A REVIEW OF APPLICATION OF WATER JET TECHNOLOGY IN AGRICULTURE
/
水射流技术在农业领域的应用研究现状

Lixue ZHU1), Wenxuan LUO1), Hongnan HU*1), Shiang ZHANG1), Yifan SHI1), Shinian HUANG
1)College of Mechanical and Electrical Engineering, Zhongkai University of Agriculture and Engineering,
Guangzhou 510225, China
** Correspondence: huhongnan@zhku.edu.cn; Tel.: +86-18301160669*

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ABSTRACT

Water jet technology, as a non-contact cutting and crushing technique, is commonly used in industries such as cleaning, rust removal, cutting, drilling, and mining. It enables a green and environmentally friendly production process by avoiding environmental pollution, heat generation, blade replacement, and sharpening issues. Cutting, cleaning, and crushing techniques are widely applied in various stages of agricultural production, but mostly through contact-based methods. The application of non-contact water jet technology in the agricultural field is still in its infancy. This paper summarized the current application status and research progress of water jet technology in different operational stages of agriculture, including sowing, management, field harvesting, and post-harvest processing. The specific requirements of key parameters for different operational objects and stages were analyzed. Furthermore, the challenges of the application of water jet technology in agriculture were discussed and the research development tendency was prospected. The review intended to provide references for the promotion and green sustainable development of water jet technology in the agricultural field.

摘要

水射流技术作为一种非接触式的切割破碎技术，常在工业中用于清洗、除锈、切割、钻孔、矿山开采等，可实现绿色环保的生产加工过程，避免污染环境、产生热量、刀片更换及磨利等问题。切割、清洗、破碎等技术被广泛应用于农业生产的各个环节，但多采用接触式方法，非接触式水射流应用在农业领域方兴未艾。本文总结了目前水射流技术在播种、管理、田间收获、采后加工等不同作业环节应用现状与研究进展；分析了不同作业对象及作业环节对射流关键参数的具体要求；探讨水射流技术在农业领域应用过程中存在的问题，并对未来的研究方向进行了展望，以期为水射流技术在农业领域应用推广和绿色可持续发展提供参考。

INTRODUCTION

In agricultural production, various cutting and shredding processes are commonly involved, such as severing stalks during harvesting, drilling soil during seeding, cutting weeds during weed control, and post-harvest processing. Currently, the mainstream approach in these operations involved direct contact with crops or soil using blades or trenchers, exerting significant force to separate the products *(Schuldt et al., 2018; Bremer et al., 2020; Ghosh et al., 2015).* However, these methods suffered from drawbacks such as low cutting efficiency, limited precision, frequent tool replacements and wear, the need for regular maintenance and upkeep of tools, different wear reduction treatments for vulnerable parts, and the potential for microbial cross-contamination and high energy consumption due to continuous contact between the tools and agricultural products. Therefore, it is necessary to develop and apply specific cutting technologies in agricultural production and processing that offer higher processing efficiency and performance. With the emergence of advanced cutting technologies like ultrasonic vibration-assisted cutting, laser cutting, plasma cutting, and water jet cutting, attempts had been made to address the limitations of traditional cutting methods *(Xu et al., 2022; Khatak, 2022; Krajcarz, 2014)*. These advanced cutting technologies were characterized by their high precision, high productivity, and green, safe, and sustainable features, that eliminated harmful chemicals, did not generate toxic gases or waste, and caused no pollution to the environment *(Gupta, 2020; Deng et al., 2018*). Water jet nozzles could achieve precise cutting and processing by allowing small movements and rotations, without compromising the material's quality and structure. Additionally, they prevent thermal deformation by avoiding high temperatures, preserving the material's original properties and shape. Furthermore, the absence of sparks and dust during operation significantly reduces the risk of worker injuries *(Chen et al., 2008)*.

As a non-thermal processing technique, water jet technology is well-suited for handling agricultural materials and serves as an excellent alternative technology *(Natarajan et al., 2020)*.

Since the early 1960s, researchers have been studying water jet processing technology and its applications. In the initial stages of development, water jet technology utilized pure water jet with limited cutting capabilities, applicable only to soft materials such as wood, fabric, and rubber *(Du et al., 1978; Wilkins et al., 1993; Hu et al., 2014)*. In 1983, the United States manufactured ultra-high-pressure abrasive water jet cutting machines that the cutting capabilities of water jet technology significantly improved. With the development of ultra-high-pressure abrasive water jet cutting, it became possible to cut almost all materials, including metals, ceramics, and granite *(Li et al., 2009)*. Water jet technology has found applications in various industrial sectors such as machining, chemical engineering, aerospace, industrial cleaning, and marine engineering, encompassing cleaning, cutting, crushing, drilling, and other processes, supported by various technologies and theories *(Lu et al., 2011; Li et al., 2008; Chen et al., 2007; Zhang et al., 2005)*. However, the research on water jet technology in the agricultural field is still relatively limited due to the diversity of agricultural materials. Moreover, the application of water jet in agriculture territory presented more complex challenges compared to factory environments, such as soil cutting and field harvesting.

