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Biological Recovery of Agricultural Soil Impacted by 110,000 ppm of Waste Motor Oil

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Abstract: In agricultural soil, the machinery used for land cropping preparation generates waste motor oíl (WMO), a mixture of aliphatic and aromatics hydrocarbons registered in México as hazardous waste under the General Law of Ecological Balance and Environmental Protection. This WMO causes loss of fertility and can even contaminate surface water and aquifers. Agricultural soil impacted by WMO can be bioremediated by the recomendations of SEMARNAT Standard 138 proposes actions for bioremediation when soil hydrocarbons mixing level exceed 4,400 ppm, by biostimulation with a detergent, a mineral solution, a crude fungal extract, a crude extract of biodetergents and lipases in order to eliminate the WMO. Therefore, the objective of this research was Biological recovery of an agricultural soil impacted by 110,000 ppm of waste motor oil. To achieve this, the agricultural soil was biostimulated with a 1% detergent, a 50% mineral solution, crude fungal extracts, biodetergents, nanoparticles of carbon, lipases and 1% H_2O_2, and field capacity at 80% during each months for 6 months, the concentration of WMO in the soil was determined by Soxhlet as well as the pH, the data were analyzed by ANOVA/Tukey (<0.05%). The results showed that soil impacted by 110,000 ppm decreased to 913 ppm of WMO, and the pH decreased from 6.8 to 4.4, these values were statistically different from those registered in soil contaminated by WMO non biostimulated, that decreased from 110,000 to 76,712 ppm due to natural attenatuion and pH change from 6.8 to 5.5 in the same period. It is concluded that this multiple biostimulation strategy in soil impacted by a high concentration of WMO, was effective in reducing it to a value below 1000 ppm, as specified by NOM-138-SEMARNAT/SSA1-2012, similar to the concentration of hydrocarbons in soils not contaminated by this type of hydrocarbon mixtures.

Keywords: Agricultural soil; Hydrocarbons mixture; High concentration; Complex bioremediation; Health environmental

Introduction

In agricultural areas of México of the world, intensive agriculture employs machinery that requires gasoline and petroleum-derived lubricating oil. When these hydrocarbon mixtures reach the end of their useful life, are improperly disposed (FAO and UNEP, 2021; Stepanova et al., 2022; Majeed et al., 2025); as well as waste motor oil (WMO), a complex mixture of aliphatic and aromatic hydrocarbons, heavy metals from engine wear, and synthetic additives. This WMO mixture limits its mineralization causes soil contamination, since altered the soil's physical, chemical, and biological properties, reduced agricultural productivity biodiversity of this environmental associated to natural attenatuion to eliminate any mixture of hydrocarbons as WMO is (Arjoon & Speight, 2020), besides that and negatively impacting surface water and aquifers (Sui et al., 2021). Therefore, in México, WMO is classified as a hazardous waste under the General Law of Ecological Balance and Environmental Protection, given its high toxicity to life in general. While NOM-138-SEMARNAT/SSA1-2012 in Mexico indicates that the maximum concentration of WMO for agricultural soil is 4,440 ppm. In México, and of the world, technology exists for the possible remediation of soil impacted by WMO, depending on factors such as the concentration of the hydrocarbon mixture, using physicochemical and biological methods (Varjani, 2017; Falih et al., 2024). Bioremediation or biological recovery by biostimulation with a detergent, since for the hydrophobic nature of aliphatic especially aromatic and polycyclic hydrocarbons, following by biostimulation with a mineral solution containing inorganic nitrogen (N) and phosphorus (P) compounds, induces the aerobic heterotrophic native microbiota to oxidize any type of hydrocarbon (Yan et al., 2015; Ji et al., 2019; Xu et al., 2021; Daâssi & Qabil, 2022). The literature reports biostimulation in soil contaminated by concentration levels between 10,000 and 100,000 ppm of WMO, but not higher, that is closer to what actually happens. Therefore, the objective of this research was biological recovery of an agricultural soil impacted by 110,000 ppm of waste motor oil.

Materials and Methods

This research at the greenhouse of the Environmental Microbiology Laboratory (EML) Research Institute in Biology and Chemistry at Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Mich., México. Under greenhouse environmental conditions with average values: T = 23.2°C, luminosity = 450 μmol • m^2/s, relative humidity = 67%. The agricultural soil was collected from 19°37’10” north latitude and 101°16’41.00” west longitude, with an altitude of 2013 meters above sea level, The agricultural soil for this experiment was collected from Tenencia Morelos, Zapata, in the municipality of Morelia, Michoacán, México, where *Zea mays* is cultivated, located at kilometer 5 of the Morelia-Pátzcuaro highway. The soil’s physicochemical properties were: a pH of 6.8, a high organic matter content of 10.44%, a medium total nitrogen content of 0.32%, and a high phosphorus content of 219.34 ppm, with a silty-clay texture which are shown in **Table 1**, based on these properties, the integrated bioremediation was applied. This soil was sieved and solarized for 48 h to reduce the risk of pests and plant diseases. On **Table 2** is showed a completely randomized experimental design with two controls and one treatment was used, for which 1.0 kg of soil was placed in the upper part of the Leonard jar and mineral solution or water in the lower part. The absolute control soil was the one not contaminated by WMO, the negative control soil was contaminated by 110,000 ppm of WMO from a mechanical workshop located in the city of Morelia, Michoacán, México, and the only treatment was the soil biostimulated initially with the commercial detergent ROMA® at 1.0% (v/v) to emulsify the WMO, then it was biostimulated with the mineral solution at 50% with the chemical composition (g/L): NH_4NO_3 10.0, K_2HPO_4 2.5, KH_2PO_4 2.0, $MgSO_4$ 1.0, NaCl 0.1, $CaCl_2$ 0.1, $FeSO_4$ 0.01, and 10.0 mL of microelement solution with the chemical composition (g/L): H_3BO_3 2.86, $ZnSO_4 \cdot 7H_2O$ 0.22, $MgCl_2 \cdot 7H_2O$ 1.81 applied every 3 days for 6 months to maintain field capacity at 80%, then biostimulated with $CaCO_3$ to maintain pH between 6.8 and 7.0; for the following biostimulation that hydrolyzes aromatics from the WMO, with a crude fungal extract (CFE) with *A. niger* and/or *P. chrysogenum* from the EML, grown in residual lignin broth from wheat straw with this chemical composition (g/L): wheat straw 10.0, casein peptone 5.0, yeast extract 1.3, K_2HPO_4 0.17, KH_2PO_4 2.61, $MgSO_4$ 1.5, NaCl 0.9, $CuSO_4$ 0.05, 2.5 mL of 10% (w/v) detergent and 1.0 mL/L of a trace element solution, adjusted to pH 5.5 sterilized at 121°C/15 min. The broth inoculated with *A. niger* and/or *P. chrysogenum* was shaken at 120 rpm/30°C/5 days; the mycelium of both fungi was separated by centrifugation at 8,000 rpm/4°C/15 min. This CFE was applied every third day for a month with a volume of 44 mL and the remainder of the mineral solution at 50%. For the next biostimulation, a crude extract of biodetergents and bacterial lipases (CEBL) was prepared from *S. rhizophila* and *X. autotrophicus* taken from the EML collection; grown in the culture medium with WMO with this chemical composition (g/L): WMO 10 mL, casein peptone 5.0, yeast extract 2.5, K_2PO_4 1.0, KH_2PO_4 1.0, $MgSO_4$ 1.0, NaCl 0.5 and 1.0 mL of trace element solution, c pH at 6.5, this WMO broth was inoculated with *S. rhizophila* and *X. autotrophicus* shaken at 50 rpm/30°C/3-5 days, then centrifuged at 5,000 rpm/15 min at 4°C to separate the bacterial cells from the WMO broth and by decantation the CEBL for the next biostimulation with a volume of 22 mL/Kg of soil every third day for a month and the difference the mineral solution at 50%. In the following biostimulation, 1% H_2O_2 was applied mixed with 44 mL/kg of soil of 1% H_2O_2 every three days with the 50% mineral solution. In the subsequent biostimulation, 36 mL of the 50% mineral solution, 36 mL of CFE, 36 mL of CEBL, and 36 mL of 1% H_2O_2 were applied every three days per 1.0 kg of soil for one month.

At the beginning and in each biostimulation, the WMO concentration was quantified by the Soxhlet method, using 10 g of soil and ether. Simultaneously, the pH was measured with 10 g of soil dissolved in 90 mL of distilled water. All experimental results were subjected to analysis of variance (ANOVA) and Tukey's HSD test ($p < 0.05$) using the Statgraphics Centurion XVI statistical package.

