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Metaverse in Agriculture: Emerging Opportunities and Associated Risks

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Abstract: *The accelerating progress of immersive systems, artificial intelligence, digital replicas, and pervasive network infrastructures has positioned the metaverse as an emerging socio-technical framework with transformative potential. Within this context, agriculture—an essential foundation for food systems and long-term sustainability—remains in the early stages of engaging with such digital transformations, largely at a conceptual and exploratory level. This study offers a theoretical investigation into the integration of metaverse environments within agriculture, examining prospective benefits, associated challenges, and avenues for future inquiry. Rather than limiting its scope to technological applications, the paper develops a structured conceptual model that links real-world farming ecosystems with interactive virtual spaces designed for capacity building, informed decision-making, stakeholder collaboration, and policy facilitation. The proposed perspective is aligned with the guiding principles of India's National Education Policy (NEP) 2020 and the United Nations Sustainable Development Goals (SDGs), situating the discussion within broader developmental priorities. Additionally, the study highlights critical considerations related to ethics, equity, data governance, environmental impact, and disparities in digital access. By synthesizing insights from recent academic discourse, this paper introduces an initial conceptual foundation intended to guide subsequent research efforts, policymaking initiatives, and the responsible advancement of digital innovations in agriculture.*

Keywords: Metaverse, Digital Agriculture, Immersive Technologies, Digital Twins, Smart Farming, Sustainable Agriculture, NEP 2020, Sustainable Development Goals

I. INTRODUCTION

The convergence of sensing technologies, data-centric intelligence, automation, and cyber–physical integration is leading to a transformative shift in agriculture. This shift is increasingly articulated through the framework of Digital Agriculture 5.0, where human-centred design, sustainable practices, resilience, and ethical considerations are prioritized over purely technocentric approaches [1], [2]. Simultaneously, the metaverse has emerged as a real-time, immersive digital ecosystem integrating the physical world with persistent virtual environments through extended reality (XR), artificial intelligence (AI), blockchain technologies, and digital twins [3], [4]. While metaverse research has expanded rapidly in domains such as education, manufacturing, healthcare, and smart cities, its systematic application in agriculture remains relatively underexplored and largely conceptual [3], [5]. Immersive virtual environment extensions provide a novel reconfiguration of agricultural education, simulation, planning, and governance, particularly given the spatial, temporal, and socio-environmental complexity inherent in agricultural systems [6]. Accordingly, metaverse-enabled agriculture should be examined not merely as an extension of digital tools but as a broader socio-technical ecosystem with implications for sustainability, equity, and policy formulation.

Agriculture today faces systemic challenges that demand integrative and anticipatory solutions. Climate change, soil degradation, biodiversity loss, water scarcity, supply chain disruptions, and demographic pressures collectively threaten global food security and rural livelihoods [7], [8]. Traditional agricultural decision-making models, often based on

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historical data and reactive management, are increasingly insufficient under environmental uncertainty and market volatility. Although digital technologies such as IoT-based sensing, satellite monitoring, machine learning, and automation have significantly improved precision farming practices [1], [9], these systems frequently operate within fragmented technological silos. The absence of immersive, interoperable, and collaborative digital ecosystems limits stakeholders' ability to simulate complex agricultural scenarios holistically and to co-design adaptive strategies in real time.

The metaverse paradigm introduces a qualitatively different digital layer by enabling persistent, shared, and interactive three-dimensional environments where physical agricultural systems can be mirrored through dynamic digital twins enriched with real-time data streams [4], [10]. Unlike conventional farm management dashboards, immersive platforms facilitate spatial cognition, embodied interaction, and multi-user collaboration [11]. Farmers, agronomists, researchers, policymakers, and supply chain actors can engage simultaneously within a shared virtual representation of agricultural landscapes, enabling participatory experimentation and collective intelligence. This convergence transforms agricultural management from static data consultation into experiential simulation and adaptive governance.

