

Agricultural Metaverse: Key Technologies, Application Scenarios, Challenges and Prospects

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Abstract

The metaverse, as an emerging concept, has garnered extensive attention from industry, academia, and research sectors. The convergence of agriculture and the metaverse will significantly propel the development of agricultural informatization and intelligence, furnishing new momentum for the intelligent transformation and upgrading of the agricultural sector. To thoroughly analyze the feasibility of metaverse application research in agriculture, this paper first examines the concept of agricultural metaverse and key enabling technologies for metaverse applications in agriculture, including blockchain, non-fungible tokens (NFTs), 5G/6G, artificial intelligence, Internet of Things (IoT), 3D reconstruction, cloud computing, edge computing, and extended reality (XR). Subsequently, it discusses primary scenarios of metaverse applications across three agricultural domains: virtual farms, agricultural education systems, and agricultural product traceability systems. Finally, it summarizes the principal challenges confronting agricultural metaverse regarding system establishment, communication infrastructure, hardware devices, and operational aspects, and outlines prospective future development directions. This paper can serve as a guide for research on metaverse applications in agriculture.

Full Text

Preamble

Agricultural Metaverse: Key Technologies, Application Scenarios, Challenges and Prospects

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Abstract: The metaverse, as an emerging concept, has garnered widespread attention from industry, academia, and research communities worldwide. The integration of agriculture and metaverse will significantly advance agricultural informatization and intelligence, providing new momentum for the intelligent transformation and upgrading of agriculture. To thoroughly analyze the feasibility of metaverse applications in agriculture, this paper first examines the concept of agricultural metaverse and its key enabling technologies, including blockchain, non-fungible tokens (NFTs), 5G/6G, artificial intelligence, Internet of Things, 3D reconstruction, cloud computing, edge computing, and extended reality. It then discusses primary application scenarios in three agricultural domains: virtual farms, agricultural teaching systems, and agricultural product traceability systems. Finally, the paper summarizes the main challenges facing agricultural metaverse in terms of system establishment, communication infrastructure, hardware devices, and operations, while outlining future development directions. This work provides theoretical references and technical support for metaverse application research in agriculture.

Keywords: agricultural metaverse; blockchain; extended reality; digital twins; parallel agriculture; virtual farm; agricultural product traceability system; agricultural teaching system

2 Key Technologies of Agricultural Metaverse

The metaverse is not a single new technology but rather a comprehensive integration and application of multiple information technologies [5]. Blockchain and non-fungible token (NFT) technologies offer decentralization and immutability, ensuring information security and transparency, and providing support for building decentralized infrastructure in the metaverse. 5G and 6G mobile communication technologies can provide reliable, flexible, and low-latency networks for connected devices, delivering the necessary power for real-time data transmission. AI can endow “avatars” in the metaverse with intelligence and learning capabilities, driving the intelligence of the metaverse. Internet of Things (IoT) and 3D reconstruction technologies can collect and provide data from the physical world, supporting the creation of virtual reality (VR) that expresses the objective world in computers. Extended reality (XR) technologies, represented by VR, augmented reality (AR), and mixed reality (MR), can “transport” people from reality into virtual spaces, providing immersive experiences.

The rise of smart agriculture signifies the deep integration of modern information technologies with the agricultural sector. The fusion of metaverse and

agriculture will bring about a new intelligent revolution in agriculture. Currently, agricultural metaverse is still in its infancy. With deeper integration between metaverse and agriculture and breakthroughs in key metaverse technologies, agricultural metaverse will gradually improve agricultural production efficiency, management efficiency, and product quality, propelling agricultural development into a new stage. Agricultural metaverse has significant interdisciplinary characteristics. Due to the biological nature of agriculture, directly applying metaverse technology to agriculture cannot effectively solve problems. Therefore, conducting cross-disciplinary research based on agricultural characteristics and deeply integrating metaverse technology with agricultural principles is paramount for agricultural metaverse development. Some key metaverse technologies have already been applied in agriculture, with the technical architecture shown in [Figure 1: see original paper].