Figure 1. Diagram of biological recovery of an agricultural soil impacted by 110,000 ppm of waste motor oil

Table 1. Physicochemical properties of agricultural soil non polluted by waste motor oil

Parameter	Value	Interpretation
pH	6.8	Moderately acid
Organic matter (%)	10.44	Very high
Texture (%)	31.8 (clay), 26.92 (sand), 42.0 (silt)	Silty-clay
Total, Nitrogen (%)	0.32	Medium
Phosphorus ppm	219.34	Very high
Sodium (Na+) ppm	153.38	High
Potassium (K+) ppm	168.61	High

Table 2. Experimental design for the integrative biostimulation of an agricultural soil contaminated by 110,000 ppm of waste motor oil.

Agricultura soil*	110,000 ppm of Waste motor oil	Detergent at 1.0%	Mineral solution	Crude fungal extract	Crude extract of biodetergents and lipases	H_2O_2 at 1%
(AC) absolute control	-	-	-	-	-	-
(NC) negative control	+	-	-	-	-	-
Integrative biostimulation	+	+	50	+	+	+

*Number of repetitions (n) = 6: added (+); not added (-)

Table 3. Concentration of residual waste motor oil in agricultural soil after integrative biostimulation

Agricultural soil*	Dynamics of waste motor oil (WMO) removal in fully bioremediated remaining agricultural soil in days (D)						
	D-0	D-30	D-60	D-90	D-120	D-150	D-180
Absolute control non polluted by WMO	-	-	-	-	-	-	-
Negative control polluted by WMO	110,000[a**]	98,983[b]	92,755[b]	89,133[b]	81,684[b]	77,019[b]	76,712[b]
Polluted by WMO with integrative biostimulation	110,000[a]	77,210[a]	61,985[a]	41,055[a]	20,320[a]	8,512[a]	913[a]

*n = 6; **different letters indicate statistical difference according to ANOVA/Tukey ($p < 0.05$).

Table 3 shows that the agricultural soil used as a negative control, contaminated by WMO without biostimulation, exhibits the natural attenatuion of this environment. Due to the interaction of a combination of physicochemical and biological factors dependent on the soil type, WMO decreased from 110.00 to 76.712 ppm in 180 days. This minimal decrease was caused by the inhibition of the activity of the native, aerobic, heterotrophic microbiota, which mineralizes WMO but has a limited capacity to absorb the toxicity of high molecular weight aromatics and some polycyclic compounds (Li et al., 2024).The remaining value of 76.712 ppm was so high that it prevents the soil from performing the fundamental environmental services that occur in soil not contaminated by hydrocarbon mixtures, such as: generating plant-based food, purifying water through filtration, serving as a source of biodiversity, and acting as a carbon reserve, since the 76.712 ppm of WMO far exceeds the maximum value of The numerical value of 76,712 ppm of WMO, compared to the 4,440 ppm limit established by NOM-138-SEMARNAT/SSA1-2012, was statistically different from the numerical value of 913 ppm registered in the same soil contaminated by 110,000 ppm WMO. In the latter case, comprehensive biostimulation reduced the WMO concentration to 913 ppm, a value lower than the 4,400 ppm limit established by NOM-138-SEMARNAT/SSA1-2012. This latter value is similar to the concentration registered in soil naturally uncontaminated by hydrocarbon mixtures. This contrasts sharply with the WMO-contaminated soil that underwent comprehensive biostimulation, initially using a detergent that emulsified the WMO (Cheng et al.,2017; Lamichhane et al., 2017), thereby reducing the surface tension of the hydrocarbon mixture and facilitating WMO diffusion to initiate the oxidation of the aliphatic hydrocarbons (Sutthicharoen et al., 2023). In the complex soil texture matrix, direct and effective contact with the diversity of aerobic heterotrophic microorganisms was achieved through biostimulation with a mineral solution containing essential nitrogen, phosphorus, and potassium compounds, as well as micronutrients (Nasr, 2019. This rebalanced the carbon: nitrogen: phosphorous (C:N:P) ratio, triggering a biological chain reaction by the aerobic heterotrophic microbiota, such as the β-oxidation of aliphatic hydrocarbons. This process decreased the WMO concentration from 110,000 to 61,985 ppm in 60 days. Subsequent biostimulation with the crude fungal extract (CEF), containing laccase and other extracellular enzymes associated with the hydrolysis of WMO aromatics, released long-chain fatty acids (Ukalska-Jaruga and Smreczak, 2020). Consequently, WMO toxicity was reduced, preventing the loss of soil biodiversity (Lamichhane et al., 2017). Integrative biostimulation of the heterotrophic aerobic microbiota by detergent, mineral solution, crude fungal extract, crude biodetergent extract, and lipases (CEBL) ensured the continuous removal of WMO, leading to its progressive mineralization from 61,985 to 41,055 ppm of WMO in 90 days. Biostimulation by CEBL increased the solubilization of hydrophobic fractions of WMO hydrocarbons that were not emulsified by the initial biostimulation with the commercial detergent at the beginning of the experiment. Biostimulation by CEBL lipases accelerated the depolymerization of the aliphatic fractions of WMO, facilitating rapid mineralization (Effendi et al., 2017: Karlapudi et al., 2018; Sánchez-Mata et al., 2023). This was further enhanced by biostimulation with the microbial mineral solution, which, by correcting the soil's nutritional balance, decreased the WMO concentration from 41,055 to 20,320 ppm by day 120 of the trial. Since the simultaneous biostimulation of H_2O_2 at 1%, ensured the mineralization of the recalcitrant hydrocarbons of the WMO, so that the concentration of the WMO was reduced from 20,320 to 8,512 ppm in 150 days. While simultaneous biostimulation with the 50% mineral solution, ECF, EBLB, and 1% H_2O_2 enhanced WMO mineralization, reducing it from 8,512 to 913 ppm after 180 days of assay, 913 ppm of WMO is relatively lower than the maximum approved by NOM-138-SEMARNAT/SSA1-2012 of 4,400 ppm (Gouthami et al., 2023) Furthermore, 913 ppm of WMO is similar to the natural hydrocarbon concentration in soil never contaminated by a mixture like WMO, implying that this soil can be used for agricultural production for safe human or animal consumption.

Table 4. pH dynamics during the integrative biostimulation of an agricultural soil contaminated by 110,000 ppm of waste motor oil

Agricultural soil*	WMO concentration per days or time						
	T-0	T-30	T-60	T-90	T-120	T-150	T-180
(AC) Absolute control non polluted by WMO irrigated with water	6.8[a]	6.8[a]	6.8[a]	6.8[a]	6.8[a]	6.8[a]	6.8[a]
(NC) Negative control polluted by WMO	6.8[a]	6.1[b]	6.1[b]	5.8[b]	5.8[b]	5.7[b]	5.5[b]
Polluted by WMO by Integrative biostimulation*	6.8[a]	5.8[c*]	5.5[c]	5.2[c]	5.2[c]	4.7[c]	4.4[c]

. *n = 6; **Different letters indicate statistical difference according to ANOVA/Tukey ($p < 0.05$)

Table 4 shows the pH dynamics in agricultural soil not contaminated with WMO, irrigated only with water, where the pH showed minimal variation. This uncontaminated soil was affected by a high level of organic matter and total available nitrogen, supporting the idea that of these essential elements explain the activity of the heterotrophic aerobic microbiota for the mineralization of native organic matter during the 180 days of the experiment. In contrast, the soil contaminated by 110,000 ppm of WMO without integrative biostimulation, used as a negative control (NC), showed a decrease in pH from 6.1 to 5.5 due to the excess of WMO hydrocarbons, especially the toxic fraction, that prevented the soil's natural attenuation from sufficiently reducing the WMO concentration. Simultaneously, there was minimal generation of hydrogen ions from the oxidation of some low-molecular-weight aliphatic hydrocarbons in the WMO. These values were statistically different from the initial pH of 6.8 when the WMO concentration was 110,000 ppm, that then decreased to 4.4 as the WMO concentration was reduced to 913 ppm (Pandolfo et al., 2023). This decrease resulted from the integrative biostimulation of the heterotrophic aerobic microbiota by the detergent and mineral solution, followed by biostimulation from a crude fungal extract containing enzymes to hydrolyzes the aromatic hydrocarbons in the WMO. Biostimulation by the crude biodetergent extract and lipases ensured the continuous oxidation of the aliphatic and aromatic hydrocarbons in the WMO hydrolyzed by the crude fungal extract, particularly through biostimulation with H_2O_2, that increased the oxygen necessary for the rapid oxidation of the various types of WMO hydrocarbons (Adedeji et al., 2022). These hydrocarbons, converted into fatty acids, acidified the soil pH, supporting the idea that despite the high concentration of WMO, it is possible to biorestore the soil's functionality for essential environmental services.