When applying jet technology in the agricultural field, the predominant method is pure water jet. The parameters that affect its operational effectiveness can be classified into dynamic parameters such as jet pressure, flow rate, and power, structural parameters such as jet initial length and jet width, and engineering parameters such as operation time, movement speed, and jet impact angle. These parameters collectively influence the operational performance of water jet technology. Additionally, there are multiple evaluation metrics for water jet operations, including cutting depth, surface roughness, microbial counts, and raw material losses, which are important indicators for assessing operational quality. Overall, this review aims to explore the current research status and application potential of water jet technology in the agricultural field, considering the specific challenges posed by complex agricultural environments. The effects of various parameters on water jet performance will be investigated, and multiple performance indicators will be utilized to assess the quality of water jet operations.

The application of water jet technology in the agricultural field is primarily focused on four aspects: seeding, field management, harvesting, and post-harvest processing. In the seeding process, water jet technology enables precise seed placement and arrangement, thereby improving seed germination rates and seedling growth quality, ultimately increasing crop yield and quality. In field management, water jet technology can be used for soil moisture retention, weed removal, and precise water supply, facilitating precision farming and enhancing soil quality. For harvesting, water jet technology can be employed in crop picking, grass cutting, and other operations, offering efficiency, precision, and non-contact characteristics, which reduce labor costs and crop losses while improving harvesting efficiency. In post-harvest processing, water jet technology finds applications in cleaning, peeling, and cutting agricultural products. High-pressure water jet cutting, as a non-contact cutting technique, avoids blade dullness or contamination, effectively preventing cross-contamination and enhancing product hygiene, safety, freshness, shelf life, and added value. The research and practices in these application areas provide technical support and decision-making references for the sustainable development of agricultural production. The paper analyzes how to achieve specific functions, improve key indicators for different functions, and enhance operational quality and efficiency. Suggestions are provided for the development direction of water jet technology in specific functional applications, including deepening mechanistic research, adopting precision agriculture, and implementing intelligent control. Overall, this research aims to explore and advance the application of water jet technology in the agricultural sector, with the goal of promoting sustainable development in agriculture, enhancing operational quality, and increasing efficiency.

Water Jet Technology: Principles, Classifications, and Simulations

During the operation of a water jet system, purified water from the supply device is filtered, compressed, and mixed with the jetting medium in different ways (pre-mixing or post-mixing) to form the working fluid. Subsequently, the working fluid is ejected from a nozzle of a specific shape, generating a high-energy density jet in the form of a needle-like stream, which impinges on the surface of the target object. Under the continuous impact of the working fluid, the object undergoes cracking or fracturing until the cutting operation is completed. Therefore, water jet cutting is a dynamic destructive process *(Cui et al., 2022; Llanto, 2021; Pogrebnyak et al., 2020; Folkes, 2009)*.

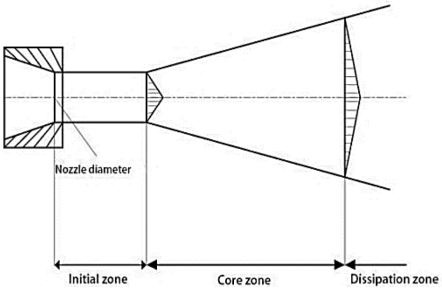


Fig.1 - Basic Structure of Water Jet

Water jet belongs to the typical fluid flow, and the jet will develop into a free jet after leaving the nozzle. Fig.1 divides the structure of a free jet into three sections: the initial zone, the core zone, and the dissipation zone *(Yu, 2018)*. In the initial zone, the jet remains compact with constant density and velocity, known as the core region of the jet. In the core zone, both the dynamic pressure and axial velocity of the jet gradually decrease. Due to the pulsation exchange with the surrounding air, the jet spreads out in a fan shape. The velocity distribution follows a similarity law, and the average velocity distribution across the jet section can be described by the following relationship *(Kang, 2016)*.

$$\frac{U}{U_c}=\left[1-\left(\frac{y}{y_{1/2}}\right)^{1.5}\right]^2 \tag{1}$$

where:

U_C denotes the velocity along the axis of the jet, while $y_{1/2}$ represents the half-value width of the jet.

The region following the main region is the dissipation region, where the axial velocity and dynamic pressure of the jet are relatively low, and the previously dense jet transforms into a large number of atomized droplets. Due to the distinct characteristics of different jet regions, their applications also vary. The initial region of the water jet is generally used for cutting and crushing, the main region is primarily used for cleaning and rust removal, and the dissipation region is mainly used for dust removal and spraying.

Water jet technology can be classified into three types based on the working medium: pure water jet, abrasive water jet, and liquid water jet *(Cheng et al., 2019; Lin et al., 2021; Li., 2009)*. The pure water jet is the traditional high-pressure water jet, where the working medium is solely water. The structure of high-pressure pure water jet cutting systems is relatively simple, but their cutting capabilities are limited and suitable only for soft materials such as paper, wood, rubber, carbon fiber fabric, etc. The abrasive jet involves adding abrasive particles like garnet or diamond, as well as solid abrasives like salt, ice, sugar grains, etc., to the working medium to enhance its cutting ability. The liquid water jet referred to a working medium that is a mixture of liquid media and water, primarily used in agricultural applications such as cutting soil for fertilization and sterilization *(Nyord et al., 2008)*. Based on whether the jet medium has been mixed with water before entering the nozzle, it could be further classified into pre-mixing and post-mixing methods *(Song, 2009)*. Pre-mixing referred to the mixing of abrasive or liquid jet media in a mixing device before entering the nozzle. Post-mixing involves mixing within the nozzle chamber itself, thereby requiring an additional inlet for the jet medium (as shown in Fig.2).