2.1.1 Blockchain and Non-Fungible Tokens

Blockchain is a new distributed infrastructure and computing paradigm that utilizes cryptography, distributed consensus mechanisms, and smart contracts to achieve decentralized peer-to-peer transactions, coordination, and collaboration among nodes in distributed systems without requiring mutual trust [6]. Blockchain features decentralization, immutability, transparency, and autonomous contracts, enabling low-cost trust-building and credit system reconstruction in multi-stakeholder scenarios [7]. As a virtual world that maps and interacts with reality, the metaverse must have sustainability and should not disappear due to decisions by any single company or government. Blockchain technology provides an ideal decentralized environment for the metaverse, offering a complete solution for decentralized data transmission, storage, and management.

NFT is a non-fungible digital asset based on blockchain technology [8], characterized by indivisibility, uniqueness, and high transparency [9]. It has been widely applied in agricultural product traceability, digital collectibles, and gaming [10]. NFT binds digital assets to unique cryptocurrency tokens, permanently preserving digital assets on the blockchain [11]. NFT can also anchor digital assets to physical goods, enabling the transfer of physical goods ownership through digital token transactions. Additionally, blockchain and NFT technologies play a crucial role in building the metaverse economic system, allowing participants to profit from the virtual economy through digital asset trading and exhibition.

Currently, blockchain and NFT technologies are mainly applied in agricultural product traceability, storing traceability information on-chain to ensure security and credibility. In agricultural metaverse, blockchain and NFT technologies are essential for constructing the underlying financial architecture, enabling virtual agricultural products to acquire real-world value and achieve value transfer.

2.1.2 5G and 6G

5G is a new generation of mobile communication technology featuring high speed, low latency, and massive connectivity [12]. As the inevitable evolution of 5G, 6G will offer higher performance and lower power consumption [13]. To achieve immersive metaverse experiences, real-time data rendering is essential. Data transmission rate and latency are critical factors affecting participant experience.

The construction of agricultural metaverse requires deploying numerous sensors in farmland for real-time data collection. 5G and 6G can provide high-speed, low-latency, and massive connectivity network communication infrastructure for agricultural metaverse. Additionally, the combination of wireless sensor networks with 5G and 6G will be fundamental for implementing agricultural metaverse in large-scale connection scenarios.

2.1.3 Artificial Intelligence

Artificial intelligence refers to the theory and technology that enables machines to learn from experience and perform various tasks. It is widely applied in natural language processing [14], computer vision [15], and recommendation systems [16]. AI is a crucial driver for metaverse development, making “avatars” in the metaverse more realistic by endowing them with the ability to learn human language and conversation styles [17], enabling them to understand human intentions and effectively express their own intentions [18]. AI can also assist with decision-making, management, and service issues for metaverse users [19]. Furthermore, AI can solve language barriers in the metaverse, enabling seamless communication among participants using different languages [20].

AI is primarily applied in precise agricultural information services and decision support. In agricultural metaverse, AI serves as the brain, providing intelligence for the metaverse and holding broad prospects in areas such as agricultural virtual characters.

2.2.1 Internet of Things

The Internet of Things (IoT) is a method for integrating data obtained from various devices into existing internet infrastructure [21]. It uses various sensor devices, radio frequency identification technology, global positioning systems, and other devices and technologies to collect various types of information in real-time, achieving extensive connections between things and people through various network accesses. In the future, IoT can transform real-world objects into intelligent “avatars” in the virtual world [22], enhancing the connection between metaverse and the physical world.

IoT is currently widely applied in agriculture, including greenhouse management [23], fresh produce production and sales [24], and disease identification [25]. In agricultural metaverse, IoT is responsible for collecting real-world agricultural

data, which can improve the consistency between the virtual and real worlds, making the virtual world more accurate in describing reality. It is one of the primary means for agricultural metaverse to obtain real-time agricultural status.

2.2.2 3D Reconstruction

3D reconstruction refers to establishing a mathematical model of objective three-dimensional objects in computers that can be processed, manipulated, and analyzed [26]. It is widely applied in civil engineering [27], urban reconstruction [28], and cultural heritage digitization [29]. For 3D environment reconstruction in virtual worlds, building reconstruction, and position correspondence between virtual and real worlds, 3D reconstruction is of significant importance.

In agriculture, 3D reconstruction technology is mainly applied in agricultural product grading [30], yield prediction [31], and crop phenotyping research [32]. In agricultural metaverse, 3D reconstruction technology provides technical support for describing the real world, supplying real-world agricultural environment data to the agricultural metaverse system and serving as a powerful supplement to IoT data collection.

