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The integration of artificial intelligence (AI) and high-throughput phenotyping (HTP) to estimate agricultural traits in crop development

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Abstract

Objective

The growing demand for food throughout the world is a serious problem that requires creative agricultural solutions to guarantee food security and sustainable farming methods. Artificial Intelligence (AI) and High-Throughput Phenotyping (HTP) are two new technologies that allow for the quick and accurate measurement and analysis of agricultural characteristics, allowing for the discovery of critical elements influencing quality and growth. HTP uses cutting-edge sensors, imaging, and other technologies to gather enormous databases on plant characteristics.

Materials and methods

Finding underlying patterns and correlations between phenotypic features and genetic data has become easier because to the combination of HTP with AI and Machine Learning (ML) algorithms. These large datasets may be processed effectively by AI-driven algorithms, which speeds up the process of identifying desired crop features for breeding initiatives.

Results

Predictive technologies that support data-driven decision-making in crop breeding have been made possible by the combination of HTP, AI, and ML. By increasing accuracy and speeding up the breeding process, these instruments help raise agricultural production and sustainability. However, issues including data complexity, established procedures, and ongoing advancements in computational models still stand in the way of completely integrating these technologies throughout agricultural systems. For AI and HTP technologies to be successfully implemented on a broader scale, cooperation between researchers, industry, and farmers is also required.

Conclusions

The benefits of these technologies, such as improved efficiency and accuracy in selecting ideal breeding characteristics, are examined in this study as it investigates the safe and efficient integration of HTP and AI to improve crop growth and quality. It shows the latest progress and real-world uses of HTP and AI in farming, showing how these new technologies have already started to change the way crops are cultivated.

Keywords: Artificial intelligence, crop development, high-throughput phenotyping, agronomic characteristics

Paper Type: Research Paper.

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Introduction

Around 7.5 billion people stay alive because of how plants grow and develop, including how they flower and do photosynthesis. Currently, farming faces three critical issues simultaneously: rising temperatures, a lack of resources, and a growing population (Khan et al. 2021). There will be 12 billion people worldwide in 30 years, a 28% rise from now. The 21st century will see more crops grown because people need more food, clothes, and energy. This is likely to be one of the most significant issues. High-Throughput Phenotyping (HTP) is a novel method for studying plants that aims to quickly and precisely determine the phenotypic features of many crops. (Yang et al. 2020). In High-Throughput Phenotyping (HTP), cutting-edge technology is used to quickly and correctly evaluate various plant characteristics in various crops. With the use of automation, imaging systems, and sensors, HTP allows for the efficient gathering of data on how plants grow, develop, and react to their surroundings. This method helps researchers find useful features for crop improvement and breeding by analysing complicated phenotypic data at an unparalleled speed and scale. Precision agriculture and the creation of more durable, more productive crops are unable to advance further without HTP. Modern technology, data analysis, and automation are used to get specific information on growth, effectiveness, resistance to stress, and disease resistance. This way of doing things has dramatically sped up progress in food genetics and improvement, which has helped researchers learn more about how plants and the world are connected. Things take a long time, and a lot of work goes into the traditional models of HTP that depend on personal measures and judgments. People need to correct their mistakes a lot (Xiao et al. 2022).

Artificial intelligence (AI) looks at pictures and notices important patterns and traits (Gill et al. 2022). AI's ability to show the difference between leaf shapes, measure crop growth factors, and spot signs of illness is essential in plant phenotyping. As part of HTP, different data types, such as pictures, genetics, and ecosystems, are put together (Surendar et al. 2024). The surroundings, genotypes, and traits are all linked in complicated ways when AI systems combine these records (Jiang & Li 2020). Prediction models that use AI can find links between feature data and genetics or environmental factors.