Agriculture operates across multiple scales, ranging from soil microbiology and crop physiology to regional ecosystems and global trade networks. Digital twins and cyber–physical systems enable the integration of micro-level sensor data with macro-level climate and economic models [10], [12]. For instance, irrigation strategies can be evaluated in relation to watershed sustainability, and crop diversification scenarios can be simulated to assess long-term resilience under climate variability. Such cross-scale integration enhances systemic awareness and supports evidence-based sustainability planning.

However, the integration of immersive metaverse technologies into agriculture introduces important socio-technical concerns. Agricultural communities are often characterised by smallholder farmers with limited digital infrastructure access. Without deliberate inclusivity measures, digital transformation risks exacerbating inequalities between technologically advanced agribusinesses and marginalised rural populations [13], [14]. Moreover, virtualization of agricultural systems raises concerns regarding data ownership, platform governance, algorithmic transparency, and cybersecurity [2], [14]. These challenges necessitate interdisciplinary frameworks that combine engineering innovation with ethical oversight and regulatory accountability.

Environmental sustainability also presents a paradox. While precision agriculture can reduce water consumption, fertiliser overuse, and carbon emissions [1], immersive metaverse infrastructures rely on high-performance computing, data centres, and XR hardware, all of which consume significant energy resources [15]. Evaluating the net sustainability impact of metaverse-enabled agriculture, therefore, requires lifecycle assessment methodologies and green computing strategies.

From an educational perspective, immersive environments offer transformative potential for agricultural training and skill development. XR-based simulations enhance experiential learning, enabling users to interact with complex farming scenarios without physical constraints [11]. Such platforms align with emerging multidisciplinary and digitally integrated educational models that emphasise innovation, skill development, and technology-enabled learning ecosystems.

Despite these promising opportunities, scholarly discourse on metaverse-enabled agriculture remains fragmented. Existing research tends to focus either on precision agriculture technologies [1], [9] or on metaverse applications in non-agricultural sectors [3], [5]. A comprehensive theoretical synthesis that integrates immersive systems engineering with agricultural sustainability and socio-economic equity is still limited. This gap underscores the need for a structured conceptual framework that situates metaverse-enabled agriculture within broader debates on responsible innovation, digital transformation, and sustainable development.

Therefore, this study conceptualises metaverse-enabled agriculture as an emergent socio-technical ecosystem rather than a speculative abstraction. By examining its layered architecture, transformative opportunities, structural risks, and governance implications, this work contributes to foundational theory building at the intersection of immersive systems engineering and sustainable agriculture.

This study makes several key contributions to the emerging discourse on immersive digital transformation in agriculture. First, it conceptualises metaverse-enabled agriculture as an integrated virtual–physical ecosystem that connects cyber–physical agricultural systems with persistent immersive environments. Second, it proposes a layered, theory-driven framework that provides a structured foundation for analytical inquiry and interdisciplinary research. Third, it systematically examines both the conceptual opportunities and the associated technological, ethical, and governance-related risks of implementing metaverse infrastructures in agricultural contexts. Finally, the study aligns the proposed vision with the objectives of NEP 2020 and the United Nations Sustainable Development Goals (SDGs), thereby situating the discussion within broader sustainability and innovation.

II. LITERATURE REVIEW

To position the proposed framework within existing scholarship, a structured review of interdisciplinary literature was conducted across IEEE Xplore, Scopus, Web of Science, and ScienceDirect databases. The review focused on peer-reviewed articles published within the last decade and analysed literature across four intersecting domains: smart agriculture, cyber–physical and digital twin systems, immersive extended reality technologies, and metaverse architectures. The findings were categorised thematically to identify technological maturity, sustainability integration, and research gaps.

a) Smart Farming and Data-Driven Agricultural Systems

Recent research emphasises the transformation of agriculture through IoT-enabled sensing, big data analytics, and AI-driven automation. Wolfert *et al.* [15] highlight how data-intensive farming enhances productivity and operational efficiency through interconnected sensor ecosystems. Similarly, Liakos *et al.* [16] systematically review machine learning applications for crop yield prediction, disease detection, and soil management. Verdouw *et al.* [17] further extend this vision through digital farming architectures integrating real-time analytics and decision-support platforms. However, these approaches primarily rely on dashboard-based monitoring systems and lack immersive, collaborative, and socio-technical integration layers.

