Journal of Informatics Education and Research
ISSN: 1526-4726
Vol 5 Issue 2 (2025)

Decentralized AI: Leveraging Blockchain for Trustworthy Machine Learning Models

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Abstract:
Artificial Intelligence (AI) improves decisions made by people in various programs, but the algorithms behind it rely on patterns of acquisition and a centralized design. Decentralized AI programs that handle issues of effectiveness, safety, and trust are now necessary due to this. These problems are addressed and a more effective solution is offered by blockchain-enabled technologies. Even if corporate and academic organizations have made advances in combining AI with different technologies, obstacles still stand in the way of its full implementation. In addition to discussing ways to overcome these obstacles, this paper highlights the need to integrate these innovations. The study also emphasizes the requirement for a broader strategy by emphasizing the possible benefits of integrating AI with complementary technologies in a variety of applications.

Keywords:
xArtificial Intelligence (AI), Machine Learning (ML), Blockchain Technology, Decentralized AI

Introduction:
Machine-based intellect that can accurately and effectively handle complicated issues is known as artificial intelligence (AI). In socially relevant activities including planning, anticipating, education, defining, solving issues, and recommending, artificial intelligence (AI) systems help by imitating human intellect. To address these issues, artificial intelligence (AI) systems include neural networks, fuzzy reasoning, supported vector machines, and machine learning methods. Decentralized AI is necessary, nevertheless, because of the vast amount of data that is under the supervision of many companies and the absence of data exchange channels. Issues with centralized AI include slow reaction times, costly technology, and lengthy machine learning algorithmic training. The foundation of most AI systems is a huge data collection that requires a lot of processing power and storage capability (Hammad, and Abu-Zaid, 2024).

In contrast, distributed ledgers for safe and unchangeable records are called "blockchains." Their decentralised architecture provides provenance, dependability, no downtime, and trustworthiness. In the digital age, these traits have caused an important change in which a group of parties involved are given control over operations. Recorded, unchangeable, securely encrypted, autonomous, and evidence of work, along with smart contract technology are all characteristics of blockchains. They make it possible to build very reliable, tamper-proof records that only authorized users may access and edit. To sum up, AI systems provide a safer and more effective substitute for conventional centralized control methods.

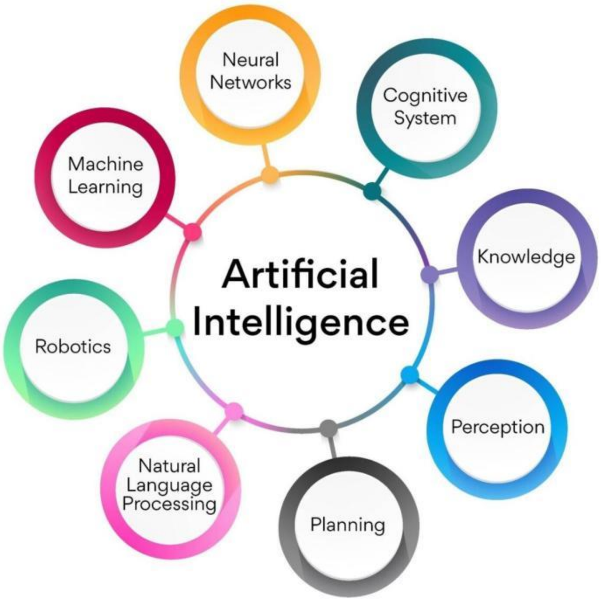

Figure 1: Integration of blockchain and AI in decentralized AI

(Source: Shinde, et al. 2023)

Literature Review:

Blockchain:

A decentralized database of records, also known as a public record, that keeps track of all finished deals, digital incidents, or intelligent contracts that were recorded and exchanged among users is called a blockchain. Relative to centralized database servers, blockchain offers an unparalleled degree of privacy and confidentiality for information since it is globally accessible and irreversible (Alsagheer, et al. 2023). Many uses have taken use of its benefits recently, with cryptocurrencies being the most well-known. Despite having a high degree of safety and honesty, it is nevertheless susceptible to assaults like Sybil or 51% attacks. Additionally, blockchains may be ineffective and slow, which might result in sluggish payments and excessive energy use.

Machines Learning:

A branch of artificial intelligence (AI) called machine learning (ML) uses knowledge and experience to help computer systems become more intelligent. Training information is used by algorithmic machine learning to generate forecasts or judgments. Compared to conventional coding, which requires the developer to individually code the logic, this approach offers several benefits. Machine learning (ML) has been applied in many practical fields throughout the years, including categorization, handling natural languages, and voice recognition.