In light of this, this study looks at how well HTP and AI can help farming grow (Angin et al. 2020). Researchers and crop farmers are making their work more accurate and faster using these tools. The research can make solid, high-yield cultivars to help fix the world's environmental and food safety problems (Pržulj et al. 2022). Moreover, data generation in agriculture and biotechnology has greatly increased in recent years due to the very rapid development of high-performance technologies (Mohammadabadi et al. 2024). These data are obtained from studying products, foods, and biological molecules to understand the role of different aspects of agriculture in determining the structure, function, and dynamics of living systems (Pour Hamidi et al. 2017). Artificial neural networks have been proposed to alleviate limitation of traditional methods and can be used to handle nonlinear and complex data, even when the data is imprecise and noisy (Pour Hamidi et al. 2017). Agricultural data can be too large and complex to handle through visual analysis or statistical correlations. This has encouraged the use of machine intelligence or artificial intelligence (Ghotbaldini et al. 2019). Thus, the main goal of this study was to incorporate AI in agriculture.

History: Machine learning (ML) techniques use previous information to make processes faster and more efficient (Koh et al. 2021). ML can create a model that makes sense and robustly

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connects sources. AI does its job better when it has more data to work with (Mumtaj Begum 2022). ML is getting better and better at HTP in plants because of this. This data can be stored and analyzed, which leads to the creation of big data sets. The use of Unmanned Aerial Vehicles (UAVs) and other self-driving devices in agriculture has a lot of promise in making crop monitoring more accurate and time-effective (Feng et al. 2021). Because computers are getting faster and more resources are available, automating machine learning (AutoML) is becoming more popular in business and academia (Jangra et al. 2021). AutoML has grown to be an excellent option for traditional ML methods. The system can provide ML pipelines that are both fast and comprehensive. These pipelines include data preparation, feature design (extracting, choosing, and building), model production (choosing and adjusting hyperparameters), and model analysis. AutoML tries to do these things with as little work or input from the user. Technology that helps computers read and understand pictures is called computer vision, and it allows HTP to grow.

Many different ML algorithms are helpful in plant science for finding diseases, guessing crop yields, and other jobs (Veerasamy & Fredrik 2023; Kim 2020). Systems and network engineering researchers have found many uses for determining how genotypes and traits are connected. Network biology has helped the system to understand the complicated chemical processes inside living things (Cho et al. 2020). ML has been crucial in forecasting new elements in plants and diseases. An innovative hybrid strategy entails combining Deep Learning (DL) with network topology metrics derived from multivariate omics information (Lube et al. 2022). This novel combination can reveal undiscovered areas within the field of plant-microbe connections. ML methods can effectively analyze HTP and gene information to understand the intricate genetic processes underlying resistance to illness and the variations in stress-related gene expression over time and space (Camgözlü & Kutlu 2023). Despite the intricate calculations the methods perform, plant researchers can still benefit from them because they include Graphical User Interface (GUI) capabilities (Zhu et al. 2021). Therefore, individuals can be relieved from concerns regarding the intricate theoretical and computational intricacies. The data gathering and curating pipeline significantly facilitates the smooth integration of ML with traditional phenotyping approaches. These ecosystems will aid in resolving various fundamental issues related to farming and guaranteeing food safety. High-Throughput Phenotyping (HTP) uses Machine Learning (ML) to analyze phenotypic data faster and more accurately, and it is also able to gather more data due to the incorporation of other cutting-edge technologies like Unmanned Aerial Vehicles (UAVs). Unmanned Aerial Vehicles (UAVs) can collect high-resolution data from expansive regions in real-time due to their sophisticated camera and sensor systems. Research on models that can adjust to complicated agricultural settings is also being helped forward by the increasing popularity of

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Automated Machine Learning (AutoML), which is standardizing the use of ML methods. Taken as a whole, these developments are advancing precision agriculture into the future by making crop monitoring and breeding easier and more scalable.