2.2.3 Cloud Computing and Edge Computing

Cloud computing involves storing and accessing data and programs via the internet rather than computer hard drives [33]. Edge computing provides end services on a “storage-computing integration” platform near the data source [34].

Agricultural metaverse inevitably generates massive amounts of data, and its scale and completeness directly depend on real-world computing and storage capabilities. Cloud computing offers significant advantages in cost, stability, security, and efficiency. Additionally, introducing edge computing can enhance system processing capabilities by bringing processing closer to users, making the metaverse experience smoother.

In agriculture, cloud and edge computing are widely applied in pest identification [35] and agricultural decision-making [36]. Given the large volume and heterogeneous nature of agricultural data, cloud and edge computing are key technologies for expanding the computing and storage capabilities of agricultural metaverse systems.

2.3.1 Extended Reality

Extended reality (XR) is a collective term for AR, VR, MR, and other technologies, referring to the combination of real and virtual environments and human-computer interaction generated by computer technology and wearable devices [37]. AR enhances user experience by overlaying digital information onto real-world objects or locations, with the ability to combine reality and digital information [38]. VR creates a sense of environmental immersion through

computer-simulated virtual environments, providing a fully immersive and engaging interactive experience. Participants can feel and touch virtual objects through special human-computer interaction devices, generating the sensation that these objects truly exist [39]. MR enhances user experience realism by introducing real-world scene information into virtual environments, establishing an interactive feedback loop between the virtual world, real world, and users [40].

To provide immersive experiences in agricultural metaverse, XR technology is essential. XR technology serves as the gateway to the virtual world for agricultural metaverse, providing access points. Participants can experience immersive metaverse experiences such as agricultural tourism and virtual planting through XR technology.

2.3.2 Brain-Computer Interface

Brain-computer interface refers to the hardware and software that controls external devices through brain activity [41]. It creates direct connections between human or animal brains and external devices to enable information exchange. Brain-computer interfaces can provide users with physical disabilities the same access experience as healthy users [42]. Current XR devices rely on screens and traditional control systems, while brain-computer interfaces aim to completely replace screens and physical hardware, implementing consumer-oriented mental control systems that provide users with more immersive metaverse experiences.

Due to cost and acceptance issues, brain-computer interface applications in agriculture are still limited. In future agricultural metaverse, brain-computer interfaces can serve as a supplement to XR technology, providing agricultural metaverse users with enhanced experiences.

2.4.1 Agricultural Digital Twins

Digital twins refer to the digital establishment and simulation of a physical entity, process, or system' s behavior in an information platform. Through virtual-real interactive feedback, data fusion analysis, and decision iteration optimization, digital twins enable understanding of physical entity status and control of predefined interface components in the physical entity [43]. This binding of physical and digital worlds is fundamental to building the metaverse—a metaverse that can only represent the digital world without interacting with the physical world is merely a “model” [44]. Furthermore, the digital world can not only represent the current state of the physical world but also simulate past states and predict future states based on physical world development and virtual-real interaction [45].

The physical system or physical world in agriculture is a complex dynamic environment encompassing multiple levels of information and characteristics including atmosphere, soil, crops, agricultural machinery, operators, and management practices [46]. Real-time information from the physical world is collected

through agricultural IoT devices for temperature, soil, light, etc., driving fusion modeling in the digital world through physical world information perception. The agricultural digital twin system architecture is shown in [Figure 2: see original paper].

The vigorous development of agricultural digital twin systems helps accelerate the implementation of agricultural metaverse. summarizes some agricultural digital twin systems, which have been applied in multiple agricultural fields, with the most extensive applications in agricultural production.

2.4.2 Parallel Agriculture

Parallel systems refer to combined systems composed of a real system and one or more corresponding virtual or artificial systems [47], achieving virtual-real integration [48]. Parallel systems form a new computational research system by integrating artificial systems, computational experiments, and parallel execution (the ACP method) to solve complex systems that are difficult to model, analyze, and predict [49][50].

