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On-Demand Manufacturing of Agricultural Spare Parts Using 3D Printing Technology

Kailashkumar B*[1], Monissh S. R[2], Mamallan R[3], Balamani N[4] and Naresh J[5]

[1-5] Department of Agricultural Engineering, Paavai Engineering College, Pachal, Namakkal - 637 018, Tamil Nadu, India

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Abstract

The increasing reliance on mechanization in agriculture has significantly boosted productivity and operational efficiency. However, the unavailability of critical spare parts, especially in remote and rural areas, often leads to prolonged equipment downtime and economic losses. This research addresses the challenge by developing a 3D printing system capable of on-demand manufacturing of durable agricultural spare parts. The proposed solution focuses on creating a scalable, user-friendly, and adaptable 3D printer designed to work with locally available materials. Emphasis is placed on selecting suitable materials that meet the mechanical strength, durability, and environmental resistance required for agricultural applications. The prototype printer was tested for its ability to produce essential spare parts efficiently, demonstrating considerable cost savings, reduced downtime, and minimized dependency on conventional supply chains. By enabling localized, on-site production, this approach enhances the self-sufficiency of farmers and small-scale producers, while promoting sustainability through reduced waste and transportation costs. The results suggest that 3D printing technology holds transformative potential in revolutionizing agricultural spare parts logistics, particularly in underserved rural regions.

***Key words*:** 3D printer, Farm tractor, Rapid prototyping, Sprayer, Spare parts

The use of additive manufacturing, particularly 3D printing, in agriculture is an emerging area of study that holds great potential for decentralizing the production of essential components. Over the past decade, researchers and innovators have explored the application of 3D printing technologies in various domains, from industrial prototyping to biomedical engineering [1]. This technology allows for on-demand fabrication, reducing dependency on centralized manufacturing and long distribution networks, a particularly impactful shift for rural and remote farming communities. In the agricultural sector, however, this technology remains underutilized despite its promising implications. 3D printing in agriculture is primarily being investigated for prototyping, spare part manufacturing, and educational purposes. According to [2], the capacity to create parts on-demand allows users to bypass complex supply chains, significantly reducing downtime in mechanical operations. This is particularly relevant in rural regions where access to replacement parts is limited due to geographical and economic barriers. One of the primary advantages of 3D printing is its ability to create custom-designed parts suited to specific local needs. The capability of 3D printing to produce parts that are not only dimensionally accurate but also functionally robust for agricultural machinery. This customization supports precision agriculture, where equipment must often be tailored to specific crop types, field sizes, and environmental conditions [3]. Material choice plays a crucial role in determining the success of printed parts in agricultural applications. While polylactic acid (PLA) is commonly used due to its biodegradability and ease of printing, its mechanical limitations necessitate alternatives. The materials such as Polyethylene Terephthalate Glycol-modified (PETG), Acrylonitrile Butadiene Styrene (ABS), and nylon offer improved mechanical properties, including impact resistance and Ultraviolet (UV) stability, making them more suitable for field applications [4].

The integration of recycled plastics into 3D printing feedstock has gained traction in recent years [5-6]. The recycled filaments, especially those derived from polyethylene-based agricultural waste, can perform comparably to virgin materials in certain applications. This aligns with the principles of circular economy and provides an eco-friendly alternative to conventional manufacturing methods [7]. In terms of economic feasibility, multiple studies have demonstrated that decentralized 3D printing setups offer significant cost advantages. The democratization of manufacturing through 3D printing can lead to greater local empowerment and economic resilience [8]. Moreover, the affordability of desktop 3D printers opens opportunities for training, entrepreneurship, and micro-manufacturing in underserved communities [9]. Despite its advantages, the deployment of 3D printing in rural agriculture is not without challenges. Infrastructure limitations, such as inconsistent power supply and lack of technical knowledge, can hinder adoption. The importance of open-source designs and user-friendly interfaces in mitigating these barriers. Additionally, the success of such technologies depends heavily on community engagement and institutional support [10]. Recent developments focus on integrating 3D printers with IoT and AI systems to enable smart manufacturing. The

***Correspondence to:** Kailashkumar B, E-mail: kkailash35@gmail.com; Tel: +91 9791843152

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coupling of 3D printing with remote diagnostics and cloud-based repositories can enable real-time support and customization for farmers. Such digital ecosystems are particularly beneficial in resource-constrained settings where expert support is limited [11].