b) Cyber–Physical Systems and Digital Twins in Agriculture

Cyber–physical systems (CPS) enable real-time interaction between computational intelligence and physical agricultural operations. Research in this domain focuses on feedback-driven automation and distributed monitoring frameworks [18]. Digital twin technologies further replicate physical agricultural assets within dynamic virtual environments for predictive simulation and optimisation [17]. While digital twins allow advanced scenario modelling, their integration into persistent, multi-user immersive ecosystems remains limited. Most applications emphasise efficiency optimisation rather than participatory governance or sustainability experimentation.

c) Edge Intelligence and Federated Learning

To address latency and connectivity constraints in rural environments, edge computing architectures process data closer to agricultural sources, reducing dependency on centralised cloud infrastructures [19]. Federated learning further enhances privacy-preserving model training by enabling decentralised AI systems [20]. These frameworks improve computational scalability and data sovereignty; however, they primarily focus on backend optimisation and do not incorporate immersive visualisation or stakeholder interaction layers essential for metaverse environments.

d) Immersive Extended Reality in Agricultural Training

Extended Reality (XR), encompassing virtual reality (VR), augmented reality (AR), and mixed reality (MR), has demonstrated significant potential in agricultural training and skill development. Dwivedi *et al.* [21] discuss the broader conceptual foundations of immersive ecosystems, while experiential learning studies demonstrate XR's effectiveness in spatial simulation and agricultural education environments [22]. Despite these advancements, XR implementations

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typically function as standalone instructional tools disconnected from real-time agricultural data streams or cyber–physical infrastructures

e) Metaverse Architectures and Socio-Technical Implications

The metaverse has been conceptualised as a persistent, interoperable digital ecosystem integrating AI, blockchain, immersive interaction, and decentralised governance [21], [23]. Bibri and Allam [24] discuss sustainability-oriented metaverse frameworks within smart city contexts, highlighting governance, environmental, and ethical dimensions. Additionally, socio-political analyses of digital agriculture emphasise concerns regarding data ownership, equity, and platform monopolisation [25]. However, existing metaverse scholarship rarely integrates agricultural CPS, sustainability modelling, and immersive collaboration into a unified socio-technical framework.

Table-1 Comparative Analysis of Prior Research on Digital Agriculture and Metaverse-Related Systems

Ref.	Study Focus	Core Technologies	Immersive / Metaverse Integration	Key Limitation Identified
[15]	Big data in smart farming	IoT, Big Data Analytics	No	Lacks immersive and governance integration
[16]	Machine learning in agriculture	ML, AI models	No	Focus on prediction, not collaboration
[17]	Digital twins in smart farming	Digital Twins, IoT	Partial (simulation only)	No persistent immersive interaction
[18]	Deep learning & CPS in agriculture	Deep Learning, CPS	No	Limited socio-technical integration
[19]	Edge intelligence architecture	Edge Computing	No	Backend-focused, no visualisation layer
[20]	Federated learning systems	Federated Learning	No	No XR/metaverse integration
[21]	Metaverse conceptual foundations	XR, AI, Blockchain	Yes (theoretical)	Not agriculture-specific
[22]	Immersive VR in education	VR/AR/MR	Yes (training only)	Not integrated with live farm data
[23]	Virtual worlds & metaverse evolution	3D Virtual Worlds	Yes	No agricultural CPS linkage
[24]	Metaverse & sustainability in smart cities	Virtual ecosystems	Yes	Not domain-specific for agriculture
[25]	Politics of digital agriculture	Digital platforms	No	Limited technical architecture