Parallel agriculture involves constructing artificial agricultural systems in virtual space to describe real agricultural system problems, using these artificial systems to estimate and optimize future development, and ultimately achieving continuous interaction, feedback, and guidance between artificial and real agricultural systems to direct agricultural development [58]. Its system architecture is shown in [Figure 3: see original paper]. Currently, parallel agriculture has been widely applied in plant growth modeling [59], yield prediction [60], and intelligent decision-making [61].

Agricultural digital twins and parallel agriculture share similarities but have different focuses. Both provide new solutions for the scientific problem of integrating information, physics, and society, and both are closely related to advanced sensing, simulation, high-performance computing, and intelligent algorithms [62]. Agricultural digital twin systems focus on mechanism-clear agricultural systems, requiring manual construction of virtual agricultural systems that correspond to real physical agricultural systems in terms of state transition, observation, and control mechanisms. Parallel agriculture, however, can construct and explain complex agricultural systems with unclear mechanisms.

2.4.3 From Agricultural Digital Twins and Parallel Agriculture to Agricultural Metaverse

Agricultural digital twins and parallel agriculture build virtual worlds to predict and control the physical world, representing the embryonic form of agricultural metaverse. However, the virtual and real worlds constructed by agricultural digital twins and parallel agriculture are relatively independent, with humans playing a supporting role rather than being immersed in the virtual world. Compared to agricultural digital twins and parallel agriculture, agricultural metaverse places greater emphasis on participant experience and interaction, focusing

on immersion rather than merely achieving virtualization of physical systems.

Future agricultural digital twins and parallel agriculture need to incorporate XR technologies such as VR and AR to enhance digital-physical world interaction, integrate blockchain and NFT technologies to solve data ownership challenges, and achieve more advanced agricultural metaverse systems.

3 Metaverse Agricultural Application Scenarios

For the agricultural sector, metaverse technology applications will provide virtual-real integrated agricultural metaverse platforms and immersive environments for agricultural digital twins, agricultural information perception, agricultural intelligent management, virtual farms, agricultural education, and agricultural product traceability, greatly promoting agricultural development.

3.1 Virtual Farm

The virtual farm is one of the most important applications of agricultural metaverse and a crucial way for agricultural metaverse to empower traditional agriculture.

3.1.1 Agricultural Production Agricultural metaverse has enormous application prospects in agricultural production. It can establish virtual farms in virtual environments to simulate the complete growth processes of crops and livestock, collecting large amounts of crop and livestock growth data in extremely short timeframes to achieve intelligent and precision agriculture. Additionally, virtual farms can simulate pest activities to determine optimal pesticide application methods and timing, enabling farmers to obtain the latest decision-making solutions without mastering complex theoretical knowledge. For livestock managers, virtual farms can achieve precise simulation from organs and tissues to entire animals. When managers operate “virtual animals,” these virtual entities mimic real animal responses, which is significant for simulating animal living environments, nutritional needs, and breed selection.

Virtual farms already have some applications in agricultural production. Alibaba DAMO Academy’s XR Lab has implemented a case of virtual-real 联动 (linkage) agricultural picking robots. By creating 3D models of orchards and fruit trees, they constructed a high-precision virtual model of the entire orchard. Picking robots can perform motion planning in the virtual world, with results mapped to the physical robot’s control system to complete automatic picking, reducing orchard management costs. Super Code Technology proposed a metaverse intelligent tea garden, which can quickly simulate tea plant growth cycles, effectively shortening agricultural operation cycles and costs while obtaining massive growth data in short timeframes. This overcomes traditional agriculture’s characteristics of long cycles and difficult quantification, laying the foundation for refined and intelligent operations. The system can also collect

multi-dimensional data on soil and meteorological conditions through IoT devices, simulate harvest yields and values based on meteorological and historical circulation data, and simulate tea quality under different weather conditions, allowing farmers to understand tea plant growth without leaving home [65]. In indoor planting, indoor agriculture growers are already using AR technology to digitize and monitor crop physiological habits, growth processes, and related data [66].

3.1.2 Leisure Agriculture Experience Leisure agriculture experience is an emerging industry combining agricultural economy with tourism. Currently, the leisure agriculture experience industry chain has formed diversified structures, full-cycle operations, multi-functional integration, and comprehensive benefits. Agricultural metaverse applications in leisure agriculture focus on constructing virtual worlds that integrate with popular adoption models, agricultural tourism, and folk experiences, exploring the combination of virtual farms and real agricultural production. In this process, consumers use XR technology to monitor farm conditions in real-time and perform remote watering and fertilizing through immersive experiences as virtual “avatars.” Additionally, agricultural planters and equipment purchasers can experience planned agricultural products and equipment through agricultural metaverse without spatial or temporal constraints.