MATERIALS AND METHODS

The integration of 3D printing technology in agriculture represents a transformative approach to addressing many of the sector's challenges, including customization, sustainability, affordability, and rapid prototyping. Known technically as additive manufacturing, 3D printing allows the creation of complex, functional parts by adding material layer by layer. In agriculture, this technology is unlocking new possibilities for equipment design, production, and innovation—especially for smallholder farmers and AgriTech startups [12-13]. One of the most significant contributions of 3D printing is in the custom fabrication of tools and equipment. Conventional manufacturing processes are often time-consuming and costly, particularly for small-scale or customized items. 3D printing enables the rapid design and production of farm tools, irrigation components, drone accessories, seed planters, and greenhouse parts tailored to specific needs. For instance, a farmer can print a customized nozzle for a drip irrigation system or a spare part for a broken tractor component without waiting for delivery or relying on imported goods. 3D printing also plays a vital role in prototyping agricultural innovations. Researchers, engineers, and students developing precision agriculture devices—like automated soil sensors, robotic planters, or drone mounts—can rapidly prototype and test their designs. This accelerates innovation cycles, reduces R&D costs, and encourages experimentation. AgriTech startups, in particular, benefit from this capability as they can pivot quickly based on field feedback without investing heavily in traditional tooling. Another key advantage lies in cost reduction and sustainability [12]. 3D printing minimizes material waste since it uses only the amount of material necessary to build the object. Farmers can use biodegradable or recycled materials, which align with sustainable agriculture practices. This not only reduces the carbon footprint but also supports circular economy models in rural areas [14-15]. In education and skill development, 3D printing serves as a hands-on learning tool in agricultural universities and vocational institutions. Students and young entrepreneurs gain exposure to digital design, fabrication, and problem-solving in real-world contexts. This fosters a new generation of tech-savvy agricultural professionals who can lead the shift toward smart farming. Moreover, 3D printing contributes to resilience and local self-reliance in rural communities. When supply chains are disrupted—as experienced during the COVID-19 pandemic—locally available 3D printing systems allow farmers to produce critical components and reduce downtime. This resilience is especially crucial in remote areas where access to spare parts and tools is limited. In the long term, the convergence of 3D printing with Internet of Things (IoT) and Artificial Intelligence will further expand its role. Smart farming systems could automatically design and print components based on predictive analytics, enhancing on-farm adaptability and efficiency [16-17].

RESULTS AND DISCUSSION

The central aim of this research is to bridge the gap between technological advancement and practical usability in farming communities. While 3D printing technology is not new, its application in agriculture, especially for manufacturing durable and functional machine components, is still an emerging domain. Traditional manufacturing techniques such as injection molding, CNC machining, and casting require significant infrastructure and investment, making them inaccessible for decentralized rural settings [18]. Moreover, the lead time associated with sourcing parts from distant suppliers can delay crucial operations such as irrigation, sowing, harvesting, or pesticide application. By integrating a 3D printer into the agricultural workflow, it becomes possible to produce components like gear wheels, sprinkler nozzles, hose connectors, bearing housings, seed planters, and protective covers on-site. This flexibility not only ensures the continuity of farm operations but also allows for customization based on specific equipment and local farming conditions [19-20]. A comprehensive analysis of the most commonly used and frequently broken parts in agricultural equipment were done. Interviews were conducted with farmers, agricultural technicians, and machinery dealers to identify components that are critical, prone to damage, and challenging to procure. The feedback revealed a high demand for plastic and lightweight metallic parts, often used in irrigation systems, seeders, threshers, and protective casings. The design criteria for the printer included robustness, affordability, ease of maintenance, material flexibility, and power efficiency. The printer was constructed using an open-frame Cartesian configuration, which is known for its simplicity and adaptability (Fig 1).