III. CONCEPTUAL FOUNDATIONS OF METAVERSE-ENABLED AGRICULTURE

The metaverse can be conceptualised as a persistent, interoperable, and synchronous digital ecosystem in which users interact with virtual representations of physical entities through immersive technologies such as extended reality (XR), artificial intelligence (AI), and distributed ledger systems [26], [27]. Unlike traditional virtual environments, the metaverse emphasises continuity, interoperability across platforms, embodied interaction, and real-time synchronisation with physical systems. In agricultural contexts, this translates into immersive and data-integrated representations of farms, crops, irrigation systems, supply chains, market infrastructures, and multi-stakeholder networks. Through digital twins and sensor-driven synchronisation, physical farm environments can be mirrored within virtual spaces, enabling continuous monitoring, predictive simulation, and collaborative experimentation [28].

Metaverse-enabled agriculture is not designed to replace physical farming operations but rather to augment them through enhanced visualisation, advanced simulation, and participatory decision-making. By embedding agricultural cyber–physical systems within immersive environments, stakeholders—including farmers, agronomists, policymakers, researchers, and market actors—can interact with shared, data-rich models of agricultural ecosystems. This augmentation paradigm aligns with Industry 5.0 principles, emphasizing human-centered technological integration, sustainability, and resilience over purely automation-driven objectives [29]. Within such an ecosystem, agricultural decision-making evolves from isolated dashboard analytics to embodied, spatially contextualised, and collaborative experiences.

From a theoretical standpoint, metaverse-enabled agriculture draws upon several interdisciplinary foundations. Cyber–physical systems theory provides the structural backbone, enabling continuous feedback loops between physical agricultural processes and computational intelligence layers [30]. Digital twin theory extends this framework by enabling high-fidelity virtual replicas of crops, soil conditions, weather systems, and agricultural machinery capable of scenario-based forecasting and risk modelling [28]. Human–computer interaction (HCI) theory contributes insights into immersive interface design, usability, and embodied cognition, ensuring that XR-based agricultural environments remain intuitive and accessible [31]. Collective intelligence and participatory governance frameworks further inform the collaborative dimensions of metaverse-enabled agriculture, where distributed stakeholders contribute knowledge and co-create solutions in shared virtual environments [32].

The convergence of these paradigms enables transformative possibilities in experiential learning, participatory planning, and policy experimentation. Immersive simulation environments can support climate resilience modelling, resource optimisation strategies, and sustainable cropping experiments without risking real-world losses. Policymakers can test regulatory interventions in controlled digital ecosystems before implementation, while educational institutions can deliver hands-on agricultural training through virtual farm laboratories. Moreover, blockchain-enabled identity and asset management systems may facilitate transparent Agri-value chain transactions and decentralised governance mechanisms [27], [33]. However, the conceptual foundation also demands critical reflection on interoperability standards, data sovereignty, environmental impacts of large-scale digital infrastructures, and ethical AI deployment within rural contexts [26], [29].

Thus, metaverse-enabled agriculture should be understood not merely as an aggregation of immersive tools but as an integrated socio-technical ecosystem grounded in cyber–physical integration, digital twin modelling, immersive interaction design, and collaborative intelligence theory. This foundation establishes the theoretical basis for the architectural framework and analytical discussions presented in subsequent sections.

IV. CONCEPTUAL FRAMEWORK AND ARCHITECTURE

a) Framework Overview: The proposed conceptual framework establishes a structured integration between physical agricultural ecosystems and persistent metaverse environments through continuous data abstraction, intelligent processing, and immersive human interaction. Unlike platform-specific implementations, this framework is intentionally theory-driven and modular, ensuring adaptability across diverse agricultural contexts and technological infrastructures. It conceptualizes agriculture as a cyber–physical–social system in which biophysical processes, computational intelligence, and stakeholder decision-making coexist within a unified architecture. The framework draws upon systems engineering principles, distributed intelligence models, and digital twin ecosystems to enable real-time synchronisation between physical farm assets and their virtual counterparts [34], [35].