Materials and methods

AI-integrated HTP model: The proposed AI-integrated HTP model is an innovative and effective tool that enables the observation and measurement of crop development and output characteristics without causing damage. It is a fast and efficient method that allows many samples to be processed. This tool can be combined with genomic techniques such as qualitative trait loci tracking, marker-supported choosing, genetic selection, and genome-wide relationship research. Using these genomic methods, the proposed model can assist farmers in adapting to dynamic weather and satisfy marketplace needs for higher yields. The effective integration of genomes and high-throughput phenotypic information will substantially facilitate the advancement of phenotyping. Figure 1 illustrates that different types of HTP play a role in characterizing plants' physical structure, functional processes, and composition. They can facilitate the advancement of multi-omics studies and uncover the control systems and biological structures involved in the advancement and progress of crops.

HTP has expedited crop breeding endeavors by enabling the swift assessment of numerous crops at different phases of development. It is no longer necessary to patiently wait for crops to reach saturation in the area, as the technique rapidly monitors for needed features at the outset. HTP is employed in regulating and real-time environments, encompassing laboratory and field environments. The assessment of plant achievement in the region can be swiftly conducted, facilitating a comprehensive assessment of the entire life cycle via less intrusive means. Data storage is improved, and the employment of environment-controlled high-throughput HTP establishments necessitates fewer copies. In most situations, phenotypic information is the most reliable indicator of results, like crop wellness, illness-based attributes, and fatalities. They are precious for acquiring accurate measures of plant features, thereby augmenting the capabilities of crop breeders and farmers.

Crop modelling: Systems are utilized to create plant modeling that mimics crop development, and forecasts yield under various circumstances. These models can assist in improving cultivation operations, forecasting results, and adjusting agricultural practices to evolving weather. There is a strong link between HTP and making plans. Assessments of crop traits are one type of data collected through HTP.