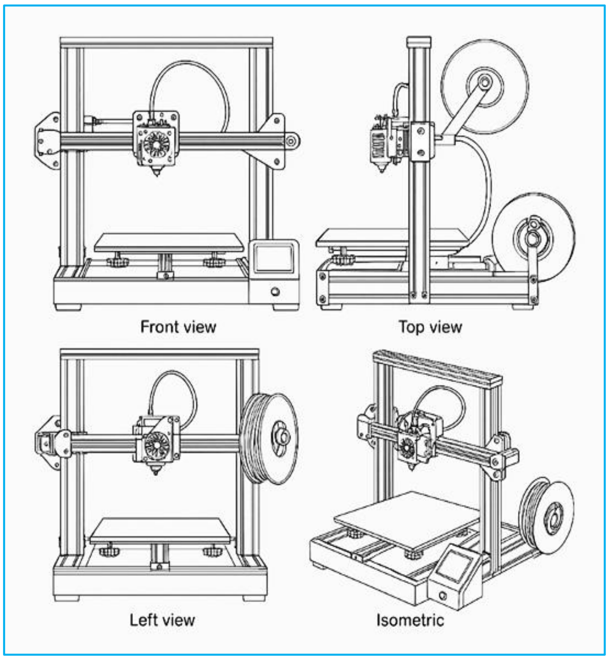


Fig 1 3D printer (Assembled view)

The key components included aluminium extrusions for the frame, NEMA 17 stepper motors for motion control, a heated bed to accommodate different filament types, and a custom-designed direct drive extruder capable of handling reinforced and recycled filaments [21-22]. Material selection played a vital role in this project. While polylactic acid (PLA) is widely used in desktop 3D printing due to its ease of use and environmental friendliness, it lacks the mechanical strength and heat resistance required for certain agricultural applications. Therefore, the research extended to other thermoplastics such as polyethylene terephthalate glycol (PETG), acrylonitrile butadiene styrene (ABS), and nylon. These materials were selected for their durability, UV resistance, and mechanical properties. To enhance sustainability, the team also experimented with filaments made from recycled agricultural plastics, such as used drip irrigation lines and greenhouse films [23].

a. *Identification of spare parts*

A preliminary survey was conducted among local farmers, machinery service centers, and agricultural equipment manufacturers to identify commonly used and frequently damaged agricultural spare parts. The criteria for selection included: (i) High demand and frequent replacement frequency, (ii) Feasibility of replication through 3D printing, and (iii) Moderate complexity and manageable size (within the printer's build volume) (Fig 2).

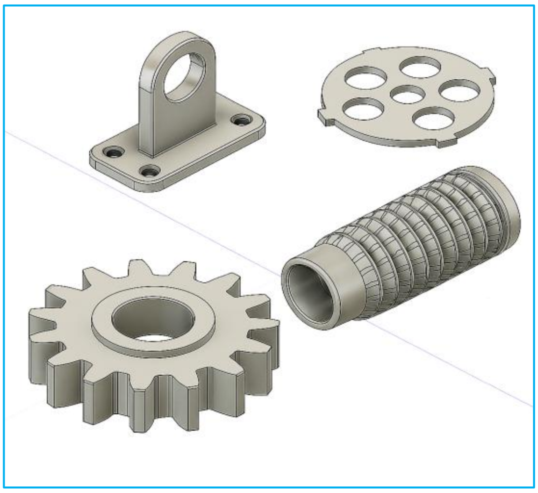


Fig 2 3D parts of agricultural machinery components

b. *Design and 3D modeling*

The selected parts were modeled using Computer-Aided Design (CAD) software (e.g., SolidWorks, Fusion 360, or FreeCAD). Where original parts were available, reverse engineering was carried out using digital calipers and 3D scanning where necessary. The models were optimized for 3D printing by considering: (i) Wall thickness and tolerance for durability, (ii) Simplification of complex geometries to reduce print time and failure and (iii) Incorporation of reinforcement features (e.g., fillets, ribs) for stress-prone zones. The final designs were exported in STL (Standard Tessellation Language) format (Fig 3-4).