At its core, the framework operationalises bidirectional coupling between real-world agricultural processes and immersive virtual environments. Data flows upward from physical systems through sensing and abstraction layers, while insights, predictive simulations, and policy interventions flow downward to influence real-world practices. Such

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recursive interaction transforms agriculture from a reactive production system into a reflective, adaptive, and learning-oriented ecosystem. This approach aligns with contemporary research on cyber–physical production systems and smart agricultural infrastructures that emphasise interoperability, resilience, and sustainability [36]. Furthermore, the integration of immersive interaction layers introduces embodied cognition and spatial decision-support capabilities, extending beyond traditional dashboard-based analytics [37].

The framework also incorporates governance and socio-economic dimensions as intrinsic architectural components rather than external considerations. By embedding policy actors, researchers, educators, and market stakeholders within the metaverse interaction layer, the system facilitates participatory experimentation, transparent value-chain visualisation, and collaborative scenario modelling. This aligns with emerging research advocating socio-technical co-design in digital transformation initiatives [38].

b) Layered Architecture: The architecture is organised into six interdependent layers, each performing distinct yet interconnected functions within the metaverse-enabled agricultural ecosystem.

The **Physical Agricultural Layer** represents the foundational biophysical environment, including crops, soil systems, livestock, irrigation networks, agricultural machinery, and environmental variables. This layer encompasses dynamic ecological processes such as plant growth, nutrient cycles, water distribution, and climate interactions. It forms the empirical basis upon which all higher-level abstractions depend. Research in precision agriculture emphasises that accurate modelling of this layer is essential for sustainable intensification and climate resilience [39].

Sensing and Data Abstraction Layer, which captures real-time information from IoT devices, remote sensing platforms, satellite imagery, climate stations, and manual observational inputs. Data collected at this layer undergoes preprocessing, normalisation, and semantic abstraction to ensure interoperability across heterogeneous systems. Advances in IoT-enabled agriculture and remote sensing analytics have demonstrated the potential for high-resolution monitoring of crop health, soil moisture, and environmental stressors [40]. Data abstraction at this level ensures scalability and compatibility with distributed computational infrastructures.

The **Intelligence Layer** constitutes the analytical core of the architecture. It integrates artificial intelligence, machine learning algorithms, predictive modelling techniques, and edge computing infrastructures to derive actionable insights from abstracted data streams. AI-driven analytics enable yield prediction, pest detection, irrigation optimisation, and risk forecasting. Edge intelligence reduces latency and enhances responsiveness in rural environments where network connectivity may be constrained [41]. Decision-support reasoning systems embedded within this layer facilitate adaptive farm management by transforming raw data into interpretable knowledge.

The **Digital Twin Layer** builds upon intelligence outputs to construct dynamic, high-fidelity virtual replicas of physical agricultural assets. Digital twins simulate crop growth patterns, climate scenarios, resource allocation strategies, and supply-chain logistics in a risk-free virtual environment. Through scenario-based experimentation, stakeholders can evaluate the implications of alternative agricultural strategies before real-world implementation. Digital twin ecosystems have demonstrated transformative potential in industrial and smart farming contexts by enabling predictive maintenance, resource optimisation, and resilience planning [35], [42].

The **Metaverse Interaction Layer** provides immersive extended reality (XR) environments in which users interact with digital twins and analytics outputs. This layer supports visualisation, spatial exploration, collaborative planning, and experiential learning. Immersive interfaces allow stakeholders to navigate virtual farm landscapes, simulate environmental stress scenarios, and co-design adaptive strategies in real time. Research in immersive systems indicates that spatial visualisation enhances cognitive understanding of complex systems, thereby improving decision quality and stakeholder engagement [37].

Finally, the **Human and Governance Layer** integrate farmers, agronomists, researchers, educators, policymakers, and Agri-market actors into the architectural ecosystem. This layer ensures that technological intelligence remains human-centred and ethically guided. It facilitates participatory governance, knowledge exchange, policy simulation, and transparent value-chain monitoring. Embedding governance within the architecture aligns with sustainability-driven digital transformation frameworks and promotes equitable access to technological benefits [38], [39].