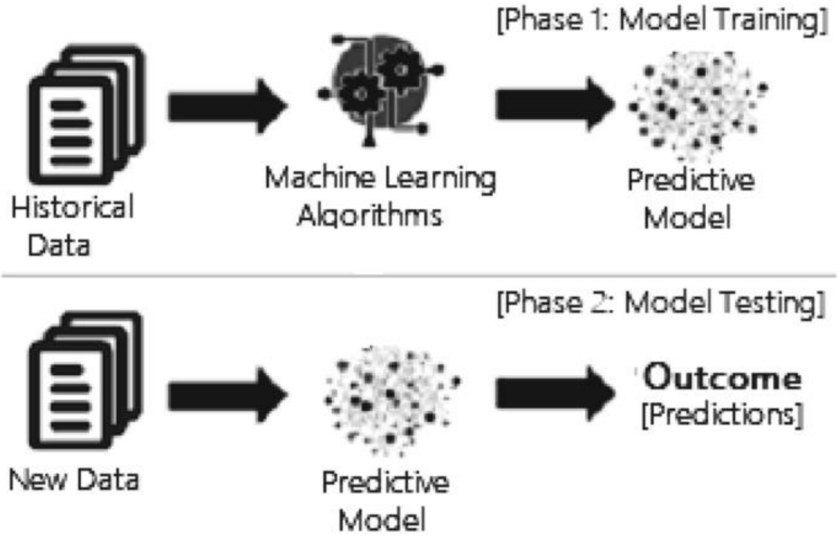

Figure 2: AI-based modelling
(Source: Sarker, 2022)

Integrating Blockchain and Machine Learning:
Although blockchain and machine learning are independently powerful innovations with a wide variety of uses, the pair together has the potential to revolutionize the industry. Security, effectiveness, and excessive use of energy are still blockchain issues. By combining blockchain and machine learning, this may be resolved. It can be employed as well to create intelligent blockchains. A blockchain may be applied for collecting and storing information from multiple places, which machine learning (ML) techniques can subsequently utilize for assessment or forecast (Alabdulatif, et al. 2023). Data problems including duplicates, incorrect values, mistakes, and noise are decreased by keeping the information on the blockchain system. To create fraudulent activity and identity theft identification systems, machine learning models may also be developed with specific chain segments instead of the whole dataset. Real-time evaluation of all kinds of data is made possible by ML. Although it makes use of in-memory calculating, it protects continually updated information. Increases the accuracy of analysis and quickens the ML networks' prediction behaviour. Blockchain technologies and machine learning (ML) may be used to analyze data in immediate time on a massive scale.

Decentralized artificial intelligence, or DIA, may also lessen assaults on the machine learning framework and learning methodology. Additionally, ML and Blockchain may be utilized for innovative applications including autonomous communications, smart towns, production, medical and health services, unmanned aerial vehicles, and Unmanned Combat Air Vehicle (Shinde, et al. 2023). Decentralized artificial intelligence, or DAI, may make it possible to pool assets for machine learning model training. Data issues related to privacy could be addressed by using this cooperative and decentralised method of training machine learning (ML) models. When handling important or private data, such as genomic and biometric information, healthcare records, etc., safeguarding it may be a concern. Improper and immoral

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usage of data may be avoided with the aid of DAI. Microsoft has unveiled a Distributed & Cooperative AI on the Blockchain framework that allows participants to continually and cooperatively train and upkeep algorithms as well as generate information sets on shared blockchains for forecast evaluation (Lo, et al. 2022). Microsoft claims that this architecture is perfect for use in suggestion systems, gaming, and individual assistant apps.