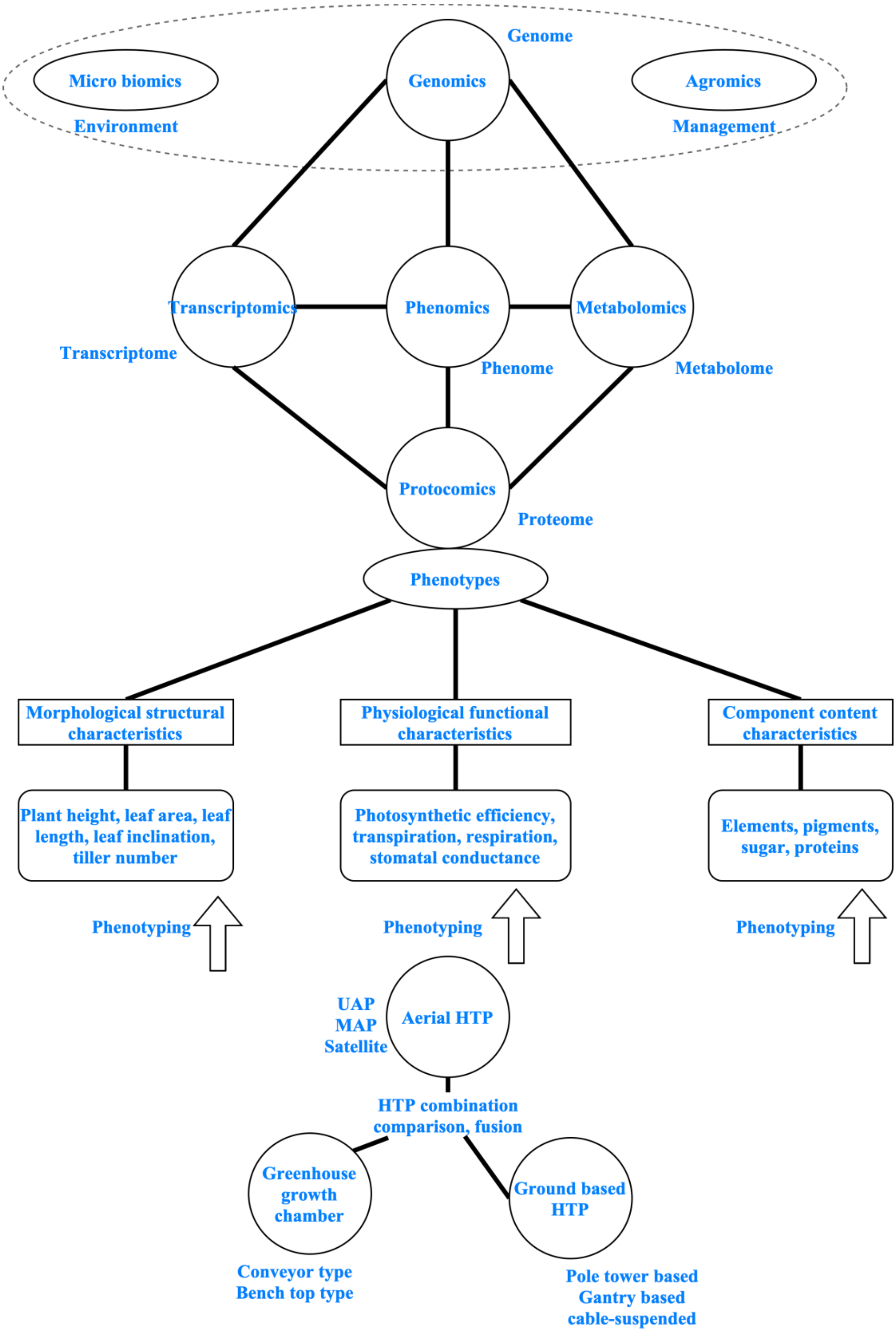

Figure 1. AI-integrated HTP model

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This data is fed into farming models to make forecasts more accurate and helpful. Crop modeling can be used to assess and study the big data that HTP generates. This could help farmers grow more crops and do their jobs better. When HTP and field modeling are used together, scientists and farmers can learn more about how plants grow. It allows them to find essential features for breeding initiatives, maximize resources, boost food yields, and develop farming methods that can last and change as needed.

Phenotypic techniques: High-Throughput Phenotyping (HTP) is a method for rapidly measuring a wide variety of plant characteristics by using specialized instruments. In HTP, phenotyping and green fluorescent protein are two important tools:

PHENOPSIS is a computerized system that captures high-quality images of plants in order to quantify their dimensions, form, and development across time. Researchers may use it to monitor plant growth in various environments.

GROWSCREEN FLUORO detects photosynthesis (the process by which plants convert light energy into food) and reports the results. In addition to identifying plants that are stronger or healthier, it may sense stress in plants, such as when they are dehydrated or unwell.

Researchers may more easily analyse plants and identify the greatest features to improve crops with the help of these instruments. With many HTP tools, the research can look at plants' biotic and abiotic stress types. These models are significant for a better understanding of how plants react to stress. These methods are some examples:

The computer tool "PHENOPSIS" can look into how Arabidopsis plants respond to having less water in the soil (Granier et al. 2006). This "GROWSCREEN FLUORO" tool studies leaf growth and checks how bright chlorophyll is (quantitative-plant). Scientists use it to see how well Arabidopsis plants can deal with bad things happening around them.

The "LemnaTec 3D Scanalyzer" tests rice for its ability to handle salt without hurting the plant, which allows for more thorough results (lemnatec). Without affecting the plants, a "HyperART" can precisely measure green properties like chlorophyll levels and disease severity (Bergsträsser et al. 2015).

The "PhenoBox" tool finds diseases like cereal head smut in Brachypodium and cereal maize smut (viennabiocenter.org). Checking how tobacco plants respond to salt levels is possible.

The "PHENOVISION" device can be found when drought stresses corn crops and when they recover (phenotyping and phenovision). It is utilized to observe how plants react to pressure.

"PhénoField" studies various outside factors that impact wheat and how plant traits are connected to stress (constructions, instrumentalization-and-measures, phenofield-phenotyping-arch). The "PlantScreen Robotic XYZ System" is used to study many things that impact rice's ability to survive drought, which offers insight into how resilience works (plant phenotyping).