Collectively, these six layers operate through continuous bidirectional feedback loops. Data originating from physical systems propagates upward through sensing and intelligence layers to inform digital twin simulations and immersive representations. Conversely, decisions, predictive insights, and policy interventions generated within virtual environments influence physical agricultural practices. This recursive architecture establishes a reflective agricultural ecosystem capable of adaptive learning, resilience enhancement, and sustainability optimisation. By structurally integrating cyber–physical systems, immersive interfaces, distributed intelligence, and governance mechanisms, the framework provides a scalable foundation for metaverse-enabled agriculture.

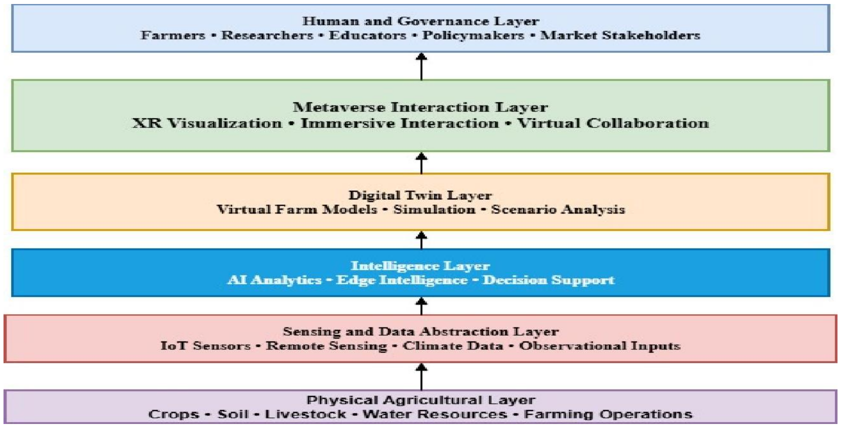

Figure-1 Layers of Smart Agriculture

V. OPPORTUNITIES

Metaverse-enabled agriculture presents a range of transformative theoretical and practical opportunities that extend beyond traditional digital farming systems by enabling immersive, interactive, and collaborative virtual environments.

Immersive Agricultural Education represents one of the most impactful opportunities within this paradigm. Virtual farms and simulated Agri-ecological scenarios can support experiential and competency-based learning aligned with contemporary educational reforms such as India's National Education Policy (NEP) 2020, which emphasises multidisciplinary integration, digital literacy, and hands-on training [43], [44]. Through XR-enabled virtual environments, students and practitioners can interact with dynamic crop growth models, soil nutrient cycles, pest outbreaks, and climate variability simulations without physical constraints. Such immersive pedagogical ecosystems can democratize access to agricultural training, particularly in rural and resource-constrained regions.

Advanced Decision Support emerges as another significant opportunity, particularly in the visualisation of complex spatial-temporal agricultural data. By integrating sensor streams, predictive analytics, and climate modelling outputs within immersive environments, stakeholders can spatially explore crop–climate interactions and resource allocation trade-offs [15], [21]. The ability to visualise multidimensional data in embodied virtual space enhances cognitive understanding and reduces uncertainty in strategic planning. Scenario-based experimentation within digital twins further allows farmers to evaluate irrigation schedules, fertiliser application strategies, and crop diversification plans before real-world deployment.

Collaborative Ecosystems and Collective Intelligence constitute a third major opportunity. Shared metaverse environments enable synchronous, multi-user engagement among farmers, researchers, extension workers, policymakers, and Agri-market actors. Such collaborative spaces support participatory problem-solving, knowledge exchange, and innovation diffusion across institutional and geographical boundaries [20], [45]. By embedding collective intelligence mechanisms within immersive systems, agricultural communities can co-create adaptive strategies for climate resilience, pest management, and sustainable intensification.