Conclusion

The relatively high concentration of WMO in agricultural soil by 110,000 ppm indicates that bioremediation through biostimulation requires a complex and combined approach, such as WMO. This demonstrates that it is possible to improve the microbial potential in agricultural soil and is a highly effective strategy for the bioremediation of impacted agricultural soil. Biostimulation and constant soil moisture control allowed for a reduction in the concentration of ARA from 110,000 to 913 ppm in 180 days, a value lower than that established by NOM-138-SEMARNAT/

SSA1-2012 and comparable to that which occurs naturally in soils not impacted by hydrocarbons and derivatives. This reduction was accompanied by a decrease in pH from 6.8 to 4.4, demonstrating the effective activation of the native microbiota and its oxidizing capacity on complex fractions of WMO. In contrast, in soil by WMO or NC, unbiostimulated the reduction was limited and microbial activity was lower. Based on this result, biostimulation can be considered a practical and ecological solution for the biological remediation of soil contaminated by a relatively high concentration of a hydrocarbon mixture such as WMO.

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Application of Smart Agriculture Technologies in Facility Vegetable Cultivation

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Abstract: Against the backdrop of the global transition of agriculture toward digitalization and intelligence, facility vegetable cultivation, as an important component of modern agriculture, urgently requires technological innovation to achieve high-quality development. Smart agriculture technologies, characterized by the deep integration of information technology and agricultural production, have provided new opportunities and development pathways for the transformation and upgrading of facility vegetable cultivation. This paper focuses on the application of smart agriculture technologies in facility vegetable cultivation, elaborating on the practical use of the Internet of Things (IoT), big data, and artificial intelligence in environmental monitoring, precision regulation, and pest and disease control. The economic, social, and ecological benefits generated by these technologies are analyzed, existing problems in the application process are examined, and targeted development strategies are proposed, aiming to provide references for promoting the intelligent development of facility vegetable cultivation.

Keywords: smart agriculture technology; facility vegetable cultivation; application

Introduction

With the continuous improvement of living standards, demand for vegetables is increasing, accompanied by higher expectations for quality and safety. Facility vegetable cultivation plays a crucial role in ensuring a stable vegetable supply and occupies a key position in modern agriculture. However, traditional facility vegetable cultivation suffers from low resource utilization efficiency, high labor intensity, and extensive production management, making it difficult to meet the requirements of high-quality agricultural development. Smart agriculture technologies, integrating advanced information technologies such as the Internet of Things, big data, and artificial intelligence, provide a new pathway for the transformation and upgrading of facility vegetable cultivation. These technologies enable precision management and intelligent decision-making, enhance overall production efficiency, and are of great significance for ensuring vegetable supply and promoting sustainable agricultural development.

1. Current Application Status of Smart Agriculture Technologies in Facility Vegetable Cultivation

In recent years, the application of smart agriculture technologies in facility vegetable cultivation has gradually expanded. In some developed regions and large agricultural enterprises, smart agriculture demonstration parks have been initially established, realizing intelligent monitoring and management of cultivation environments and production processes. For example, some parks have deployed sensors and intelligent equipment to collect environmental data in real time and use intelligent control systems to automatically regulate greenhouse environments, significantly improving vegetable yield and quality. However, overall, the application of smart agriculture technologies in facility vegetable cultivation remains at a developmental stage, characterized by uneven application coverage and limited technology penetration. Most small- and medium-scale growers have yet to widely adopt smart agriculture technologies.

2. Analysis of Key Smart Agriculture Technologies Applied in Facility Vegetable Cultivation

2.1 Internet of Things (IoT) Technology

IoT technology forms the foundation of smart agriculture applications in facility vegetable cultivation. By deploying temperature and humidity sensors, light sensors, soil moisture sensors, and carbon dioxide sensors within greenhouses, environmental parameters such as air temperature, humidity, light intensity, soil moisture, and CO_2 concentration can be collected in real time. These data are transmitted to data centers via wireless networks, enabling growers and managers to monitor greenhouse conditions through mobile applications or computer terminals. Based on preset environmental thresholds, IoT systems can automatically control ventilation equipment, shading nets, irrigation systems, and supplemental lighting facilities, thereby achieving precise regulation of vegetable growth environments.

2.2 Big Data Technology

During facility vegetable cultivation, IoT devices generate massive volumes of data, including environmental data, production data, and pest and disease data. Big data technology enables efficient storage, management, and analysis of such data [1]. By analyzing historical environmental and crop growth data, vegetable growth models can be established to reveal growth patterns of different vegetable varieties under varying environmental conditions, providing a scientific basis for precision cultivation. In addition, big data technology can analyze market data to predict price trends and demand changes, helping growers optimize planting plans and reduce market risks.

2.3 Artificial Intelligence Technology

Artificial intelligence technology is primarily applied in pest and disease diagnosis and production decision-making in facility vegetable cultivation. Using image recognition technology, disease and pest symptoms on vegetable leaves can be captured and analyzed. By comparing these images with pest and disease databases, the system can quickly and accurately identify pest types and provide corresponding control measures. In production decision-making, AI algorithms integrate environmental, growth, and market data to offer intelligent recommendations on crop variety selection, planting density, fertilization, and irrigation schemes, further enhancing the scientific and precise nature of production management.

2.4 Intelligent Irrigation Technology

Intelligent irrigation technology combines soil moisture sensors with irrigation control systems to achieve on-demand irrigation. By monitoring soil moisture in real time and adjusting irrigation volume and timing according to water requirements at different growth stages, intelligent irrigation can reduce water consumption by 30%–50% compared with traditional methods. It also effectively prevents soil compaction and root diseases caused by over-irrigation, significantly improving water use efficiency and vegetable growth quality.

2.5 Intelligent Greenhouse Control Systems

Intelligent greenhouse control systems integrate IoT, big data, and artificial intelligence technologies to realize comprehensive automated control of greenhouse environments. These systems automatically regulate temperature, humidity, light, and CO_2 concentration based on crop growth requirements, creating optimal growth conditions. More importantly, real-time monitoring and analysis enable early detection of abnormalities and timely alerts, allowing growers to take corrective measures to ensure normal crop growth.

3. Problems in the Application of Smart Agriculture Technologies in Facility Vegetable Cultivation

3.1 High Technology Costs

Smart agriculture technologies require significant initial investment in sensors, intelligent equipment, and software systems. For small- and medium-scale growers, the high cost of equipment is often prohibitive. In addition, operation and maintenance expenses, including equipment repair, data transmission fees, and system upgrades, further increase application costs.

3.2 Shortage of Professional Talent

Smart agriculture technologies are interdisciplinary, requiring professionals proficient in both agricultural production and information technology. At present, China faces a shortage of specialized agricultural technical personnel, particularly high-level professionals skilled in smart agriculture. Most growers lack the knowledge and skills to effectively apply these technologies, while agricultural enterprises also struggle to attract and retain qualified talent.

3.3 Data Security and Privacy Protection Issues

Smart agriculture systems generate large volumes of agricultural data, including sensitive production and operational information. As the value of agricultural data increases, data security and privacy protection face serious challenges [2]. Data leakage or tampering could cause significant economic losses and production risks. Furthermore, existing laws and regulatory frameworks for agricultural data security and privacy protection remain insufficient.

3.4 Insufficient Technology Integration and Compatibility

Smart agriculture involves multiple technologies and products from different manufacturers, often with incompatible communication protocols and data formats. This increases integration difficulty and limits data sharing across systems, undermining overall effectiveness. In addition, older facility vegetable production bases often face compatibility issues between existing equipment and new technologies, further increasing costs and implementation challenges.

4. Development Strategies for Smart Agriculture Technologies in Facility Vegetable Cultivation

4.1 Strengthening Policy Support and Financial Investment

Policy guidance and financial support are critical drivers for promoting smart agriculture technologies. Governments should establish systematic policy frameworks covering research, promotion, and application. Special development plans should define objectives, key tasks, and implementation pathways, incorporating smart agriculture into local agricultural modernization strategies.

A diversified funding mechanism should be established, including special subsidies covering 30%–50% of equipment purchase costs. R&D investment should focus on key bottleneck technologies such as low-cost sensors and domestically produced intelligent control chips.

4.2 Enhancing Professional Talent Development

To address talent shortages, a comprehensive system integrating academic education, vocational training, and talent introduction should be established. Universities should expand smart agriculture-related programs, while vocational institutions focus on practical skill training. For existing growers, tiered training programs combining online and offline platforms and field-based instruction should be implemented. Competitive incentive policies should be introduced to attract high-level professionals and improve career development pathways [3].

4.3 Improving Data Security and Privacy Protection Systems

A comprehensive framework integrating legislation, technology, and supervision should be established. Laws such as an Agricultural Data Security Management Regulation should clarify data rights and responsibilities. Advanced technologies such as homomorphic encryption and federated learning should be adopted to protect data. Dedicated regulatory agencies and security certification systems should be implemented to ensure compliance with international standards.