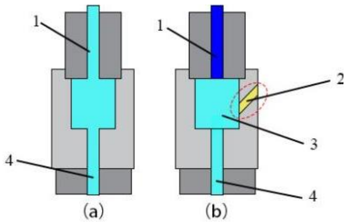


Fig.2 - Different jet nozzle structures of two mixing methods

(a) Pre-mixing jet nozzle; (b) Post-mixing jet nozzle

1.Fluid inlet; 2. Post-mixing medium inlet; 3. Mixing chamber; 4. Working fluid outlet

Currently, research methods for water jet applications in the agricultural field are mainly focused on traditional experimental approaches and optimization, with limited emphasis on simulation studies. Simulation research can assist in understanding the application effects of water jet technology in different processes, optimizing design parameters, improving efficiency, and reducing resource consumption.

Table 1

Several Mainstream Water Jet Simulation Methods

Simulation methods	Principle of operation	Applications
Computational Fluid Dynamics *(Zou et al., 2003; Song et al., 2019; Prisco et al., 2008; Kamarudin et al., 2016)*	Simulate water jets by solving fluid flow equations on discretized grids	Study parameters such as velocity distribution, pressure distribution, and jet shape
Finite Element Method *(Jianming et al., 2010; Jiang et al., 2020; Du et al., 2020)*	Modeling the interaction between the fluid and the material as deformation and fracture behavior	Analyze the cutting effects and stress distribution on different materials
Discrete Element Method *(Du et al., 2020; Horabik et al., 2016; Cheung et al., 2008; Zhao et al., 2013)*	Discretizing the particle system into individual particles and simulating their interactions forces and motion rules	Study the interaction between particles or between particles and fluids
Smoothed Particle Hydrodynamics *(Jianming et al., 2010; Jiang et al., 2020; Du et al., 2020; Vasudevan et al., 2022)*	Simulation technique based on the particle method	Simulate the motion and interaction of fluids and solids

Zou et al., (2023), employed the Euler Method-Volume of Fluid (VoF) model, a computational fluid dynamics (CFD) simulation method, to investigate the multiphase flow of air-water in abrasive water jet (AWJ) systems. The Euler-Lagrange method was further utilized to study the multiphase flow of abrasive particles. Valuable insights were provided to address the mixing issues in AWJ, improve abrasive acceleration processes, and extend nozzle lifespans. *Song et al., (2019),* used computational fluid dynamics methods to simulate the internal and external flow fields of nozzles. They compared and analyzed the velocity distribution in the flow fields of four commonly used conical convergent nozzles with different structures in water jet technology, as well as the impact pressures on target surfaces. Their findings concluded that the conical short-line nozzle is the most suitable nozzle for high-pressure water jet technology used in weld joint reinforcement. *Wang Jianming et al., (2010),* proposed a coupled Smoothed Particle Hydrodynamics (SPH)/Finite Element Method (FEM) approach to simulate abrasive water jet machining (AWJM) and analyze the material removal mechanisms. This method provided a useful approach for simulating AWJM and analyzing material removal mechanisms, which can be applied to optimize operational parameters and enhance process efficiency. *Hongxiang Jiang et al. (2020),* developed a numerical model for rock fragmentation using a coupled Smoothed Particle Hydrodynamics (SPH) and Finite Element Method (FEM). They simulated rock fragmentation under different conditions, investigated the assisting effect of high-pressure water jet on rock fragmentation, and evaluated the disturbance of water jet assistance on rock stress. The conclusion indicated that high-pressure water jet assistance could improve the working conditions of impact by reducing the peak stress on the punch head by more than 30%. *Mingming Du et al. (2020),* proposed a coupled SPH-DEM-FEM modeling approach to simulate the abrasive water jet (AWJ) machining process. The newly developed AWJ modeling method integrated SPH, DEM, and FEM into a single numerical model, enabling the reproduction of the actual high-speed response of workpieces and a better understanding of the incision formation process.

By establishing accurate simulation models, visual results such as flow field distribution, droplet trajectories, and pressure variations can be generated, which are advantageous for agricultural practitioners to gain a better understanding of the behavior and effects of water jets. This approach offers cost-effectiveness, improves efficiency in agricultural production and research, and promotes sustainability.

Application Status of Water Jet in the Agricultural Field

Seeding

Traditional seeding methods involve the use of arrow shovel-type trenchers, disc trenchers, and other tools. During operation, the seeding machine is driven forward by a tractor, and the pointed end forms a certain angle with the ground, facilitating soil penetration. The trench formed during the process is relatively even, but it comes with drawbacks such as high resistance, high energy consumption, significant soil disturbance, and susceptibility to wear, soil adhesion, and blockage caused by weed entanglement *(Liu, 2021; Wang et al., 2018; Lu, 2020)*.

Experimental research conducted by *Yang Yazhou et al., (2010),* on cutting corn straw with dynamic blades showed that the cutting performance deteriorates after the blades have been in operation for more than 660 minutes, necessitating blade replacement or sharpening. High-pressure water jet technology, as a non-contact cutting technique, can effectively address this challenge.