Policy and Planning Laboratories offer another transformative dimension. Virtual experimentation platforms allow governments and research institutions to simulate agricultural subsidy structures, climate adaptation programs, land-use regulations, and market interventions in controlled digital environments. This supports evidence-based policymaking by enabling scenario comparison, impact visualisation, and long-term sustainability modelling before physical implementation [8], [46]. Such digital policy sandboxes reduce the risks associated with regulatory experimentation and enhance transparency in governance processes.

Sustainability Awareness and Environmental Stewardship represent a critical opportunity for long-term resilience. By simulating carbon emissions, water consumption, biodiversity impacts, and soil degradation processes within immersive environments, stakeholders can visualise the environmental consequences of agricultural practices in real time [7], [47]. This heightened ecological awareness encourages responsible resource management, climate-smart farming strategies, and alignment with global Sustainable Development Goals (SDGs). The immersive representation of sustainability metrics can also foster behavioural change by making abstract environmental data tangible and actionable.

Collectively, these opportunities suggest that metaverse-enabled agriculture has the potential to reshape agricultural education, decision-making, collaboration, governance, and sustainability engagement. However, the realisation of these benefits depends on inclusive design, ethical data governance, infrastructure readiness, and interoperability standards, which are examined in the subsequent section on risks and challenges.

VI. RISKS AND CHALLENGES

Despite its transformative potential, metaverse-enabled agriculture introduces a complex set of technological, socio-economic, ethical, and regulatory risks that must be critically examined to ensure responsible innovation. These risks extend beyond technical feasibility and encompass issues of equity, governance, sustainability, and cultural integrity.

Digital Divide and Exclusion represent one of the most significant structural challenges. The deployment of immersive XR systems, high-bandwidth connectivity, IoT infrastructures, and AI-driven analytics presupposes reliable digital access and advanced technological literacy. However, rural regions—particularly in developing economies—often face infrastructural limitations, including inadequate broadband coverage, high device costs, and insufficient digital training programs. Such disparities may exacerbate existing inequalities by privileging technologically advanced agribusinesses while marginalising smallholder farmers and indigenous communities [48], [49]. Without inclusive policy design and capacity-building initiatives, metaverse-enabled agriculture risks reinforcing rather than reducing rural socio-economic divides.

Data Privacy and Sovereignty concerns arise from the continuous collection, abstraction, and virtualisation of agricultural data. Persistent digital twins and immersive farm environments depend on real-time data streams related to crop yields, soil health, climate patterns, and market transactions. The aggregation of such data within centralised or platform-controlled infrastructures raises questions about ownership rights, surveillance risks, algorithmic bias, and cross-border data flows [50]. Agricultural data is not merely technical information but also an economic asset, and its misuse could lead to exploitative market practices or corporate monopolisation. Ensuring secure architectures, transparent governance mechanisms, and farmer-centric data sovereignty frameworks is therefore essential.

Ethical and Cultural Concerns further complicate the implementation of immersive agricultural systems. Over-reliance on virtual simulation and AI-driven decision-support tools may inadvertently diminish traditional ecological knowledge and localised farming practices that have evolved over generations. Indigenous agricultural systems often embody culturally embedded knowledge networks that cannot be fully codified into algorithmic models [51]. The substitution of experiential wisdom with automated recommendations may undermine human agency and reduce the diversity of agricultural approaches. Ethical deployment requires balancing technological augmentation with respect for cultural heritage and farmer autonomy.

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Environmental Costs of Digital Infrastructure present an additional paradox. While metaverse-enabled agriculture aims to promote sustainability and resource optimisation, the underlying computational infrastructure—including data centres, blockchain networks, XR rendering engines, and edge computing systems—can be energy intensive. Large-scale immersive environments and persistent digital twins require substantial processing power and storage capacity, potentially contributing to increased carbon emissions and electronic waste [52]. If not powered by renewable energy sources or optimised for energy efficiency, such infrastructures may conflict with broader environmental sustainability goals.

