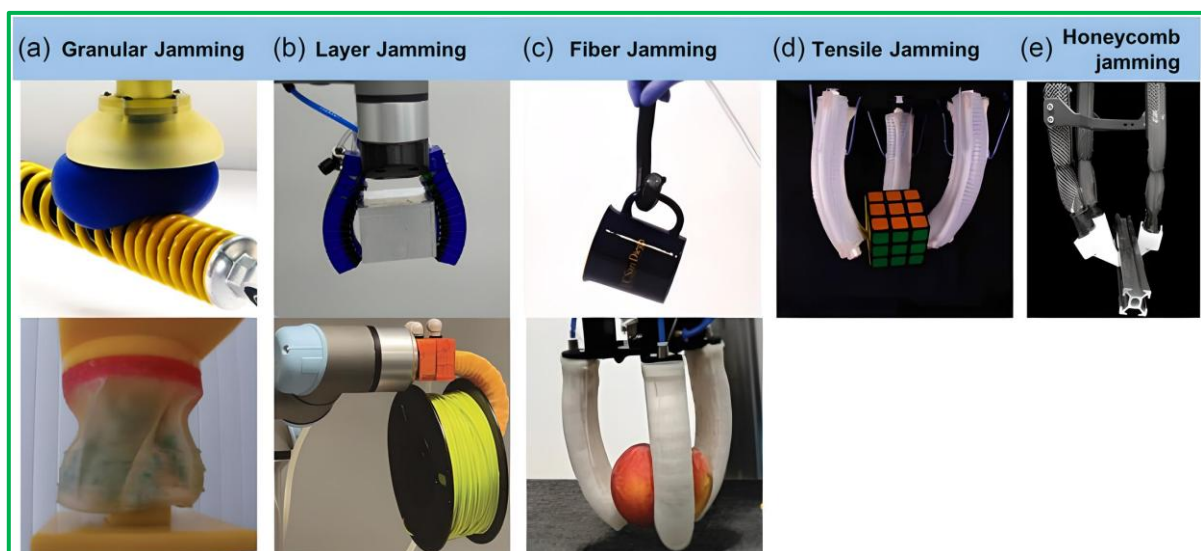


Fig.4 Soft grippers enabled by jamming technology (Source: Liu et al., 2023)

Soft Grippers in Robotic Harvesting

Robotic harvesting is one of the most promising applications of soft grippers in agriculture. Harvesting requires delicate handling, selective picking, and precise manipulation, all of which are difficult to achieve using rigid robotic systems. Soft grippers enable robots to pick fruits without damaging the surrounding plant structure or the fruit itself. The harvesting process begins with computer vision systems that identify ripe fruits using color, texture, and shape recognition algorithms. Once the fruit is detected, the robotic arm positions the soft gripper near the target. The gripper then gently encloses the fruit and applies controlled pressure to secure it. A twisting or pulling motion is used to detach the fruit from the stem, after which it is placed in a storage container. Research has demonstrated the successful use of soft grippers in harvesting strawberries, tomatoes, apples, cucumbers, and citrus fruits. These systems significantly reduce crop damage and improve harvesting efficiency, making them highly suitable for commercial agricultural applications.