Fluid jet seeding is a high-pressure water jet technology for non-contact seed placement, offering advantages such as reduced energy consumption, fertilizer volatilization, soil disturbance, and environmental pollution *(Zheng et al., 2019)*. In 2001, *Du Ruicheng* proposed the concept of fluid jet seeding and designed an experimental device for water jet seed placement, verifying its feasibility on soil with a moisture content of 15.5% to 18.5%. *Du Ruicheng et al. (2006)* determined the parameter ranges for direct water jet seeding on leveled bare soil to be a water jet time of 0.6 seconds and a jet pressure of 0.5-0.6 MPa. For water jet seeding under plastic film, the parameter ranges were a water jet time of 0.6-1.0 seconds and a jet pressure of 1.8-2.0 MPa (as shown in Fig.3). These experimental findings demonstrated the feasibility of fluid jet seeding.

(a) Experiment result of punching without film mantled

(b) Experiment result of punching with film mantled

Fig. 3 - Experiment result of punching (*Du et al., 2006*)

To achieve high-speed jet flow, Sun Jie designed the nozzle in the shape of a conical convergent-divergent tube and ensured that the nozzle outlet size satisfied two principles. Firstly, it needed to provide sufficient outlet velocity since a larger nozzle size would result in lower outlet velocity under constant pressure. Secondly, it needed to ensure smooth seed ejection, necessitating a nozzle diameter larger than the maximum radial diameter of the seeds *(Sun, 2006)*.

Yang Zidong, (2010), designed a water content-controlled jet seeding device, which employed an AT89C51 microcontroller as the core and integrated various functional modules to complete the entire control process. Seed placement was achieved through water jet hole formation and pneumatic acceleration of seeds into the holes. The experimental results showed that the seed placement rate exceeded 98% when the seeding machine's moving speed was below 1 m/s. When the speed exceeded 2 m/s, the percentage of seeds properly placed in the holes reached 95%. This technology has pioneering and innovative significance for the study of non-contact seeding methods.

In recent years, conservation tillage has been widely promoted. The benefits of conservation tillage are mainly reflected in effective reduction of soil erosion, water and nutrient retention, increased soil organic matter content, simplified farming operations, cost reduction, and its crucial role in ensuring high and stable crop yields. No-tillage seeding is a key component of conservation tillage *(Zhou, 2022)*. No-tillage seeding involves complex field conditions with abundant crop residues covering the surface. The tough and difficult-to-cut crop residues can lead to issues such as blockage and seed drying during the no-tillage seeding process, thereby affecting seeding efficiency and quality. Therefore, it is necessary to cut the crop stems to prevent blockages. In recent years, research on improving residue cutting and blockage prevention has mainly focused on optimizing the shape and structure of passive cutting disc devices. However, tool wear affects cutting efficiency and is an unavoidable issue in direct contact-based passive cutting methods.

Hu Hongnan et al. conducted a full factorial design with three operational parameters as variables to investigate the effect of pure water jet cutting parameters on the cutting performance of corn stalks *(Hu et al., 2019)*. A depth model for pure water jet cutting of corn stalks was established. The experimental results revealed that higher jet pressure, lower traverse speed, and shorter target distance led to improved cutting performance and increased cutting depth. According to the research findings, all the samples of corn stalks can be effectively cut when the isolation distance is less than 10 mm and the water jet pressure is 280 MPa (as shown in Fig.4).

Taking into account the field operating conditions, Hongnan Hu recommends using water jet pressure of 280 MPa or higher and maintaining a target distance between 10 mm and 15 mm for cutting corn stalks. These parameters are suggested for the cutting operation of corn stalks, considering the practical conditions encountered in agricultural fields.

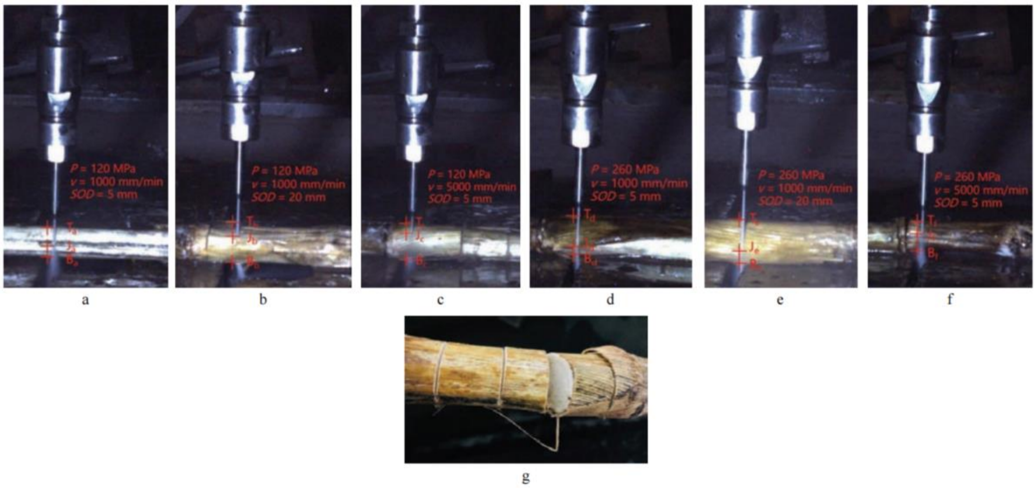


Fig.4 - High speed photographs of maize stalks with different operation parameters(a-f), and (g) maize stalks after waterjet cutting (*Hu et al., 2019*)

T represents the top point of the maize stalks; B represents the bottom point of the maize stalks; J represents the deepest point of waterjet.