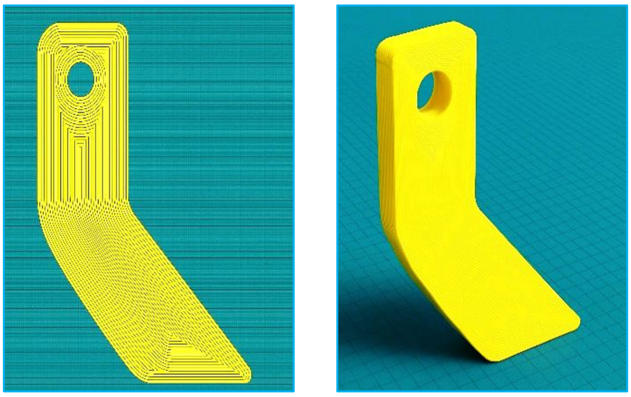


Fig 3 STL file printing axis pattern (Tyne)

c. *Material selection*

Material selection was based on the operational environment of the parts, including: (i) PLA (Polylactic Acid) for low-stress components with minimal exposure to heat or moisture. (ii) PETG (Polyethylene Terephthalate Glycol) for parts requiring flexibility, UV resistance, and moderate mechanical strength. (iii) ABS (Acrylonitrile Butadiene Styrene) and Nylon for high-stress and heat-exposed parts. Mechanical property requirements such as tensile strength, wear resistance, and thermal tolerance were matched with appropriate filament types.

Fig 4 STL file printing axis pattern (Fruit Picker Basket)

d. *3D printing process*

(i) *Mesh quality*

The STL mesh quality has a direct effect on the print quality. Gaps, self- intersections, and non-manifold geometry can lead to printing defects. Mesh repair programs tend to employ algorithms for correcting these faults, based on topological and geometric analysis.

(ii) *Slicing algorithm*

3D printing software cuts the 3D object into thin layers, establishing the route that the printer's extruder will travel. The theory consists of intricate algorithms that compute the intersection of the model with a sequence of parallel planes. These algorithms maximize print speed, quality, and material use:

(ii) *G code generation*

3D printing software converts the sliced model into G-code, which is a language used to command the printer's movement, extrusion, and temperature. The theory entails comprehending the syntax and semantics of G-code generation commands within the slicing.

(iv) *Infill and delivery structures*

3D printing software makes it possible to specify infill patterns (internal support structures) and to create external support structures to avoid overhang collapse. The infill pattern theory includes optimizing for weight, strength, and printing time. Printing was carried out using a Fused Deposition Modeling (FDM) 3D printer (Fig 5). Parameters were optimized for each material and part type: (i) Layer Height: 0.1 – 0.3 mm (based on resolution requirements), (ii) Infill Density: 50–100% (based on load-bearing needs), (iii) Print Speed: 40–60 mm/s, (iv) Nozzle Temperature: Adjusted per material (200–

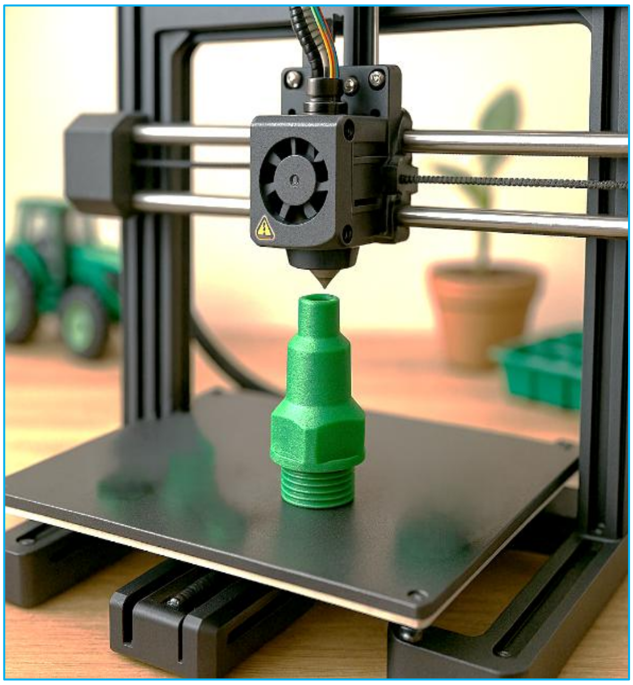
250°C) and (v) Bed Temperature: 60–100°C based on material for optimal adhesion. Each part was printed with adequate support structures and brim/raft to prevent warping.

e. *Post-processing and quality control*

Post-processing involved removal of support structures, sanding, and, where necessary, annealing for thermal resistance. Dimensional accuracy and mechanical integrity were assessed using: (i) Vernier calipers for dimensional verification (±0.2 mm tolerance), (ii) Manual fit testing with the original machinery, (iii) Mechanical testing (e.g., compression, torsion) for selected high-stress components.

f. *Field testing and evaluation*

The printed parts were installed in relevant agricultural machinery (e.g., irrigation systems, seed drills) and subjected to field testing under real operational conditions for a period of 30–45 days. Parameters evaluated included: (i) Functional compatibility and fit, (ii) Wear and deformation patterns, and (iii) Farmer/user feedback on usability and durability.