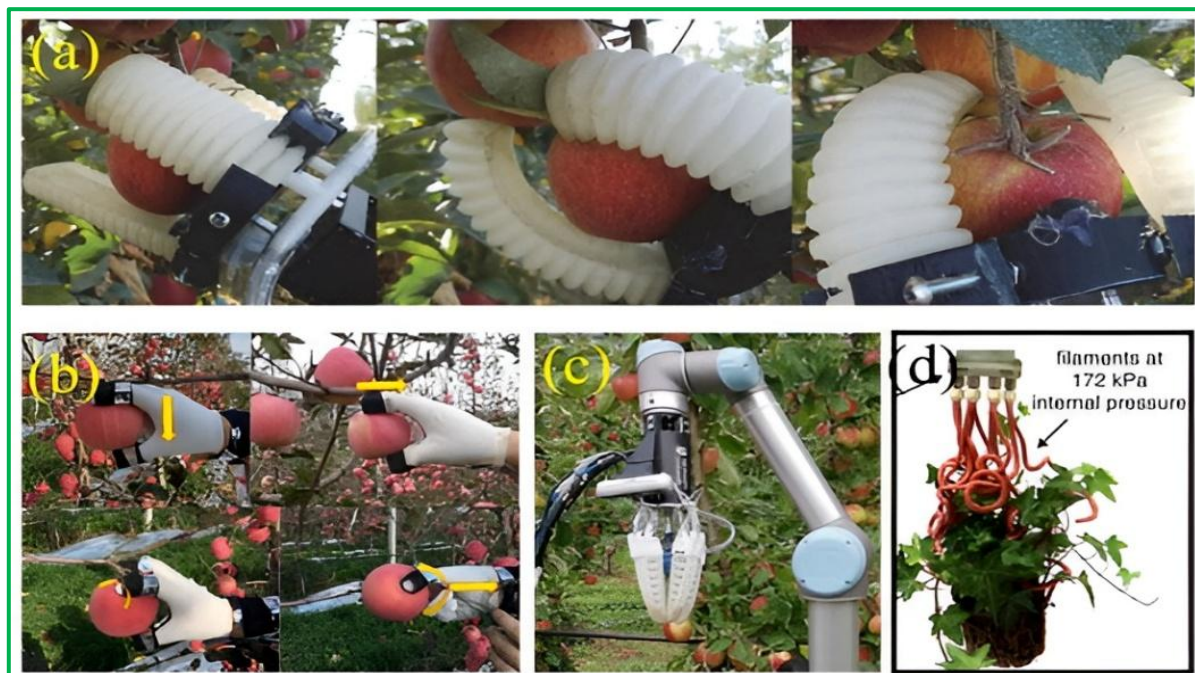


Fig.5 Pneumatic soft gripper with claw structure for use in agricultural harvesting.

(a) The three-finger pneumatic soft gripper. (b) Demonstration of different gripping and picking strategies for apples. (c) The soft gripper with gripping and adsorption. (d) The soft gripper based on collective mechanics (Source: Zhang et al., 2025)

Soft Grippers in Food Product Handling

Soft grippers are equally valuable in post-harvest operations where food products must be handled hygienically and gently. Food processing and packaging industries require automation solutions that meet strict safety and cleanliness standards. Soft grippers made from food-grade materials provide a safe and hygienic alternative to manual handling. In food processing facilities, soft grippers are used to sort, pack, and transport fragile products such as eggs, berries, and baked goods. Their gentle grasping mechanism reduces waste and improves product quality. Automated packaging lines equipped with soft robotic grippers enhance productivity while maintaining food safety standards.

Design Innovations and Technological Advancements

Recent advancements in materials science and manufacturing technologies have accelerated the development of soft grippers. Additive manufacturing techniques such as 3D printing allow rapid prototyping and customization of gripper designs. Researchers are exploring bio-inspired structures that mimic natural gripping mechanisms found in plants and animals. The integration of artificial intelligence and sensor technology has further enhanced the capabilities of soft grippers. Intelligent control systems allow robots to adapt to dynamic agricultural environments and perform complex manipulation tasks with minimal human intervention.

Challenges and Future Prospects

Despite significant progress, challenges remain in terms of durability, load capacity, and cost-effective manufacturing. Field conditions expose robotic systems to dust, moisture, and temperature variations, which can affect performance. Future research aims to develop more robust materials, improve sensor integration, and reduce production costs. Soft grippers are expected to play a central role in the future of Agriculture 4.0. Continued advancements will enable large-scale deployment of agricultural robots capable of performing multiple tasks autonomously.

Conclusion

Soft grippers represent a breakthrough technology in farm robotics. Their ability to safely manipulate delicate crops and food products makes them essential for the automation of

agricultural harvesting and post-harvest operations. As Agriculture 4.0 continues to evolve, intelligent soft robotic grippers will play a key role in ensuring sustainable food production, reducing labor dependency, and minimizing food waste. Continued advancements in materials, control systems, and manufacturing will accelerate their adoption in real-world farming applications.

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