Additionally, Hongnan Hu employed the Arbitrary Lagrangian-Eulerian Finite Element Method (ALE-FEM) to simulate the process of water jet cutting of stalks. The accuracy of the model was verified through high-speed cameras. Building upon the simulation studies conducted by Hongnan Hu, further field experiments were carried out using an ultra-high-pressure water jet-assisted no-tillage planter (*Hu et al., 2020*). This field experiments demonstrated that, compared to the hoe-type furrow opener, the double-disc furrow opener combined with the ultra-high-pressure water jet (Fig.5) showed better performance. Optimization analysis indicated that when the water jet pressure ranged from 267 MPa to 280 MPa, the jet impact angle was between 80.2° and 90.0°, and the forward speed was between 4.00 km/h and 4.42 km/h, the straw cutting rate exceeded 95% when the non-contact jet cutting device and the double-disc furrow opener worked in conjunction, with no occurrence of blockage during the operation. *Francesco Perotti (2021),* conducted experimental research on abrasive water jet cutting of wheat straw and found that adding a small amount of abrasive powder to pure water jet can effectively enhance the cutting ability.

Fig. 5 - Non-contact jet cutting stalk-free tillage anti-blocking device *(Hu et al., 2020)*

Currently, high-pressure water jet has been applied in agricultural seeding and has achieved certain results. However, further optimization of the structure and water jet parameters is still needed in practical applications. Moreover, it is important to deepen the research on the mechanism of high-pressure jet cutting of plant stems and soil impact. This will contribute to reducing the size and weight of the entire machine, lowering costs, and offering extensive prospects and societal value. Continuous exploration and innovation are required in this field.

Field Management

Fertilization

In the field of crop fertilization, traditional methods such as broadcasting, furrow application, and foliar spraying have been found to have low fertilizer utilization efficiency, high soil disturbance, and potential environmental damage *(Xiang et al., 2008)*. Deep placement of fertilizers has emerged as a promising direction for development. This method involves injecting liquid fertilizers directly into the soil using high-pressure water jets, allowing them to be deposited near the roots of crops. As a result, the efficiency of fertilizer utilization is significantly improved.

The use of liquid fertilizers eliminates issues related to uneven distribution, nutrient loss, and blockages associated with solid fertilizers. Compared to traditional fertilization methods, this approach minimizes soil disturbance while achieving high fertilizer utilization rates.

Studies conducted by *Lu Yulong et al. (2016),* on the distribution of rice seedling root systems revealed that the main longitudinal range of rice seedling roots is within 0-50 mm. Therefore, a cutting depth of 50 mm is sufficient to meet the depth requirements for fertilization. *Niemoeller et al. (2011),* investigated the feasibility of injecting pure water using high-pressure water jets. Experimental results showed that different injection depths can be achieved by adjusting various parameters of the high-pressure jet. In soil with an average moisture content of approximately 25%, an injection depth of 70-90 mm was achieved under the conditions of 40 MPa water pressure, 7.5 L/min volumetric flow rate, and 2 m/s propulsion velocity. It should be noted that soil moisture significantly influences the injection depth of the pure water jet under the same parameters. The experimental results demonstrated that the cohesion of the soil in dry conditions is considerably strong, and the injection depth increases with increasing soil moisture content. *Zheng Wenzhan et al. (2019),* conducted design and experimental research on a jet-type fertilization machine for rice. The machine employed a high-pressure jet to introduce liquid fertilizer into a mixing chamber, where negative pressure generated by the mixing chamber allowed the liquid fertilizer to be sucked in. The fertilized mixture was then sprayed through a nozzle, representing a fertilization technique involving liquid and water mixing injection. Simulation experiments indicated that the cutting ability of the soil was strongest when the inlet and outlet diameters of the liquid fertilizer were 0.6 mm and 0.8 mm, respectively. The highest fertilization volume was achieved when the inlet and outlet diameters were both 1.0 mm. Under experimental conditions with a jet pressure of 12 MPa, forward velocity of 0.5-0.7 m/s, and fertilization target distance of 10-30 mm, the fertilization depth could reach 25-45 mm. Zheng Wenzhan also compared the yields obtained from different fertilization methods, and the results showed that the jet-type fertilization machine for deep placement had a significant yield-increasing effect compared to traditional broadcasting and topdressing operations.

The application of jet impact technology with appropriate pressure parameters for soil fertilization is a development direction with broad application prospects. It is of great significance in improving fertilizer utilization efficiency, reducing environmental pollution, and minimizing soil disturbance. Further research is needed to deepen our understanding of the mechanisms involved in jet impact on soil and to develop more comprehensive simulation models for jet impact on soil. This will provide a broader space for practical production applications and the future development of jet technology.