Using these instruments, one can carefully examine how various plants handle stress. Finding out more about how plants deal with stress is helpful.

Results and discussion

Progresses in imaging techniques and AI-integrated HTP models: Progress image techniques using HTP and AI have become powerful tools for improving plants and producing more. It checks the traits and output of big groups of plants quickly and accurately, which leads to more focused and effective breeding methods. Hyperspectral photography, thermal images, 3D images, and fluorescence images are some of the more advanced imaging methods that scientists can use to get correct information about many parts of plants. These include leaf shape, canopy design, physiological processes, and how the plant reacts to stress.

Machine learning (ML) greatly improves the accuracy and speed of phenotypic data processing in High-Throughput Phenotyping (HTP), and the use of UAVs and other new technologies is further increasing the capacity to gather data. Unmanned Aerial Vehicles (UAVs) equipped with sensors, such as hyperspectral cameras, may provide vital information about plant health by picking up on minute variations in light reflectance that can be signs of stress, illness, or lack of nutrients. The ability to monitor plant conditions that are unseen to the human eye and identify diseases early on are both made possible by these cameras' ability to record data across several wavelengths. It is now possible to evaluate growth phases, canopy structure, and geographical distribution with pinpoint accuracy because of 3D imaging technology, which records intricate structural information about plants. Researchers can better monitor growth patterns and anticipate production potential with the use of 3D modeling and hyperspectral imaging to study plant development. Research on models that can adjust to complicated agricultural settings is also being helped forward by the proliferation of Automated Machine Learning (AutoML), which is standardizing the use of ML methods. Improved and more scalable methods of crop monitoring and breeding are made possible by these advancements, which are propelling the field of precision agriculture into the future.

The employment of non-intrusive artificial instruments in HTP enables the simultaneous assessment of several plant attributes without harming the plants.This technology allows researchers to quickly and correctly get genetic information about many plants. This data includes growth, output, disease defense, diet, and the body's capacity to deal with stress. Correct information about plants' leaf area, size, biomass, growing period, and disease resistance must be gathered quickly for HTP to work.

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Disease identification: Integrated genetic information and AI methods have been used to build systems that can find diseases. These algorithms can find complex links and relationships between differences in physical traits and certain illnesses. Massive, labeled databases can be used to teach them about the trends and traits that are linked to different diseases. When HTP and AI are used together, pictures or sensor data can be looked at to find signs of diseases or insects, which makes it easier to identify problems quickly and take the proper steps. ML algorithms trained on large sets of pictures of sick plants can accurately find and spot plant illnesses.

Characteristics discovery: AI and advanced image technology can work together to help find and measure new or complicated traits that might be hard to quantify. AI systems can find slight differences in the color, texture, or illness symptoms of leaves, which could mean that each plant has its unique genetic makeup. Looking at past data, weather trends, and agricultural features, HTP-based AI systems can forecast harvest rates and improve farming methods. This data enables farmers to strategize their gathering, preservation, and advertising strategies efficiently.

Crop control: By integrating imaging methods with AI, it is possible to generate immediate suggestions for irrigation planning, applying fertilizer, and pest management. These suggestions are derived from sensor information, the environment, and plant reactions. The improvement of crop managing practices enhances the preservation of resources and boosts productivity. Sophisticated imaging technology and AI track and maximize plant development in practical conditions. Through the ongoing analysis of plant wellness, tension levels, and nutritional needs, farmers made choices about fertilizers, watering, and pesticide control. This ultimately results in enhanced resource effectiveness and increased crop production.