4.4 Promoting Technology Integration and Standardization

4.4.1 Formulating National Standards

National standards covering sensor interfaces, communication protocols, and data formats should be developed to ensure interoperability and standardization in facility vegetable cultivation systems.

4.4.2 Encouraging Enterprise Participation in International Standardization

Enterprises should be encouraged to participate in international standard-setting activities to enhance China's influence in global smart agriculture development [4].

4.4.3 Strengthening Industry–University–Research Collaboration

Collaborative innovation platforms should be established to support joint research and demonstration projects, providing replicable application models.

4.4.4 Promoting Enterprise Innovation and Product Upgrading

Enterprises should be encouraged to develop proprietary core technologies and improve equipment compatibility. Policy incentives and technology transfer platforms should accelerate the transformation of research achievements into practical applications.

Conclusion

Smart agriculture technologies hold broad prospects and significant potential in facility vegetable cultivation. They can substantially enhance economic, social, and ecological benefits and promote agricultural modernization. Although challenges such as high costs, talent shortages, data security risks, and insufficient integration persist, these issues can be gradually addressed through strengthened policy support, talent development, data security systems, and technology integration. Ultimately, smart agriculture technologies will play a greater role in ensuring vegetable supply and advancing sustainable agricultural development.

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Original Research Article

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Constraints and Recommendations for the Promotion of Agricultural Machinery Technology

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Abstract: The promotion of agricultural machinery technology is constrained by multiple factors, including dependence on external technologies, inadequate equipment performance, low integration between agricultural machinery and agronomy, underdeveloped infrastructure, insufficient policy and financial support, and limited acceptance among farmers. To advance agricultural mechanization, it is recommended to strengthen independent research and development, improve the performance and adaptability of agricultural machinery, deepen the integration of machinery and agronomy, enhance infrastructure development, improve policy systems and increase investment, and reinforce farmer training to raise technology acceptance. Through these measures, the widespread promotion and application of agricultural machinery technology can be facilitated, thereby improving agricultural production efficiency and quality.

Keywords: promotion of agricultural machinery technology; constraining factors; recommendations

Introduction

The promotion of agricultural machinery technology is a key measure for advancing agricultural modernization and improving agricultural production efficiency. However, in the practical process of promotion, many constraints remain, such as insufficient independent innovation in agricultural machinery technology, inadequate equipment performance, weak integration between machinery and agronomy, imperfect policy support and service systems, and limited acceptance of new technologies by farmers. This paper analyzes these constraining factors in depth and proposes targeted recommendations to provide effective support for the promotion and application of agricultural machinery technology.

1. Current Status of Agricultural Machinery Technology Promotion

1.1 Development History of Agricultural Mechanization

The development of agricultural mechanization can be traced back to the Industrial Revolution in the 18th century, when the application of steam-powered machinery marked the beginning of agricultural mechanization. At the end of the 19th century, the invention of the internal combustion engine gave rise to key agricultural machinery such as tractors, driving revolutionary changes in agricultural production. Entering the 21st century, with the rapid development of intelligent technologies, agricultural mechanization has entered a new stage, with intelligent agricultural machinery and precision agriculture technologies becoming major development trends.

1.2 Major Achievements in the Promotion of Agricultural Machinery Technology

(1) Improvement in agricultural machinery equipment levels.

In recent years, China has made remarkable progress in the research, development, and manufacturing of agricultural machinery equipment. A number of high-end intelligent agricultural machines, such as pneumatic electric-driven high-speed precision seeders and intelligent high-speed rice transplanters, have been successfully introduced to the market, breaking long-term dependence on imports and significantly improving the overall level of agricultural machinery equipment.

(2) Expansion of mechanized operation areas.

With the increasing level of agricultural mechanization, the coverage of mechanized operations has expanded continuously, encompassing more farmland and crop types. Especially during key farming seasons, such as the “Three Summers” period, the deployment of large numbers of combine harvesters has ensured the stable supply of grain and other important agricultural products.

(3) Improvement in agricultural production efficiency.

The widespread application of agricultural mechanization has significantly improved production efficiency, reduced production costs, and increased farmers’ incomes. The use of intelligent machinery and precision agriculture technologies has further promoted the development of agricultural production toward greater efficiency, precision, and sustainability.

2. Analysis of Constraints on the Promotion of Agricultural Machinery Technology

2.1 Limitations of Agricultural Machinery Products

(1) Dependence on imported core technologies and key components.

China’s agricultural machinery products are highly dependent on imports for core technologies and key components, which not only increases manufacturing costs but also restricts independent innovation and market competitiveness. Once international supply chains are disrupted, domestic machinery production and supply will be directly affected, thereby threatening agricultural production stability.

(2) Insufficient performance and adaptability of domestic machinery.

Although domestic agricultural machinery has improved significantly in recent years, considerable gaps remain compared with advanced foreign machinery, particularly in adapting to different regions and crop production requirements. Further research and development are needed to meet diversified agricultural production demands [1].

(3) Low industrial development level and severe homogenization.

The overall development level of China’s agricultural machinery equipment industry remains relatively low, and insufficient innovation capability has led to serious product homogenization. This intensifies market competition, reduces overall equipment quality, and hinders the formation of core competitiveness, which is unfavorable for the sustainable development of the industry.

2.2 Coordination Issues Between Machinery, Agronomy, and Farmland

(1) Insufficient integration of agricultural machinery and agronomy.

Agricultural machinery and agronomy are two pillars of modern agricultural production, and their integration is essential for modernization. Currently, insufficient consideration of agronomic requirements in machinery design leads to operational mismatches, negatively affecting operation quality and efficiency.

(2) Lagging infrastructure for mechanized operations.

Inadequate infrastructure, such as narrow field roads and uneven farmland, results in difficulties such as “difficulty entering fields” and “difficulty in operation.” These issues increase operating costs and restrict the widespread application of agricultural machinery.

(3) Mismatch between farmland layout and mechanized operation requirements.

Complex terrain and fragmented plots in some areas prevent effective mechanized operations, limiting the role of machinery and slowing the mechanization process.

2.3 Insufficient Policy Support and Management Services

(1) Incomplete agricultural mechanization policy

system.

Although various policies have been introduced, deficiencies remain in implementation and enforcement, affecting the overall progress of agricultural mechanization.

(2) Weak public service capacity and low informatization.

Agricultural machinery promotion institutions in some regions lack demonstration sites, equipment, and transportation facilities. Limited informatization also prevents farmers from accessing timely technical and market information.

(3) Insufficient and poorly structured talent pool.

The shortage of high-quality professionals and an unbalanced talent structure limit innovation and efficiency in machinery promotion [2].

2.4 Limited Funding for Technology Promotion

(1) Insufficient fiscal investment at national and local levels.

Limited funding restricts the acquisition of advanced machinery for demonstration and promotion.

(2) Uneven allocation of promotion funds.

Disparities in funding distribution result in uneven promotion outcomes across regions.

2.5 Farmer Acceptance and Human Capital Constraints

(1) Low acceptance of new technologies among farmers.

Concerns over costs, risks, reliability, and adaptability discourage farmers from adopting new technologies.

(2) Impact of rural aging and low educational levels.

Population aging and skill shortages hinder effective technology adoption and modernization.

3. Recommendations for Improving the Effectiveness of Agricultural Machinery Technology Promotion

3.1 Strengthening R&D and Manufacturing Capacity

(1) Enhancing independent R&D of core technologies and components.

Special funds, enterprise innovation incentives, and industry–university–research collaboration should be strengthened, alongside intellectual property protection.

(2) Improving performance and adaptability of domestic machinery.

Testing, evaluation, and targeted optimization should be enhanced to meet diverse production needs.

(3) Promoting high-quality industrial development and reducing homogenization.

Industry planning, standard setting, and support for innovative enterprises should be reinforced to cultivate internationally competitive manufacturers [3].

3.2 Advancing Coordination Between Machinery, Agronomy, and Farmland

(1) Strengthening machinery–agronomy integration.

Promoting integrated technologies tailored to different crops and systems can improve efficiency.

(2) Improving operational infrastructure.

Investments in field roads, irrigation, drainage, and maintenance facilities are essential.

(3) Optimizing farmland layout.

Land consolidation and circulation should be encouraged to support mechanized operations.

3.3 Improving Policy Systems and Public Services

(1) Formulating and refining mechanization policies.

Clear objectives, effective implementation, and supervision mechanisms are required.

(2) Enhancing public service systems and informatization.

Digital platforms and information sharing should be expanded to improve service coverage.

(3) Cultivating and attracting professional talent.

Training systems, talent mobility, and incentive mechanisms should be strengthened [4].

3.4 Increasing Investment in Technology Promotion

(1) Expanding fiscal investment.