Metaverse leisure agriculture experiences have attracted widespread attention. On April 21, 2022, Suning Tesco cooperated with Yuchu World to launch the metaverse agricultural e-commerce project “Five Farmers Digital Dairy Cows,” where consumers can raise dairy cows in virtual pastures, achieving 确权 (rights confirmation), transaction, and milk yield benefits in the metaverse-constructed virtual ranch. Simultaneously, consumers receive high-quality milk in the real world. “Five Farmers Digital Dairy Cows” combines real-world commodity value attributes with virtual mapping experiences, allowing consumers to enjoy virtual farm life while receiving real-world product rewards. Due to the significant impact of COVID-19 on Thai tourism, the Thailand National Tourism Authority launched the “Metaverse Amazing Thailand: Amazing Durian” project in cooperation with 10 durian orchard owners in eastern Thailand, stimulating leisure agriculture development through Web3 platforms to provide tourists with new leisure agriculture experiences [67]. The Conghua Lingnan Fruit Industry Association uses agricultural metaverse to demonstrate intelligent planting of Conghua lychees, creating a virtual lychee orchard experience for planting + customized bases [68]. Consumers who adopt a lychee tree can watch real-time planting conditions through VR video, achieving immersive experiences of remote watering and fertilizing. The combination of agricultural metaverse and agricultural tourism allows visitors to experience the joy of personal farming through three-dimensional, visualized virtual worlds.

Virtual characters can also serve as tour guides for leisure agriculture experiences, enabling visitors to experience rural pleasures more 立体化

(three-dimensionally) and intuitively.

3.1.3 Virtual Characters Virtual characters are an important component of the metaverse. On October 31, 2021, the metaverse virtual character Liu Yexi gained millions of fans with her debut video, accumulating hundreds of millions of views across four videos in less than two months, bringing metaverse virtual characters into the public eye. The core function of virtual characters is helping real-world people handle virtual world affairs.

In agriculture, metaverse virtual characters have significant application potential in agricultural product promotion and live-stream sales. In recent years, live-stream sales have remained popular, but in rural China, farmers' reluctance to appear on camera and low participation willingness are still common issues. Metaverse virtual characters can replace real people for live-stream sales, offering unique advantages such as good image, standard Mandarin, and 24-hour availability. Additionally, metaverse virtual characters can serve as virtual butlers for agricultural products. On December 20, 2021, Guangdong Province launched the first agricultural virtual character "Xiao Ganmei" as the virtual butler for Deqing Tribute Oranges. On January 10, 2022, "Xiao Ganmei" first appeared in video form, entering Deqing Tribute Orange orchards and interacting with local farmers. In the virtual orchard, "Xiao Ganmei" provides services for tree adoption, remote watering, fertilizing, monitoring, and fruit picking, as well as year-round digital management. Subsequently, Guangdong launched the first pre-made dish virtual character "Xiao Xianmei" [69], positioned for deep integration with market and product promotion needs to increase consumer interaction and online experiences. Zhejiang Province also launched the metaverse intelligent tea garden virtual character "Xiao Mage" [70], responsible for introducing tea plant growth conditions in the metaverse world.

3.2 Agricultural Teaching System

The metaverse teaching system creates instructional systems in virtual worlds resembling natural scenes, adding metaverse spatial perception and virtual-real interaction [71]. The Third Plenary Session of the 15th CPC Central Committee stated that "the fundamental way out for agriculture lies in science, technology, and education." Only by developing science, technology, and education can agricultural resource advantages be transformed into commodity advantages and traditional agriculture be transformed into modern agriculture. Agricultural metaverse teaching systems can save training time and improve training efficiency through fragmented "micro-courses," allowing planters to learn by doing in immersive environments. Planters can receive training and education worldwide, with immersive, interactive learning that is clearer and more intuitive [72]. Related learning content can be customized for language and training environment factors. For situations urgently needing planting technicians, agricultural metaverse teaching systems also support technical training unlimited by time or space.