Governance and Regulatory Ambiguity constitute another major challenge. The rapid evolution of immersive digital ecosystems has outpaced the development of clear regulatory frameworks governing data rights, platform accountability, digital asset ownership, and algorithmic transparency. Agricultural metaverse platforms operate at the intersection of multiple regulatory domains, including agriculture, telecommunications, cybersecurity, intellectual property, and environmental law [53]. The absence of harmonised governance standards may lead to jurisdictional conflicts, inconsistent enforcement, and limited recourse for affected stakeholders. Establishing interoperable standards, ethical AI guidelines, and transparent oversight mechanisms is critical to mitigate systemic risks.

Collectively, these risks underscore that metaverse-enabled agriculture should not be viewed as a purely technological upgrade but as a socio-technical transformation requiring ethical foresight, inclusive governance, sustainable infrastructure planning, and participatory stakeholder engagement. Addressing these challenges proactively will determine whether immersive agricultural ecosystems evolve as equitable and sustainable innovations or exacerbate existing structural vulnerabilities.

VII. ALIGNMENT WITH NEP 2020 AND SDGS

Metaverse-enabled agriculture demonstrates strong alignment with the objectives articulated in India's National Education Policy (NEP) 2020, particularly in its emphasis on multidisciplinary learning, experiential pedagogy, digital literacy, research innovation, and equitable access to technology-enabled education [54]. NEP 2020 advocates the integration of emerging technologies into higher education and vocational training to foster problem-solving skills, critical thinking, and applied research competencies. Immersive virtual farm environments and simulation-based agricultural laboratories support these objectives by enabling experiential learning beyond traditional classroom and field constraints. Through XR-enabled platforms, students can engage in climate modelling, soil diagnostics, crop lifecycle analysis, and supply chain simulations, thereby bridging theoretical knowledge with practical application [55]. Furthermore, metaverse ecosystems facilitate collaborative research and innovation hubs that connect universities, agricultural institutes, and rural communities in digitally mediated knowledge networks, consistent with NEP's focus on research-driven national development.

From a global sustainability perspective, metaverse-enabled agriculture contributes to multiple United Nations Sustainable Development Goals (SDGs). By enhancing predictive yield modelling, resource optimisation, and food system resilience, it supports **SDG 2 (Zero Hunger)** through improved agricultural productivity and food security planning [56]. Its immersive and accessible training environments advance **SDG 4 (Quality Education)** by democratising agricultural education and lifelong learning opportunities. The integration of AI, IoT, digital twins, and immersive infrastructures promotes **SDG 9 (Industry, Innovation and Infrastructure)** by fostering technological modernisation in rural economies. Through virtual urban–rural connectivity and participatory governance platforms, it indirectly strengthens **SDG 11 (Sustainable Cities and Communities)**. Simulation-based resource management and circular economy visualisation align with **SDG 12 (Responsible Consumption and Production)**, while climate scenario modelling and adaptive planning tools directly support **SDG 13 (Climate Action)** by enabling evidence-based mitigation and adaptation strategies [57]. Thus, the metaverse-enabled agricultural paradigm operates at the intersection of educational reform, technological innovation, and sustainable development, reinforcing both national policy priorities and global sustainability commitments.

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VIII. CONCLUSIONS

This paper conceptualized metaverse-enabled agriculture as an integrated cyber–physical–social ecosystem that connects physical farming environments with immersive digital spaces through layered architecture and bidirectional data feedback. By synthesising IoT, artificial intelligence, digital twins, and extended reality within a unified framework, the study highlights how immersive environments can enhance agricultural education, decision support, collaborative innovation, policy experimentation, and sustainability awareness. The alignment with NEP 2020 and multiple UN Sustainable Development Goals further reinforces its strategic relevance at both national and global levels. At the same time, significant challenges—including digital divide, data sovereignty, ethical concerns, environmental costs, and regulatory ambiguity—must be addressed to ensure equitable and responsible implementation. Overall, metaverse-enabled agriculture represents a promising yet complex socio-technical paradigm whose success will depend on inclusive design, sustainable infrastructure, and transparent governance.

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