Stable funding mechanisms and social capital participation should be encouraged.

(2) Optimizing fund allocation.

Scientific project evaluation and strict supervision should ensure efficient use of funds.

3.5 Enhancing Farmer Acceptance and Capacity

(1) Strengthening publicity and awareness.

Training, demonstrations, and online outreach should highlight technological benefits.

(2) Improving skills and technological literacy.

Comprehensive training systems and practical education bases should be established.

(3) Introducing incentive mechanisms.

Subsidies, rewards, and recognition can encourage adoption and demonstration effects.

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Conclusion

In conclusion, the promotion of agricultural machinery technology faces multiple challenges. However, through strengthening independent innovation, improving machinery performance, deepening machinery–agronomy integration, and enhancing farmer training, these obstacles can be effectively addressed. With continued technological advancement and improved policy environments, agricultural machinery technology will play an increasingly vital role in advancing agricultural modernization and high-quality agricultural development in China.

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Original Research Article

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Exploration of Organic Vegetable Cultivation Techniques

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Abstract: With the growing awareness of healthy diets and environmental protection, organic vegetable cultivation techniques have attracted increasing attention. This paper provides a comprehensive exploration of organic vegetable cultivation techniques. Starting from the definition and characteristics of organic agriculture, it systematically analyzes the basic requirements and key technologies of organic vegetable production, including variety selection, soil management, irrigation and drainage, and integrated control of pests, diseases, and weeds. In response to common problems encountered during cultivation, corresponding solutions are proposed. The aim is to promote high-quality and efficient production of organic vegetables, meet market demand, and foster sustainable agricultural development.

Keywords: organic agriculture; vegetable cultivation techniques; problems and solutions

Introduction

In today's pursuit of green, healthy, and sustainable development, organic vegetable cultivation techniques have gained increasing importance. Based on natural laws and ecological principles, these techniques reject synthetic chemical substances and genetic modification technologies, aiming to maintain ecological balance and enhance the quality of agricultural products. This paper conducts an in-depth study of organic vegetable cultivation techniques, covering definitions and characteristics, key technologies, as well as common problems and corresponding solutions. The objective is to provide comprehensive guidance for growers, promote the development of organic agriculture, and achieve harmonious coexistence between agriculture and the environment.

1. Overview of Organic Vegetable Cultivation Techniques

1.1 Definition and Characteristics of Organic Agriculture

(1) Concept, principles, and differences from conventional agriculture.

Organic agriculture is a production system that follows natural laws and ecological principles. It emphasizes sustainability by optimizing interdependent relationships within agricultural ecosystems without using synthetic chemical substances or genetically modified technologies. The core principles of organic agriculture include environmental protection, biodiversity conservation, soil health maintenance, and the production of safe and healthy food. Compared with conventional agriculture, organic agriculture places greater emphasis on ecological balance and environmental protection, avoiding pollution and ecological damage. It replaces chemical fertilizers and pesticides with organic fertilizers and biological pesticides, controlling pests, diseases, and weeds through natural methods and achieving harmony between agricultural production and the natural environment.

(2) Advantages and challenges of organic agriculture.

The advantages of organic agriculture are mainly reflected in the following aspects. First, it helps protect the environment by reducing chemical pollution and maintaining ecological balance. Second, organic agricultural products are more nutritious, have better taste, and are more favored by consumers. Finally, the development of organic agriculture can promote the optimization and upgrading of agricultural industrial structures, increase farmers' income, and stimulate rural economic development. However, organic agriculture also faces challenges such as high production costs, strict technical requirements, and relatively low market recognition. These issues require joint efforts from governments, enterprises, and consumers through policy support, technological innovation, and market guidance.

1.2 Basic Requirements for Organic Vegetable Production

(1) Selection and construction requirements of production bases.

The selection of production bases is crucial for organic vegetable production, as it directly affects product quality and safety. Production bases should be far away from pollution sources such as chemical plants and sewage treatment facilities to ensure clean soil, water, and air. The soil should have good physical properties and fertility, be rich in organic matter, and be free from chemical contamination. In addition, production bases should be equipped with sound irrigation and drainage systems to ensure adequate water and nutrient supply during vegetable growth. During construction, environmental protection concepts should be followed, and eco-engineering technologies should be adopted to minimize environmental impact.

(2) Types and application standards of organic fertilizers.

Organic fertilizers are indispensable in organic vegetable production. They mainly originate from animal and plant residues, excreta, and organic wastes, which are converted into plant-available nutrients through microbial action. Common organic fertilizers include compost, well-decomposed crop residues, and manure. When applying organic fertilizers, scientific and standardized principles should be followed, with reasonable formulation and application based on soil test results and vegetable growth requirements. Fertilizers must be fully decomposed to prevent the spread of pests and diseases and avoid soil pollution.

(3) Principles and methods of pest, disease, and weed control.

Pest, disease, and weed control is a key component of organic vegetable production. The principle of prevention first and integrated control should be followed, combining biological, physical, and chemical control measures. Biological control includes the use of natural enemies and plant extracts; physical control relies on factors such as light, heat, electricity, and sound; chemical control strictly limits the use of pesticides and only allows low-toxicity and low-residue products when necessary. Strengthening field management, improving the growth environment, and enhancing plant resistance can further reduce the incidence of pests and diseases.

2. Key Technologies for Organic Vegetable Cultivation

2.1 Variety Selection and Seed Treatment

(1) Selection of varieties adapted to local soil, climate, and market demand.

Variety selection in organic vegetable cultivation should fully consider local natural conditions, including soil type, climate, and water resources. Varieties well adapted to local conditions can improve survival rates and yields while reducing pest and disease problems caused by environmental stress. Market demand is also an important factor; varieties favored by consumers and with strong market potential should be selected to ensure economic benefits.

(2) Seed selection and treatment methods with strong resistance and adaptability.

High-quality seeds are the foundation of high vegetable yields. Priority should be given to seeds with strong resistance to pests and diseases and good adaptability. Seeds should undergo necessary treatments such as disinfection and germination promotion to enhance germination rates and stress resistance. Disinfection can eliminate pathogens and insect eggs on seed surfaces, while germination treatment accelerates emergence and improves uniformity [1].

2.2 Sowing and Seedling Cultivation Techniques

(1) Selection of sowing time and determination of sowing rate.

Sowing time significantly affects vegetable growth and yield. Appropriate sowing periods should be determined based on local climate conditions and crop growth characteristics. Sowing too early or too late may result in poor growth or reduced yields. Sowing rates should also be scientifically determined to ensure efficient land use while avoiding excessive density that can lead to poor ventilation, light penetration, and increased pest and disease incidence.

(2) Seedling cultivation methods.

Seedling cultivation is a critical stage in vegetable production. Scientific methods can produce strong seedlings and lay the foundation for high yield and quality. Suitable substrates, such as mixtures of decomposed organic fertilizers and river sand, should be selected to provide favorable growth conditions. Temperature, humidity, and light should be strictly controlled during seedling cultivation to meet growth requirements.

2.3 Soil Management and Fertility Improvement

(1) Methods to enhance soil organic matter content and fertility.

Soil is the basis of vegetable growth. Increasing soil organic matter and fertility is essential for improving yield and quality. This can be achieved through the application of organic fertilizers, straw incorporation, and green manure planting. Regular deep plowing and loosening improve soil structure and enhance water and nutrient retention capacity.

(2) Types of organic fertilizers and application techniques.

Organic fertilizers vary in nutrient content and effectiveness. During application, fertilizers should be appropriately selected and combined based on soil test results and crop nutrient requirements. Attention should be paid to the degree of decomposition and application rates to avoid root or seedling damage.

(3) Soil improvement and fertilization planning.

For soil problems such as acidification or salinization, targeted improvement measures should be implemented, such as applying lime or gypsum to regulate pH, and using organic and microbial fertilizers to improve structure and fertility. Fertilization plans should be developed according to crop growth stages and nutrient demands and strictly implemented.

2.4 Irrigation and Drainage Management

(1) Selection of irrigation methods and water control.

Irrigation is essential for vegetable growth. Appropriate irrigation methods and precise water control can improve water use efficiency and promote growth. Water-saving methods such as drip and sprinkler irrigation reduce evaporation and seepage losses. Irrigation volumes should be adjusted according to growth stages and weather conditions.

(2) Design and maintenance of drainage systems.

Well-functioning drainage systems prevent waterlogging, reduce soil moisture, and lower pest and disease risks. System design should consider terrain and soil conditions to ensure smooth drainage. Regular maintenance and cleaning are necessary to prevent blockages and damage [2].

(3) Water quality safety and water resource management.

Irrigation water quality directly affects vegetable safety and quality. Monitoring and management should ensure compliance with standards. Water-saving technologies should be promoted to improve efficiency and reduce waste.