The Faculty of Agriculture at the National University of Laos built a metaverse agricultural teaching system [73], using egg chicken farm agricultural courses as examples for teaching agricultural knowledge, techniques, layout, and farm locations.

3.3 Agricultural Product Traceability System

Agricultural product traceability systems have become effective means for agricultural product supply chain management by reducing quality and safety risks, improving product recall efficiency, and protecting public health [74]. Traceability allows consumers to understand production information and see the entire production process, increasing confidence in enterprises and products. However, due to large spatiotemporal spans, numerous and dispersed participants, and difficulties in centralized management, coupled with lack of constraint mechanisms during data collection, information opacity often leads to low traceability credibility. Improving traceability credibility has become an important issue for sustainable traceability system applications [75]. Introducing agricultural metaverse technology into agricultural product traceability can display production and circulation processes to consumers through more realistic scenes and diverse forms, significantly reducing the cost of obtaining agricultural product quality information and enabling clearer understanding of planting, production, processing, and circulation links. This is important for combating market fraud, protecting geographical indication brands, and promoting healthy development of China's agricultural industry.

Current integration of agricultural product traceability systems with agricultural metaverse mostly occurs in the blockchain field, using blockchain's immutability, traceability, and high transparency to build agricultural product blockchain traceability systems [76]. With agricultural metaverse technology development, the connection between agricultural metaverse and rural e-commerce will become important for resolving food safety and supply-demand contradictions and promoting effective communication between consumers and producers. Consumers can view all conditions at production sites through agricultural metaverse terminals and select products according to personal needs, achieving full control from picking to home delivery.

4.1 Main Challenges

Although agricultural metaverse has achieved certain technical breakthroughs and applications in multiple agricultural fields, it remains in its infancy, with research in related technical areas still facing issues requiring resolution.

- (1) **Difficulties in establishing agricultural metaverse systems.** The agricultural system in the physical world is a complex dynamic system with numerous uncertainties in agricultural production processes, such as regional differences, climate variations, frost damage, pests and diseases, and animal epidemics, making virtual world establishment challenging.

- (2) **Weak communication infrastructure for agricultural metaverse.** Although rural broadband networks have covered villages, coverage rates for individual households and agricultural parks remain low. Issues such as unstable 4G signals, few 5G base stations, and high communication costs urgently need resolution. In agricultural plains where wired layout is impossible, “gateway+sub-node” approaches require kilometer-level communication distances, making research on low-power wireless communication technologies critical.
- (3) **Immature hardware devices for agricultural metaverse.** XR devices cannot simultaneously achieve miniaturization, portability, and low cost. Issues such as dizziness from prolonged XR device wear and insufficient realism have resulted in limited metaverse application implementation.
- (4) **Uncertain operations for agricultural metaverse.** Actual metaverse revenue is concentrated in highly compatible industries such as gaming and news, with limited exploration in agriculture and unclear operational models for agricultural applications.

4.2 Future Development Outlook

With continuous development of miniaturized, low-cost, low-power XR devices and deep integration of metaverse with AI, cloud computing, IoT, and blockchain technologies, scientific and efficient metaverse applications in agriculture will greatly promote agricultural informatization and intelligence development. Therefore, metaverse has broad prospects and enormous development potential in agriculture. Considering various challenges, future agricultural metaverse research should focus on the following areas:

- (1) **Conduct applicability research of metaverse in agriculture.** The physical system or world in agriculture is a complex dynamic environment. Only by more closely integrating agricultural characteristics such as regionality, seasonality, diversity, and periodicity can agricultural metaverse models that better conform to crop growth laws be established.
- (2) **Conduct agricultural growth mechanism research.** Establish multidisciplinary research teams in computer science, automation, electrical engineering, and agronomy to advance agricultural informatization and intelligence, laying a solid foundation for agricultural metaverse applications.
- (3) **Research low-power wireless communication technologies for agricultural applications and establish rural broadband networks covering households.** Integrate IoT, wireless sensor networks, and the internet to achieve comprehensive farm network coverage.
- (4) **Promote industrialized applications of agricultural metaverse.** Explore industrialized applications across multiple agricultural metaverse

scenarios, focusing on in-depth research in virtual farms and agricultural teaching systems to achieve large-scale industrial application as soon as possible.

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