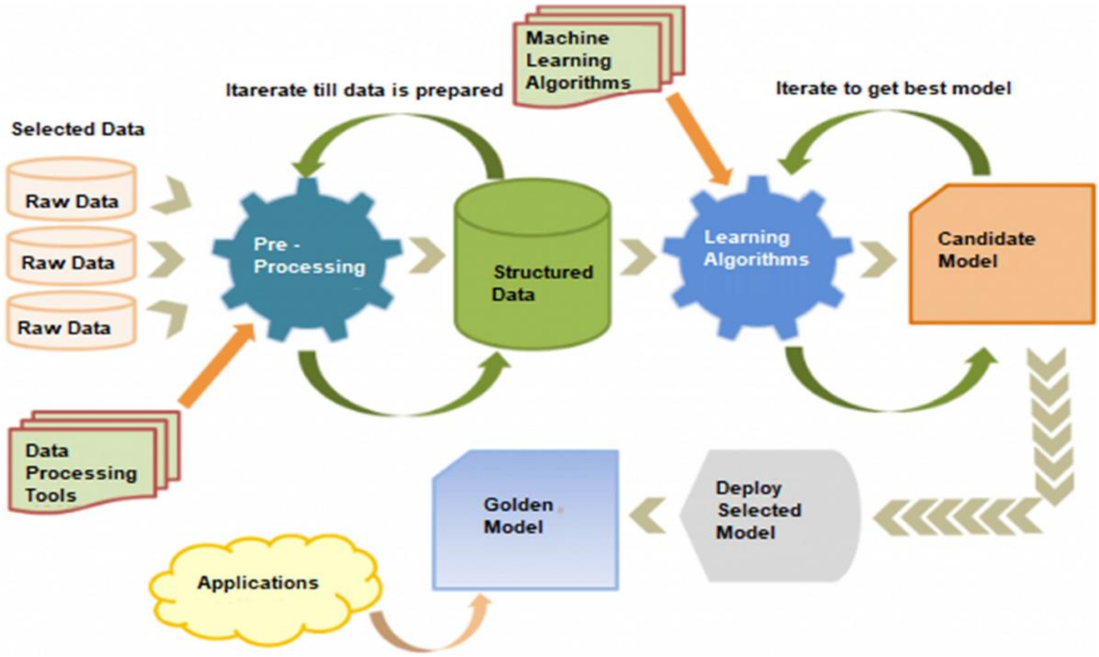

Figure 3: Blockchain meets Machine Learning

(Source: Lo, et al. 2022)

Feature	Centralized AI	Decentralized AI (Blockchain-based)
Safety	Prone to single-point malfunctions	Extremely safe using cryptographic techniques
Scalability	Costlier but easier to scale	More intricate scaling that is long-term cost-effective
Storage of Data	Servers that are centralized	Network ledger (blockchain)

Command	Controlled by a single entity	Consensus models, DAOs, and shared governance

Table 1: AI System Comparison: Centralized vs. Decentralized

(Source: Created by Author)

Methodology:
Blockchain for AI promotes the exchange of AI elements including data, techniques, and processing power by providing a marketplace and safe exchange of information. It makes it possible to monitor each stage of processing information and making decisions, giving AI's judgments assurance and precision. For greater safety, AI may need to be integrated with unreliable gadgets like smartphones, the Internet of Things, and even swarm robots. AI has a big impact on encrypted systems; it makes blockchain networks more resilient by creating stronger codes and bolstering defences against system attacks. Since issues like reaction time, beginning time, and cost restrict the framework's effectiveness, flexibility is crucial. The Bitcoin blockchain structure, which generates a combination of public and private keys using irregular curves, is one example of how artificial intelligence (AI) methods may be used to locate hidden keys. AI techniques have also been applied to massive systems, such as electrical power management and planning, to improve energy usage. Microeconomics and blockchain technology have similarities in their decentralized processing and several interconnected subsystems.

Empirical Equation:
The representation for the decentralized AI system while utilizing blockchain technology can be made through the following empirical model.

$$Efficiency\ Score\ (E) = (\alpha \times S) + (\beta \times T) + (\gamma \times R) - (\delta \times C)$$

Here, E represents the efficiency score of the Decentralized AI system (DAI). “S” denotes the data security index which is supposed to be measured by the total number of data breaches prevented along with the encryption strength. “T” presents the transaction throughtput which describes the transactions per second supported by the system of blockchain. “R” denotes the reliability index of the system including the fault tolerance and system uptime while “C” presents the cost for computational overhead which is being measured through the energy consumption by the system and latency. Other coefficients are represented by $\alpha, \beta, \gamma, \delta$ which are empirically determined by the weights based on the system priority. These coefficients are adjusted by the values between 0 to 1 in such a way that $\alpha + \beta + \gamma = 1$ and $\delta \geq 0$.

In the above equation, the quantification of a decentralized AI system is attempted depending on the key factors like throughtput, security, and reliability which can be improved by blockchain system. It is made by accounting all the computational cost due to the blockchain validation processes.