2.5 Pest, Disease, and Weed Control Technologies

(1) Application of biological control methods.

Biological control is an environmentally friendly and effective approach. Introducing natural enemies and applying plant extracts can suppress pests. For example, lady beetles and hoverflies can control aphids, while neem and matrine extracts are effective against various pests without harming the environment or human health.

(2) Physical control measures.

Physical control directly interferes with pest habitats. Common methods include yellow sticky traps, light traps, and pheromone traps. Yellow traps exploit pest attraction to color, light traps use phototaxis, and pheromone traps disrupt mating behavior, reducing reproduction rates [3].

(3) Agricultural control measures.

Agricultural control optimizes ecosystem structure and management, including crop rotation, intercropping, and scientific field management. Rotation disrupts pest habitats, while intercropping uses plant interactions to suppress pests. Timely weed removal, pruning, and thinning also reduce pest incidence.

(4) Principles and restrictions of chemical control under special conditions.

Although organic agriculture avoids chemical pesticides, limited use of low-toxicity, low-residue, bio-based pesticides is permitted under severe outbreaks when other methods fail. Strict standards must be followed, including approved pesticide selection, proper dosage, and residue safety assurance, along with enhanced supervision and testing.

3. Problems and Solutions in Organic Vegetable Cultivation

3.1 Common Problems Encountered

During organic vegetable cultivation, common challenges include insufficient soil fertility and frequent pest and disease outbreaks. Poor soil fertility directly affects growth and quality, leading to yield reduction, while pest and disease outbreaks increase costs and threaten product safety and consumer trust.

3.2 Analysis of Causes

The main causes include improper cultivation techniques, inadequate management, and unfavorable environmental conditions. Some growers lack scientific knowledge of soil improvement, fertilization, and pest control. In addition, organic cultivation requires refined management and continuous monitoring, which may be neglected. Adverse environmental factors such as extreme weather and soil pollution also negatively affect production.

3.3 Solutions and Improvement Measures

(1) Strengthening technical training and guidance.

Governments, agricultural departments, and industry associations should enhance training and promotion of organic cultivation techniques. Experts should provide on-site guidance through training courses and field demonstrations to improve growers' skills and management capacity.

(2) Improving soil management and fertilization plans.

Scientific soil management and fertilization plans based on soil testing and crop requirements are essential. Organic fertilizers should be applied rationally to increase organic matter and improve structure. Crop rotation and intercropping reduce nutrient loss and enhance fertility [4].

(3) Integrated application of multiple control measures.

Pest and disease control should follow preventive and integrated approaches, prioritizing biological and physical methods to reduce environmental impact. Chemical pesticides, if necessary, should strictly comply with organic standards and application guidelines.

Conclusion

In summary, organic vegetable cultivation techniques represent not only an innovation over traditional agricultural models but also a proactive exploration of sustainable development. These techniques require respect for nature and environmental protection, using scientific methods to enhance quality and yield. In the face of challenges, continuous strengthening of technological research, extension, and grower training is essential. Only through joint efforts can organic vegetable cultivation be widely promoted, achieving green, healthy, and sustainable agricultural development and leaving a better planet for future generations.

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Original Research Article

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Research Challenges and Optimization Strategies for Agricultural Robots in Smart Agriculture Scenarios

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Abstract: With the rapid advancement of science and technology, smart agriculture, as an important direction of agricultural modernization, is gradually transforming traditional agricultural production models. Agricultural robots, as a key supporting technology of smart agriculture, play a vital role in improving agricultural production efficiency, reducing labor intensity, and realizing precision agriculture. However, at present, agricultural robots face numerous difficulties in the process of research and development, which severely restrict their widespread application in actual agricultural production. This paper aims to conduct an in-depth analysis of the research and development challenges of agricultural robots in smart agriculture scenarios and proposes targeted optimization strategies, providing theoretical support for promoting the development and application of agricultural robot technologies.

Keywords: smart agriculture; agricultural robots; R&D challenges; optimization strategies

1. Introduction

Smart agriculture is a new type of agricultural production mode that deeply integrates modern information technologies with agriculture, encompassing advanced technologies such as the Internet of Things, big data, artificial intelligence, and robotics. As an important component of smart agriculture, agricultural robots can perform various tasks in complex agricultural environments, including sowing, fertilization, weeding, and harvesting. Their application not only alleviates the shortage of agricultural labor but also significantly improves the precision and efficiency of agricultural production, reducing resource waste and environmental pollution [1]. However, due to the particularity and complexity of agricultural production environments, the research and development of agricultural robots is highly challenging and faces a series of difficulties related to technology, cost, and the market. Therefore, in-depth research on these challenges and the proposal of effective optimization strategies are of urgent practical significance.

2. R&D Challenges of Agricultural Robots in Smart Agriculture Scenarios

2.1 Technical Bottlenecks and Insufficient Control and Coordination

Agricultural production environments are complex and variable, with factors such as light intensity, temperature, humidity, and terrain constantly affecting the perception systems of agricultural robots. In natural environments, continuous changes in light intensity and angle can lead to unstable image quality captured by vision sensors, thereby affecting the accuracy of identifying crop growth conditions, pest and disease status, and obstacles [2]. In orchards, fruits are often occluded by leaves, making it difficult for traditional vision-based target recognition algorithms to accurately detect and locate fruits, resulting in inefficient operation of harvesting robots. In addition, different soil textures and terrain conditions pose challenges to robot navigation and mobility, as existing positioning technologies often suffer from reduced accuracy in complex terrains, leading to positioning deviations.

Secondly, agricultural production tasks are diverse, requiring a high degree of operational flexibility from robots. Taking harvesting operations as an example, different crops vary greatly in shape, size, and maturity, and fruits differ in attachment positions and growth postures. This requires harvesting robots to have highly flexible and adaptive end-effectors capable of gently grasping fruits in different states while avoiding damage. However, most existing agricultural robots are equipped with relatively simple end-effector structures that lack sufficient flexibility and intelligent control capabilities, making it difficult to meet diversified operational requirements [3]. Moreover, current multi-task collaborative control algorithms for agricultural robots are still underdeveloped, with insufficient coordination among different tasks. Decision-making processes lack adequate intelligence and autonomy, making it difficult to cope with complex and dynamic agricultural production scenarios. When faced with sudden adverse weather conditions or equipment failures, robots are often unable to respond promptly and appropriately, leading to operational interruptions or low efficiency.

2.2 High Costs of R&D, Manufacturing, and Maintenance

The research and development of agricultural robots involves the integration of multiple disciplines, including mechanical design, electronic circuits, artificial intelligence, and sensor technologies, requiring substantial investments of human, material, and financial resources. To achieve high-precision environmental perception and complex task execution, advanced sensors, high-performance computing chips, and sophisticated control algorithms must be developed, all of which demand significant financial support [4].

Manufacturing costs mainly include raw material costs, component costs, and production and assembly costs. To ensure stable operation in harsh agricultural environments, high-quality and corrosion-resistant materials and components must be used, resulting in high raw material and component costs. In addition, due to the relatively small production scale of agricultural robots, economies of scale similar to those in industrial robot manufacturing cannot be realized, leading to high unit production and assembly costs. For example, the price of a standard orchard harvesting robot may reach several hundred thousand yuan, far exceeding the purchasing capacity of ordinary farmers, thereby limiting market promotion and application.

2.3 Diverse Market Demand and Complex Application Scenarios

China has a vast territory, with significant differences in agricultural production conditions, crop types, and the economic strength and needs of farmers across regions. In southern rice-growing areas, there is strong demand for rice transplanting and harvesting robots suitable for paddy fields, while in northern dryland farming areas, robots for sowing, fertilizing, and harvesting wheat and maize are more urgently needed. Moreover, agricultural producers of different scales have varying requirements for robot functionality, performance, and price. Large agricultural enterprises may prefer high-end robots with comprehensive functions and a high level of intelligence, whereas small-scale farmers are more inclined toward affordable and easy-to-operate economic robots. This diversified and personalized market demand poses significant challenges for the R&D and production of agricultural robots, making it difficult for enterprises to develop a universal product that meets all needs.

Currently, most agricultural practitioners in China are relatively older and have lower levels of education, resulting in limited acceptance of new technologies and equipment. As high-tech products, agricultural robots require certain professional knowledge and skills for operation and maintenance, discouraging many farmers. In addition, some farmers are skeptical about the actual effectiveness of agricultural robots, worrying that robots may not perform tasks as precisely as manual labor, thereby affecting crop yield and quality.

In some regions, farmers are accustomed to traditional farming methods and are resistant to adopting new technologies, further hindering the promotion and application of agricultural robots in rural areas. The complexity and diversity of agricultural production scenarios, combined with variations in planting models, growth cycles, and agronomic requirements across crops and regions, also make it difficult to establish unified standards and specifications for agricultural robot applications.