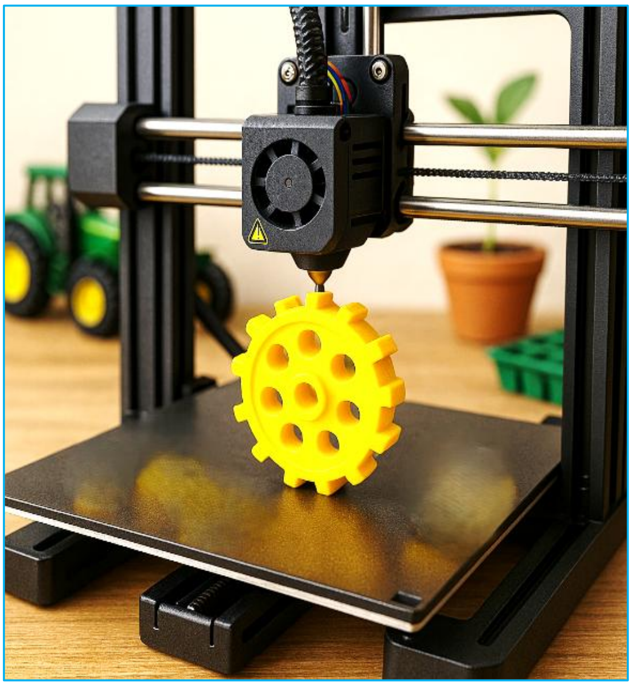


Fig 5 Printing of sparyer nozzle and seed metering disc

The plastic waste was shredded, extruded into filament, and used in prototype manufacturing. The results were promising, with recycled PETG showing performance comparable to virgin filament, thereby promoting a circular economy model within the agricultural domain. The software integration for the printer involved firmware customization and slicing optimization. Marlin firmware was selected for its open-source support and wide community adoption. It was fine-tuned to accommodate custom extruder temperatures, bed levelling routines, and filament retraction settings based on the materials in use. Cura and Prusa Slicer were utilized for slicing, with print profiles developed specifically for each material and target part. The slicing settings were optimized to balance speed, strength, and surface finish, taking into account the functional demands of the parts [21-23]. For instance, components exposed to high mechanical loads, such as gear wheels or clamps, were printed with higher infill densities and thicker walls. On the other hand, parts used for enclosure or guiding channels were printed with standard settings to reduce material usage and printing time. The prototyping phase involved the fabrication of over 30 different parts commonly used in farming operations. These parts were tested under real field conditions to evaluate their mechanical integrity, weather resistance, and overall usability. The testing methodology included static load testing, dynamic fatigue testing, and thermal cycling to simulate environmental exposure. Farmers from partner villages participated in the evaluation process, providing feedback on installation ease, fitment accuracy, and functional performance. Most of the 3D printed parts met or exceeded the performance benchmarks of their conventional counterparts [24-25]. For example, a 3D printed hose connector made from PETG was able to withstand water pressure up to 4 bar without leakage or failure. Similarly, a seed drill component printed in reinforced nylon demonstrated excellent wear resistance after prolonged usage in abrasive soil conditions. Compared to market prices of equivalent components, which often include transportation and dealer margins, the 3D printed parts were up to 70% cheaper. Additionally, the turnaround time was reduced from several days or weeks to just a few hours [26]. This reduction in cost and lead time has a direct impact on the operational continuity and profitability of small-scale farming operations. Moreover, the ability to print parts on-site fosters a culture of innovation and self-reliance among farmers and rural technicians, encouraging them to design and adapt tools based on their unique needs. To ensure the long-term sustainability and scalability of the initiative, the research also focused on training and capacity building. Workshops and training sessions were organized for farmers, agricultural students, and local entrepreneurs on the basics of 3D printing, design using CAD tools, maintenance, and troubleshooting of the printer. A user manual was developed in local languages with visual guides for each step. Additionally, a digital repository of printable part designs was created, which can be accessed through mobile phones or community internet centers. This repository includes STL files, material recommendations, and print settings, allowing users to select and print parts without extensive technical knowledge. And also, the efforts are underway to integrate AI-based part recommendation systems to guide users in selecting the right design based on equipment type and issue description.