Conclusions: The paper highlights how AI and High-Throughput Phenotyping (HTP) might completely change the activity when it comes to improving crops. New possibilities for optimizing crop breeding, increasing yield, and strengthening tolerance to environmental challenges arise when HTP, in conjunction with AI and ML, allows for the quick and precise monitoring of plant characteristics. To speed up breeding program decision-making, these technologies may reveal trends in genomic and phenotypic data, according to key results. But there are still obstacles to overcome, especially when it comes to integrating genomic data with phenotypic features in functional evaluations of crop genomes. Research in the future should be on making AI models more accurate, finding better ways to integrate data, and creating better tools for genome-wide analysis. The uniformity of results from different research and the increased use of these technologies in farming both need the establishment of standard methods. Implications for food security and environmental sustainability might be far-reaching if these difficulties are addressed by future advances in HTP and AI, which could lead to more efficient, accurate, and sustainable crop breeding.

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Conflict of Interest: There is no conflict of Interest.

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مجله بیوتکنولوژی کشاورزی
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ادغام هوش مصنوعی (AI) و فنوتیپ با توان عملیاتی بالا (HTP) برای تخمین صفات کشاورزی در توسعه محصول

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چکیده

هدف: تقاضای فزاینده برای غذا در سراسر جهان یک مشکل جدی است که نیازمند راه حل‌های خلاقانه کشاورزی برای تضمین امنیت غذایی و روش‌های کشاورزی پایدار است. هوش مصنوعی (AI) و فنوتیپ با توان بالا (HTP) دو فناوری جدید هستند که امکان اندازه‌گیری و تجزیه و تحلیل سریع و دقیق ویژگی‌های کشاورزی را فراهم می‌کنند و امکان کشف عناصر حیاتی مؤثر بر کیفیت و رشد را فراهم می‌کنند. HTP از حسگرهای پیشرفته، تصویربرداری و سایر فناوری‌ها برای جمع‌آوری پایگاه‌های اطلاعاتی عظیم در مورد ویژگی‌های گیاه استفاده می‌کند.

مواد و روش‌ها: یافتن الگوهای اساسی و همبستگی بین ویژگی‌های فنوتیپی و داده‌های ژنتیکی به دلیل ترکیب HTP با الگوریتم‌های هوش مصنوعی و یادگیری ماشین (ML) آسان‌تر شده است. این مجموعه داده‌های بزرگ ممکن است به طور موثر توسط الگوریتم‌های مبتنی بر هوش مصنوعی پردازش شوند، که روند شناسایی ویژگی‌های محصول مورد نظر را برای طرح‌های اصلاحی سرعت می‌بخشد.

نتایج: فن‌آوری‌های پیش‌بینی‌کننده که از تصمیم‌گیری مبتنی بر داده در اصلاح محصول پشتیبانی می‌کنند، با ترکیب HTP، AI و ML امکان‌پذیر شده‌اند. این ابزار با افزایش دقت و سرعت بخشیدن به فرآیند اصلاح به افزایش تولید و پایداری کشاورزی کمک می‌کند. با این حال، مسائلی از جمله پیچیدگی داده‌ها، رویه‌های تعیین‌شده، و پیشرفت‌های مداوم در مدل‌های محاسباتی همچنان

مانع از ادغام کامل این فناوری‌ها در سراسر سیستم‌های کشاورزی هستند. برای اجرای موفقیت آمیز فناوری‌های هوش مصنوعی و HTP در مقیاس وسیع تر، همکاری بین محققان، صنعت و کشاورزان نیز لازم است.

نتیجه‌گیری: مزایای این فناوری‌ها، مانند بهبود کارایی و دقت در انتخاب ویژگی‌های اصلاحی ایده‌آل، در این مطالعه بررسی شد، زیرا ادغام ایمن و کارآمد HTP و AI برای بهبود رشد و کیفیت محصول را بررسی می‌کند. این آخرین پیشرفت‌ها و استفاده‌های واقعی از HTP و AI در کشاورزی را نمایش می‌دهد و نشان می‌دهد که چگونه این فناوری‌های جدید شروع به تغییر روش کشت محصولات کرده اند.

واژه‌های کلیدی: توسعه محصول، فنوتیپ‌سازی بالا، ویژگی‌های زراعی، هوش مصنوعی

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