3. Optimization Strategies for R&D Challenges of Agricultural Robots in Smart Agriculture

3.1 Technological Innovation and Breakthroughs

To overcome the impact of complex environments on robot perception systems, greater efforts should be made to develop multi-sensor fusion technologies. By integrating vision sensors, LiDAR, millimeter-wave radar, and ultrasonic sensors, the complementary advantages of different sensors can be fully utilized to achieve comprehensive and high-precision environmental perception. Vision sensors provide crop appearance information, LiDAR measures terrain and obstacle distances, and millimeter-wave radar maintains stable detection performance under adverse weather conditions. Data fusion algorithms can integrate information from multiple sensors to enhance perception accuracy and reliability. Meanwhile, deep learning algorithms tailored to agricultural environments should be developed and trained on large-scale agricultural scene datasets to improve the recognition and adaptability of models for crops, pests, diseases, and obstacles in complex environments. For example, generative adversarial networks (GANs) can be used to generate crop images under various lighting conditions, expanding training datasets and improving model robustness to lighting variations.

In terms of operational flexibility, flexible and adaptive end-effectors should be developed. By adopting new flexible materials and biomimetic design concepts, end-effectors can imitate human hand movements to gently grasp and manipulate crops. Shape memory alloys and intelligent polymers can be used to produce deformable gripping components that automatically adjust grasping methods and forces according to crop shape and size, enabling damage-free harvesting and transplanting. Force feedback control and tactile sensors should be introduced to allow robots to sense real-time force and pressure changes during contact, enabling precise control and preventing crop damage. Furthermore, enhanced research on robot motion control algorithms is needed to improve joint motion accuracy and flexibility, enabling more complex and precise operations. To enhance multi-task coordination and decision-making capabilities, control algorithms based on reinforcement learning and distributed intelligence should be developed, allowing robots to continuously learn from interactions with the environment and optimize behavior strategies for efficient multi-task execution.

3.2 Cost Control and Optimization

During the R&D stage, industry–university–research collaboration should be strengthened to integrate the resource advantages of universities, research institutions, and enterprises. Universities and research institutions excel in basic research and technological innovation, while enterprises have rich experience in product development and market application. Collaboration can achieve complementary advantages, improve R&D efficiency, and reduce costs. Governments should increase financial support for agricultural robot R&D by establishing special research funds and encouraging breakthroughs in key technologies. In addition, shared R&D platforms should be established to share equipment, data resources, and research result, avoiding redundant development and further reducing costs. For example, shared agricultural scene datasets can allow different teams to optimize algorithms and train models on the same data, reducing data collection and labeling workloads.

In manufacturing, standardization and modularization of components should be promoted. Unified component standards can enable interchangeability and common use across different robot models, increasing production scale and reducing costs. Modular design divides robots into functional modules—such as power, perception, and execution modules—produced by specialized manufacturers. Enterprises can assemble robots by selecting appropriate modules according to needs, improving efficiency and reducing costs. Meanwhile, new manufacturing processes and materials should be explored to identify cost-effective alternatives with comparable performance, reducing raw material costs while maintaining quality and performance.

To reduce maintenance costs, intelligent fault diagnosis and prediction systems should be developed. By installing sensors to monitor operational status and key component parameters in real time, big data analysis and machine learning algorithms can predict potential failures and issue early warnings for preventive maintenance. A comprehensive after-sales service system should be established, with enhanced training for maintenance personnel to improve response speed and service quality. Remote maintenance technologies should also be developed to enable remote diagnosis and control via the internet, reducing on-site maintenance frequency and costs. Extending robot service life through optimized structural design and high-quality components is another important approach to lowering maintenance costs. 3.3 Market Cultivation and Expansion

Agricultural robot enterprises should strengthen market research to gain in-depth understanding of the actual needs of agricultural producers in different regions and of different scales, enabling precise product positioning and development. Close cooperation with agricultural enterprises, large growers, and cooperatives should be established to conduct field research and demand analysis. Customized agricultural robot products should be developed based on feedback and application scenarios. For small-scale farmers, simple, affordable, and easy-to-operate handheld or portable robots—such as small weeding robots or fruit-picking aids—can be developed. For large agricultural enterprises and large-scale farms, highly intelligent, efficient, and integrated robotic systems—such as unmanned farm operation platforms and fully automated fruit and vegetable harvesting lines—should be prioritized. Accurate market positioning can enhance product adaptability and competitiveness.

To improve acceptance among agricultural practitioners, governments and enterprises should intensify training efforts. Training courses on agricultural robot operation should be organized, with professionals providing on-site instruction in rural areas, explaining working principles, operation methods, and maintenance knowledge through demonstrations and case analyses. To address the complexity and lack of standardization in application scenarios, industry associations, research institutions, and enterprises should collaborate to promote standardization of agricultural robot application scenarios. Unified agricultural operation standards and norms should be established, standardizing planting models, agronomic processes, and field management requirements for different crops, providing a consistent reference for robot design and application.

4. Conclusion

The research and development of agricultural robots in smart agriculture scenarios plays a crucial role in advancing agricultural modernization in China. Although significant challenges remain in technology, cost, market, and application, targeted optimization strategies—such as strengthening technological innovation, controlling costs, and cultivating markets—can effectively overcome these obstacles and promote the development and application of agricultural robot technologies. In the future, with continuous technological progress and joint efforts from all stakeholders, agricultural robots are expected to play an increasingly important role in agricultural production, achieving efficient, precise, and sustainable development. Continuous investment in advanced environmental perception technologies, enhanced operational flexibility, and improved multi-task collaborative decision-making will enable robots to better adapt to complex agricultural environments and perform more refined and diversified tasks. Effective cost control measures will enhance cost-effectiveness and market competitiveness, while market cultivation and expansion strategies will improve acceptance and create favorable conditions for large-scale application through standardization.

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Research on the Exploration of Organic Agricultural Vegetable Cultivation Technology

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Abstract: This paper conducts an in-depth exploration of organic agricultural vegetable cultivation technology, systematically expounding its significant meaning and advantages in terms of ecological environmental protection, health quality, and economic benefits. Through investigation and analysis of the current development status of organic agricultural vegetable cultivation, it reveals existing technical difficulties, cost constraints, market supervision, and other issues. Key technical strategies are proposed from the dimensions of soil management, pest and disease control, variety selection, and cultivation management. In response to challenges such as promotion and marketing, the paper suggests coping strategies and looks forward to development trends such as integration with modern information technology and industrial diversification, aiming to provide theoretical reference and practical guidance for promoting the technological progress and sustainable industrial development of organic agricultural vegetable cultivation.

Keywords: Organic agriculture; Vegetable cultivation; Cultivation technology; Ecological environmental protection; Sustainable development

Introduction

With the improvement of people's living standards, the pursuit of food safety and quality has become increasingly urgent. Traditional vegetable cultivation relies on chemical pesticides and fertilizers; although they increase yield, they cause issues such as pesticide residues and soil pollution, endangering health and agricultural sustainability. Organic agricultural vegetable cultivation follows natural laws, replacing chemical synthetics with organic fertilizers and biological control to produce safe, high-quality vegetables, possessing both ecological protection and industrial development value. However, challenges remain in technical promotion and industrial upgrading. In-depth exploration of organic vegetable cultivation technology is of far-reaching significance for ensuring food safety and promoting agricultural ecological balance.

1. Significance and Advantages of Organic Agricultural Vegetable Cultivation

1.1 Ecological Environmental Protection Value

Organic agricultural vegetable cultivation is an important way to safeguard the ecological environment. Traditional cultivation relies on chemical pesticides, which destroy biodiversity while killing pests, leading to ecological imbalances in farmland. In contrast, organic cultivation abandons chemical pesticides, adopting biological control methods such as the release of Trichogramma wasps, combined with physical measures like insect-proof nets and insect-trapping lamps to precisely control pests while creating living space for beneficial insects and microorganisms. In terms of fertilizer application, organic fertilizers such as farmyard manure and green manure are decomposed by microorganisms to optimize soil structure and enhance water and fertilizer retention, avoiding soil compaction and salinization caused by chemical fertilizers. This cultivation model significantly reduces chemical inputs, lowers non-point source pollution, and helps the agricultural ecosystem enter a virtuous cycle.

1.2 Health and Quality Advantages

Organic agricultural vegetables have significant advantages in safety and nutrition. Because chemical synthetic pesticides and fertilizers are prohibited throughout the process, pesticide residues and harmful chemical pollution are eliminated at the source, greatly improving consumption safety. Scientific research shows that organic vegetables are richer in Vitamin C, minerals, and antioxidant components; taking organic tomatoes as an example, their Vitamin C content is 10%-20% higher than ordinary varieties, and their taste and flavor are superior [1]. At the same time, organic vegetables follow natural growth rhythms with longer growth cycles, allowing for the full accumulation of nutrients. Coupled with careful maintenance of soil and the ecological environment, vegetables grow in a healthy environment. Long-term consumption of organic vegetables can both enhance human immunity and avoid health hazards caused by pesticide residues, aligning with consumers' pursuit of high-quality diets.