The environmental impact of 3D printing in agriculture were also analysed. Traditional part procurement involves packaging, transportation, and warehousing, all of which contribute to carbon emissions. In contrast, localized 3D printing reduces transportation needs and supports the reuse of plastic waste. Each kilogram of recycled filament used in place of virgin plastic saves approximately 6 kg of CO^2 emissions. By integrating solar panels with battery storage to power the 3D printer, the entire fabrication process can be made energy independent and eco-friendly, further enhancing its appeal in rural and off-grid locations. Pilot installations in off-grid villages demonstrated successful 24/7 operation using solar energy, validating the feasibility of green fabrication hubs in agriculture [27-28]. The next phase of the project involves miniaturization and ruggedization of the 3D printer design to make it even more field-portable. The integration of Internet of Things (IoT) modules for remote monitoring, predictive maintenance, and automated inventory tracking of parts is also a future scope of research in this domain. By connecting the printer to a cloud platform, it becomes possible to remotely update firmware, push new design files, and receive feedback from users. This digital integration opens up possibilities for cooperative farming communities to share resources, knowledge, and designs, creating a decentralized manufacturing network that is agile, resilient, and farmer-friendly. Furthermore, partnerships with agricultural equipment manufacturers are being pursued to obtain open-source designs of proprietary parts, fostering a more inclusive and collaborative approach to agricultural innovation.

CONCLUSION

The development and implementation of a 3D printing system tailored for the on-demand production of agricultural spare parts present a significant advancement in addressing the recurring challenges faced by the agricultural sector, particularly in rural and remote areas. This research successfully demonstrates the feasibility, practicality, and potential impact of integrating 3D printing technology into the agricultural ecosystem. The study outlines the complete lifecycle of the innovation—from conceptualization, design, and prototyping to material selection, testing, and field evaluation—highlighting the system's capability to offer sustainable, cost-effective, and scalable solutions for localized spare parts manufacturing. One of the core motivations behind this research was the frequent and often costly breakdown of agricultural machinery due to wear and tear, which results in substantial downtime and productivity loss for farmers. Traditional supply chains for spare parts, especially in rural areas, are fragmented, slow, and inefficient, leading to further operational delays. By deploying a localized 3D printing system, farmers can produce spare parts on-site with minimal delay, using either digital part files or reverse-engineered models. This autonomy reduces reliance on centralized manufacturing and external suppliers, thereby significantly cutting lead times and associated costs. The prototype 3D printer developed in this study was designed with a strong emphasis on usability, ruggedness, and adaptability. These features are critical in rural settings where technical expertise may be limited and where environmental conditions may challenge the reliability of advanced equipment. The system's compatibility with locally sourced or easily available materials ensures sustainability and cost-effectiveness while reducing environmental impact associated with transportation and packaging waste. Material selection played a crucial role in ensuring the performance and durability of the printed parts. Through careful testing and analysis, materials like PLA, PETG, ABS, and Nylon were evaluated for their mechanical strength, environmental resistance, and long-term viability under agricultural operating conditions. The successful field deployment of the printed parts and positive feedback from users underscore the practical viability of the proposed system. Moreover, this study contributes to the broader vision of decentralizing manufacturing and promoting self-reliant farming communities. By empowering local cooperatives and small-scale producers with the tools and knowledge to fabricate essential components independently, the system enhances operational resilience and encourages innovation at the grassroots level. The potential for digital sharing of spare part designs also opens new avenues for collaborative development and support networks among farming communities. The on-demand 3D printing of agricultural spare parts is not only technically feasible but also economically and environmentally advantageous. This research demonstrates that a well-designed, locally adaptable 3D printing system can significantly reduce machinery downtime, lower maintenance costs, and improve the overall efficiency of agricultural operations. The approach promotes sustainability, resilience, and self-sufficiency in farming, laying the groundwork for future innovations in digital agriculture and decentralized manufacturing.

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