Weed Control

Chemical weed control methods pose challenges in terms of pollution, while biological weed control can disrupt the ecological balance, and traditional mechanical methods require regular sharpening, cleaning, and blade replacement *(Wang et al., 2016; Coleman et al., 2019; Colquhoun et al., 2019)*. In contrast, high-pressure water jet weed control provides a new non-contact mechanical approach that can overcome these issues *(Zhang, 2012)*. *Zhang Lin (2013),* conducted experiments using Artemisia annua as the test subject and found that a water jet pressure of 13.5 MPa was sufficient to cut it. Among the four factors affecting hydro-cutting, the nozzle's lateral movement speed had the greatest impact, followed by water jet pressure, target distance, and nozzle diameter. *Ishida Yasumasa (2005),* conducted experiments on cutting rice seedlings and found that the best cutting effect was achieved under the experimental conditions of a nozzle diameter of 0.4 mm, a water jet angle of 45 degrees with the seedlings, and the highest water jet pressure. *Assirelli et al., (2022),* designed a high-pressure water jet weeder with four nozzles, each with a diameter of 0.16 mm, a constant water jet pressure of 100 MPa, and a movement speed of 1.2-2.6 km/h. Experimental studies showed that the weeding effect was directly related to the distance between the nozzle and the weeds, and comparative tests demonstrated that the high-pressure water jet weeder performed comparably to inter-row hoeing machines. The use of high-pressure water jet weed control is a promising and sustainable weed management solution. However, the experiments did not demonstrate effective capability in maintaining parallelism between the working head and the soil surface, directly affecting the weeding ability. Alberto Assirelli also pointed out that from the perspective of precision agriculture, the water quantity of the high-pressure water jet weeder can be quantitatively adjusted to intervene efficiently according to different operational requirements, even doubling the intervention at specific necessary points. To ensure the quality of the operation, Alberto Assirelli designed the weeder with a water jet pressure of 100 MPa, which may lead to excessive pressure and resource waste. However, many experimental studies have shown that high water jet pressures are not necessary for weed control operations and precise regulation of water usage can help reduce the size of agricultural machinery, increase working hours, and improve efficiency (as shown in Fig.6) *(Assirelli et al., 2022; Schield, 1972)*. The adoption of new weed control technologies needs to demonstrate high efficiency, reliability, and proven economic feasibility.

Fig. 6 - Weed soil coverage (%) immediately after the Grass Killer test on 11 November 2020.
Left and right picture represent GK 2.7km h^{-1} and GK 1.2km h^{-1} forward speeds, respectively

Harvesting

Due to the complex field environment, there has been limited research on the application of high-pressure water jet in field harvesting of crops, and the depth of research is relatively shallow. As early as 1972, *Schield (1972)* verified the feasibility of water jet harvesting of lettuce and designed a horizontal jet cutting machine for harvesting lettuce crops. It was pointed out that when using a given nozzle system to cut different crops, the toughness of vascular fibers is more important than the stem diameter. To reduce the weight of mobile machines for harvesting sugar beets using high-pressure water jets, *Juenemann et al., (2010),* studied jet spreading and impact during high-pressure water jet cutting of sugar beets. The experiments showed that almost all cutting water could be collected in a compact area. To achieve this, a compact water collection device was designed to recycle the cutting water, thereby reducing the amount of water that needs to be carried. The recovered cutting water contains impurities such as sludge and sugar, which do not meet the water quality requirements of the high-pressure pump. Therefore, an appropriate wastewater treatment process needs to be determined. *Junemann et al., (2011),* pre-treated the wastewater by centrifugation for solid-liquid separation to counteract the clogging effect of the filter. Then, qualitative filter paper and quantitative membrane filters were used for filtration operations to ensure that the maximum particle size was below 0.5 μm or 1 μm. Regarding the removal of dissolved components, especially sugar, it can be achieved through reverse osmosis. Sugarcane mechanical harvesters use rotating base cutting machines for cutting operations, but the rotating cutting tool components are prone to entanglement with leaves, and materials such as stones and weeds in the field environment also accelerate blade wear. Therefore, high-pressure water jet cutting is considered an effective alternative. Valco pointed out that the cutting efficiency of sugarcane straw is mainly determined by the magnitude of the impact force rather than the erosion of the water jet on the material, and the erosion time-dependent effect is not the primary cutting mechanism for sugarcane *(Valco, 1979)*. *Valco et al. (1989),* conducted cutting experiments on sugarcane under experimental conditions of nozzle diameter of 0.23-0.36 mm, nozzle pressure of 200-400 MPa, movement speed of 1.6-4.8 km/h, and target distance of 3-23 cm. It was concluded that the target distance had a significant impact on sugarcane cutting, while the nozzle pressure and nozzle size had a significant impact, and the influence of lateral movement speed was not significant.

Water jet cutting capacity and the sustainable working time of the nozzle system are important indicators for field harvesting equipment. These can be improved through methods such as using appropriate abrasives, increasing the utilization rate of cutting water, and adjusting machine parameters. Further research is needed in this area.