1.3 Economic Benefit Potential

Organic agricultural vegetable cultivation holds enormous economic value. With the awakening of consumer health awareness, the market demand for organic vegetables continues to climb, with prices commanding a premium of 30% to 100% over ordinary vegetables; for instance, the unit price of organic lettuce can reach 10-15 yuan per catty, far exceeding the 3-5 yuan price of ordinary lettuce. Although high initial costs are required for soil improvement, organic fertilizer purchase, and biological control, long-term returns are significant due to high-quality and high-price market positioning. Furthermore, the industry can drive upstream and downstream sectors such as organic fertilizer production and biological control R&D, forming a complete industrial chain, creating jobs, injecting vitality into the rural economy, and effectively promoting the implementation of the rural revitalization strategy.

2. Status and Problems of Organic Agricultural Vegetable Cultivation

2.1 Development Status

Currently, the scale of organic agricultural vegetable cultivation in China is expanding, and cultivation areas are gradually increasing. In some economically developed regions and areas with good ecological environments, such as Shandong, Zhejiang, and Yunnan, organic vegetable cultivation has developed rapidly, forming a certain scale of cultivation bases. The variety of cultivated vegetables is also increasingly rich, covering common varieties such as leafy vegetables, rhizomes, and melons/fruits, such as organic lettuce, organic carrots, and organic cucumbers. In terms of cultivation models, common ones include monoculture, intercropping, and relay cropping. For example, in organic vegetable bases, lettuce and garlic are intercropped to use the odor emitted by garlic to repel pests; amaranth is relay-cropped under cucumber racks to fully utilize space resources and improve land utilization. Moreover, sales channels for organic vegetables are diversifying; besides traditional farmers' markets and supermarkets, they are sold through e-commerce platforms, organic product specialty stores, and Community Supported Agriculture (CSA) models, making channels more convenient for consumers.

2.2 Existing Problems

The process of organic vegetable cultivation faces many technical difficulties. (1) Soil improvement is the foundation of organic agriculture, but the cycle is long and the cost is high. To make soil meet organic cultivation standards usually requires 2-3 years or even longer for fertilization and conditioning, requiring large amounts of organic fertilizer, manpower, and material resources. In pest control, although biological and physical methods have environmental advantages, their effectiveness is sometimes unstable, making it difficult to completely control outbreaks. For instance, in hot and humid summers, vegetables are susceptible to pests, and biological methods alone may not effectively control the condition, leading to yield reduction. (2) High cultivation costs are also a major factor restricting development. The price of organic fertilizer is relatively high and requires large quantities; the R&D and production costs of biological control products are also high. Since organic cultivation has strict requirements for the environment and process, organic certification is required, and certification fees further increase the burden [2]. Additionally, the production efficiency is relatively low and yield growth is slow, affecting growers' enthusiasm to some extent. (3) Insufficient market supervision is a prominent problem. Organic product certification is non-standardized; some enterprises or individuals, driven by profit, use organic labels illegally without meeting standards, which disrupts market order. Consumers lack sufficient knowledge and find it difficult to distinguish authenticity, leading to the phenomenon of "bad money driving out good," affecting the interests of legitimate growers and hindering the healthy development of the industry.

3. Key Technical Strategies for Organic Agricultural Vegetable Cultivation

3.1 Soil Management Technology

Soil management is a key link in organic vegetable cultivation.

(1) First, soil improvement must be carried out. The application of organic fertilizers is an important measure. Farmyard manure such as decomposed pig, cattle, and chicken manure is rich in organic matter and nutrients, which can increase soil fertility and improve structure. Returning green manure to the field is also a common method; for example, planting green manure crops like Astragalus sinicus and vetch, and plowing them into the soil during their peak growth period to be converted into organic fertilizer through microbial decomposition. (2) Adopting crop rotation and intercropping can effectively improve the soil ecological environment. Rotation avoids nutrient depletion and reduces pest occurrences. Intercropping, such as maize with chili peppers, allows maize to provide shade for the peppers while the different root distributions utilize soil nutrients fully. (3) Cultivating soil microorganisms is also crucial. Microbial inoculants like Bacillus subtilis and lactic acid bacteria can be added to increase beneficial microorganisms, promote the decomposition of organic substances, and improve soil fertility and activity.

3.2 Pest and Disease Control Technology

Organic vegetable cultivation adopts integrated management to control pests and diseases.

(1) Agricultural control is the foundation. Selecting disease- and pest-resistant varieties is an effective method. Measures such as rational dense planting, scientific fertilization, and cleaning the fields also enhance resistance. Maintaining field ventilation and light prevents overcrowding; timely removal of diseased remains reduces infection sources. (2) Physical control methods are simple and effective. Installing insect-proof nets can prevent pests from entering, such as covering the top and sides of greenhouses [3]. Insect-trapping lamps utilize the phototaxis of pests for trapping and killing moths and beetles. Yellow sticky boards are also common for trapping aphids and whiteflies. (3) Biological control is an important means. Introducing natural enemy insects is a primary method, such as releasing predatory mites to control spider mites or using ladybugs for aphids. The use of biopesticides like Bacillus thuringiensis (Bt) and Beauveria bassiana is also critical, as they have specific pathogenic effects on pests and are environmentally friendly.

3.3 Variety Selection and Cultivation Management

(1) Selecting suitable varieties based on regional climate and soil conditions is key. In warm and humid southern regions, thermophilic and hygrophilic varieties like cucumbers and eggplants are preferred; in dry northern regions with large temperature differences, tomatoes, carrots, and onions are more suitable. (2) Scientific cultivation management is vital. During sowing, the appropriate time and method must be chosen based on variety characteristics and local climate. For example, seeds requiring higher temperatures like cucumbers are sown after spring temperatures rise; cold-resistant seeds like spinach are sown in autumn or early spring. (3) Regarding irrigation and fertilization, principles of organic agriculture must be followed. Water-saving methods like drip and sprinkler irrigation should be used based

on water requirements. Fertilization focuses on organic types; in the early growth stage, nitrogen-rich fertilizers promote plant growth, while during flowering and fruiting, phosphorus and potassium fertilizers are increased to improve yield and quality.

4. Challenges and Development Trends of Organic Agricultural Vegetable Cultivation

4.1 Facing Challenges

(1) Although organic technology has advantages, its high technical requirements mean growers need to master a range of skills. Currently, many growers lack the relevant knowledge and experience. The training and promotion system is imperfect, lacking professional technicians for guidance, meaning problems cannot be solved timely. (2) In market expansion, organic vegetables face insufficient consumer awareness and fierce competition. Some consumers are unclear about the difference between organic and ordinary vegetables and have doubts about price and quality, leading to slow demand growth. Additionally, there are many brands with homogenized products, lacking market competitiveness. (3) Capital investment is a major constraint. The early stage requires significant funds for land conversion, organic fertilizer, and equipment, while the production cycle is long and capital recovery is slow. For most small-scale growers, the financial pressure is difficult to bear, limiting large-scale development.

4.2 Development Trends

(1) In the future, organic cultivation will integrate deeply with modern information technology to achieve intelligent management. Utilizing Internet of Things (IoT) technology, sensors can monitor environmental parameters like soil moisture and light in real-time, with intelligent systems automatically adjusting irrigation and ventilation. Big data and AI can analyze growth data to predict pest outbreaks and optimize management schemes. (2) Organic cultivation will develop toward a diversified industrial model, combining with ecological tourism and leisure agriculture. Constructing organic vegetable sightseeing parks allows tourists to experience planting and picking while learning about organic agriculture. Developing processed products like organic vegetable juices and dried vegetables can extend the industrial chain [4]. (3) With increasing demand and gradual standardization, the industry will move toward large-scale, standardized, and branded development. Government departments will strengthen support, formulate standards, and enhance supervision. Enterprises will focus more on brand building and service levels to create competitive organic vegetable brands.

Conclusion

As an important practice of sustainable agriculture, organic agricultural vegetable cultivation is of far-reaching significance for protecting ecological balance, ensuring food safety, and helping farmers increase income. Although it currently faces challenges like technical bottlenecks, cost pressures, and market chaos, its development prospects remain broad through the innovative application of scientific technology and industrial upgrades. With the deep integration of technologies like IoT and big data, the industry will surely leap from traditional to modern and from scattered to large-scale, continuously providing momentum for building a green agricultural ecology and meeting the needs for a better life.

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