Post-harvest Processing

Cutting

Irwansyah et al. (2012), conducted experiments using high-pressure water jet cutting on samples of polycarbonate, polystyrene, and polyethylene with a thickness of 2mm, which have similar properties to agricultural products. The results showed that the water jet system has great potential for cutting materials with suitable contour surfaces and can also improve the surface quality of cut food products. *Wulfkuehler et al., (2014),* used a water jet with a nozzle diameter of 0.1 mm and water pressure of 250 MPa to cut red oak leaf lettuce. The experiments showed that compared to blade cutting, water jet cutting does not affect the microbiological, physiological, and sensory qualities of fresh cut lettuce. *Carreño-Olejua et al., (2010),* conducted cutting experiments using a kitchen knife, a handheld slicer, and a high-pressure water jet. The water jet parameters used were pressure of 240 MPa, nozzle diameter of 0.1 mm, cutting speed of 5 mm/s, and distance of 15 mm. The experimental results showed that the surfaces of the specimens cut by water jet had better surface smoothness compared to traditional cutting tools and handheld slicers. *Alitavoli et al., (1998),* conducted research on water jet cutting process planning for soft materials and identified control variables during the cutting process, including water jet pressure, transverse speed, nozzle diameter, and distance between the nozzle and the workpiece. *Becker et al., (1992)*, used a water jet cutting machine to slice potato tubers and observed the irregularities on the cut surface using non-specific protein staining. The study showed that among five samples with cutting pressures ranging from 69 to 345 MPa, the sample with the highest water jet pressure of 345 MPa exhibited the least irregularities in groove shape and depth on the potato cut surface. By controlling the water pressure, nozzle hole diameter, and cutting speed, the sub-surface damage depth was obtained. The results showed that regardless of water pressure or cutting speed, the smallest nozzle plate diameter resulted in the least cell damage and achieved the best cutting performance. As the cutting size increased, the influence of water pressure and cutting speed became more significant, and at lower cutting speeds and moderate water pressures, surface cell damage was more severe. In order to improve labor efficiency, *Lin, J. et al., (2017),* designed an automatic strawberry calyx removal machine equipped with a jet pressure of 206.8 MPa, which combined color-based machine vision. Using Autodesk Inventor 2012 software to solve constraint equations, the optimal direction of strawberries was determined through dynamic simulation at a conveyor speed of 300 mm/s. Tests showed that when the machine processed medium-sized strawberries at a maximum speed of 2270 kg/h, the weight percentages of calyx-free berries, berries with calyx white shoulder, residual fruits, and reversed fruits were 49.6%, 18.2%, 8.1%, and 24.1%, respectively. Within a 95% confidence interval, the errors were 4.2%, 2.5%, 2.7%, and 4.3%, respectively. It is worth noting that reversed fruits can be fed back to the AVID machine for a second processing. This second processing will generate yields similar to the first processing, depending on the quality of the fruits. The results showed that it is a feasible and cost-effective option for automated industrial-scale calyx removal. To further improve product quality, they also suggested developing a more reliable multi-axis calyx removal system to accommodate a wider range of shapes and sizes.

When using pure water jet technology for cutting agricultural products, typically ultra-high-pressure jet pressures of 200 MPa or above are employed. Higher cutting pressures are advantageous for improving the cutting capability and quality of pure water jet cutting, including enhancing surface smoothness and reducing cell damage. Due to the atomization spray of the water jet column, it is preferable to minimize the distance between the nozzle and the target object. In terms of nozzle selection, using the smallest nozzle can achieve optimal cutting results. When performing cutting operations on specific agricultural products, water jet parameters should be adjusted according to their specific geometric shapes. It is particularly important to note that cost can be effectively reduced and economic benefits can be enhanced by lowering hydraulic parameters.

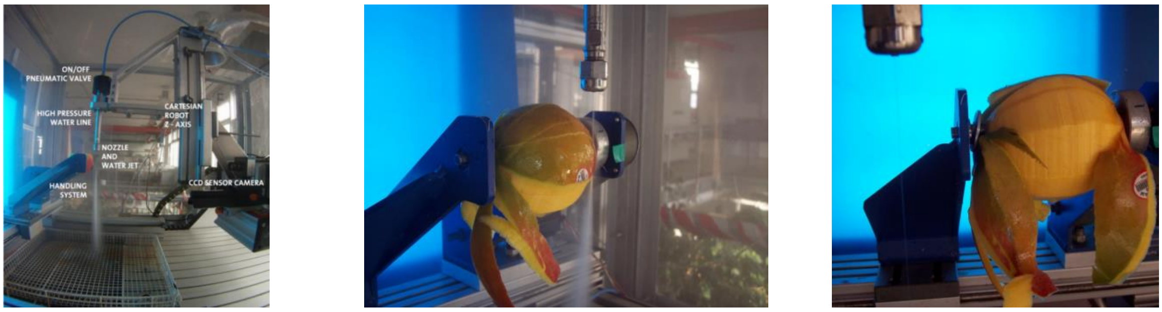
Peeling Processing

With the development of water jet technology, water jet has also been applied to the peeling process of agricultural products. Mainstream methods such as friction peeling, chemical peeling, and high-pressure steam peeling are difficult to meet production needs *(Chen et al., 2016; Fadeyibi et al., 2020; Singh et al., 1995)*. Friction peeling relies on friction to remove the skin of fruits and vegetables, which can easily damage the surface and affect color. Chemical peeling can alter the color of the skin and affect taste and color. High-pressure steam peeling can cause surface ripening, potentially affecting quality. However, using water jet peeling can avoid these problems.

The quality requirements for peeled lotus seeds are relatively high. In 2009, Cao Zhiqiang designed an integrated lotus seed shelling and peeling machine *(Cao, 2009)*. In this machine, lotus seeds are individually washed and peeled using high-pressure water jets, achieving a peeling rate of over 97%. The processed lotus seeds have a quality comparable to manual processing, and the water consumption is only one-third of conventional methods. Most lotus seed shelling and peeling machines on the market use a bilateral structure. In response to the complexity and maintenance difficulties of bilateral machines, *Xu Xieqing et al., (2021),* designed a lotus seed peeling machine with a single-sided structure.

Compared to bilateral machines, this single-sided structure machine is more compact, stable, and has reduced maintenance difficulties and machine failure rates. In addition, the issue of not being able to repeat processing on lotus seeds using lotus seed shelling and peeling machines often requires additional manual labor for hand peeling. *Xu Xieqing, (2014),* designed a fresh lotus seed peeling machine based on water jet peeling that can repeat the processing of lotus seeds. This machine uses two symmetric water jets to strike the surface of the rotating lotus seed along its longitudinal axis in a clamped state, completing the peeling process. When using water jet peeling on lotus seeds, it is important to determine the range of jet impact force to ensure that the force is just enough to remove the skin without damaging the lotus flesh and affecting the quality. Based on multiple repeated experiments, it has been found that the maturity of lotus seeds has a significant impact on the peeling effect. Typically, the peeling pressure parameters for mature lotus seeds range from 0.6 to 0.8 MPa. In addition, water jet pressure, water jet angle, and processing speed are also key factors affecting the peeling effect. By using Design-expert software, the influence of these factors on various indicators can be determined and the operating parameters can be optimized. The water jet test pressure range for the fresh lotus seed peeling machine is 0.6 to 0.8 MPa, and the optimal operating parameter is determined to be 0.7 MPa. Experimental results show that the optimized fresh lotus seed peeling machine achieves a peeling rate of 92.63%, which basically meets the operational requirements.

Carreño-Olejua conducted water jet cutting and peeling operations on agricultural products using an automated experimental setup. Under the condition of water jet pressure at the nozzle ranging from 292 to 308 MPa, they obtained the water jet cutting pressure variation graph by using the nozzle diameter and motor frequency as control variables. Based on this graph, they were able to perform cutting and peeling operations on agricultural products. The University of Applied Sciences of Konstanz, Germany, has applied for patents for several methods using this technology for fruit peeling. They have also conducted cutting tests on various geometrically shaped agricultural products such as apples, melons, mangoes, and pineapples, determining parameters such as traverse speed, spacing, material thickness of different agricultural products, and impact angle. *Olejua et al., (2009),* combined robotics, water jet technology, and image processing techniques to achieve peeling and cutting operations on fruits such as cantaloupes, mangoes (as shown in Fig.7), and pineapples, demonstrating the potential of the system in terms of agricultural product processing quality. They suggested that the use of stereoscopic vision can be optimized as it can eliminate errors caused by eccentric fruits, thereby improving processing quality.



(a) Experiment setup of water-jet automation

(b) Cut of a mango cortex controlled by photography

(c) Final product

Fig.7 - Water Jet Cutting Mango *(Olejua et al., 2009)*

In the process of using waterjet technology for peeling agricultural products, particularly those with high-quality requirements, it is essential to conduct prior experimental research on their physical and mechanical characteristics. This research aims to determine suitable waterjet parameters and optimize them using specialized software. Currently, the application of waterjet technology for peeling agricultural products relies on specific structural designs and parameter ranges based on the physical and mechanical characteristics, as well as geometric shapes of different agricultural products. Integration with technologies such as image processing and robotics can further optimize the peeling process, minimize peel loss, and enhance peeling efficiency.

Summary and prospects

Water jet technology, as a non-contact advanced technique, holds great potential for various applications in the agricultural field. Its unique advantages include the absence of heat generation, blade wear, and pollution. Extensive research has been conducted on the application of water jet technology in four key areas: sowing, field management, harvesting, and post-harvest processing. Water jet technology has become an important tool in agricultural production. However, its application in the agricultural sector is still in its early stages, especially in complex outdoor environments where weather conditions significantly affect its performance, posing challenges for implementation.

When targeting specific objectives, the parameters of water jet technology have varying degrees of influence, different ranges, and distinct research focuses. Currently, adjustments to jet parameters and working media are mainly achieved through experimental trials to enhance operation quality and efficiency, with limited emphasis on simulation studies. To further promote the application of water jet technology in agriculture, in-depth research should be conducted in the following three areas: Firstly, combining simulation and experimental investigations to deepen the understanding of the impact mechanism of water jet technology on agricultural products, soil, and other operational objects. This research will help clarify the evolution process of jet impacts and identify influential factors. Secondly, optimizing the design of agricultural machinery, adjusting parameters such as jet angles, movement speeds, and jet pressures. These optimizations will contribute to improving cutting capabilities, reducing equipment size, and lowering costs. Lastly, moving towards the development of intelligent agricultural equipment by integrating technologies such as machine vision, robotics, and image processing with water jet technology. This integration will enable real-time monitoring of the operational process and automatic adjustment of parameters, expanding the scope of technological convergence across multiple domains.

By delving into these research directions, the application of water jet technology in agriculture can be further enhanced, unlocking its full potential for improving productivity, efficiency, and sustainability in agricultural operations.

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