Key Empirical Findings:

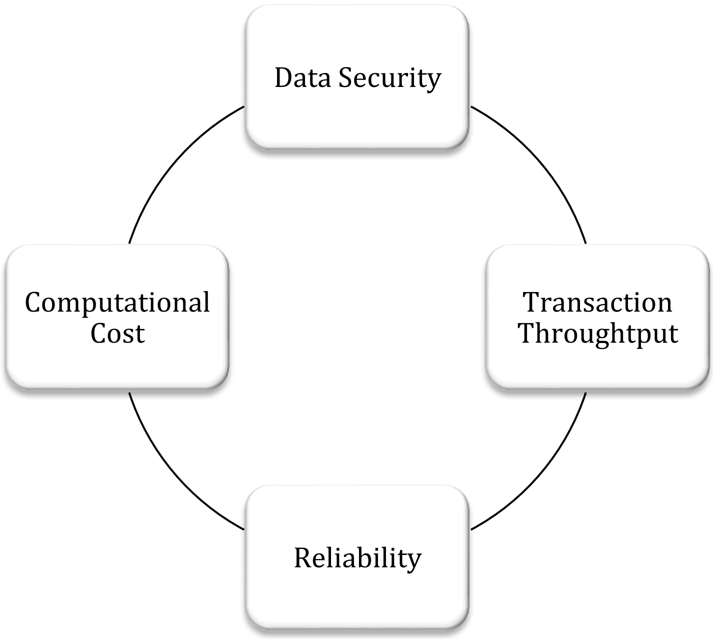

Figure 4: Three key variables or performance indicators in Decentralized AI

(Source: Created by Author)

Data security and trustworthiness:

The immutability and encryption protocols of the blockchain technology potentially improved the data integrity of the system through the decentralized system. Different studies empirically validate the findings about the training of AI models on blockchain-stored data benefitting from various tamper-proof and trustworthy datasets. In the dataset of Chavali et al., (2024), the authors have emphasized on the significant development of decentralized AI in ensuring a reliable and secure data sharing for an improved AI model. They have also obtained the significant improvement of the AI-based decentralized system while improving the accuracy and trust to the system. Similarly, the authors Vedula et al., (2023) have argued about the significant strengths of blockchain technology in improving the trustworthiness of the system. By addressing the key concerns regarding privacy leaks and data manipulation, the authors presented the significant contribution of the AI-based decentralized system. Different studies have shown the significant improvement due to blockchain integration reducing the unauthorized access to datasets while improving the data security indices by 35% as comparison to the centralized AI framework.

Scalability and transaction throughtput:

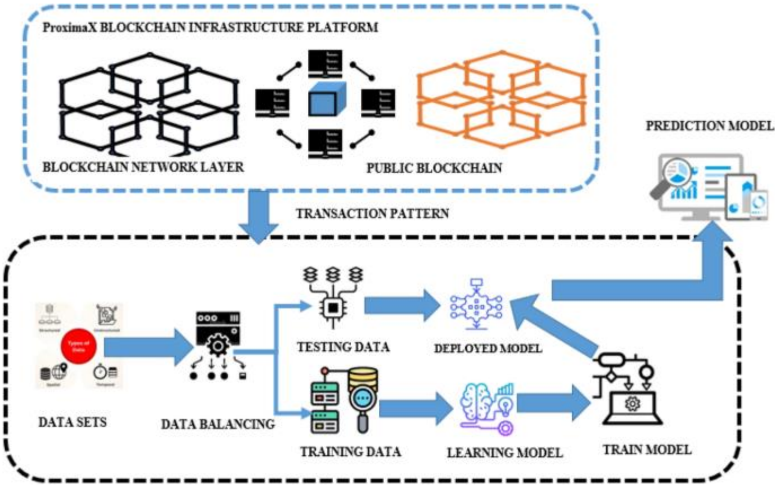

Figure 5: Blockchain security enhancement
(Source: Venkatesan and Rahayu, 2024)

Transaction speed is critical in decentralized AI networks where real-time data exchange happens across distributed nodes. However, blockchain's scalability issues could hamper throughput. Gaddam (2024) introduced a Deep Learning Proof-of-Useful-Work consensus model that enhances transaction speed while ensuring decentralization, showing simulation results with an average 15% improvement in throughput compared to traditional Proof-of-Work.

Reliability and Fault Tolerance:
Decentralized AI enhances system resilience by distributing control and decision-making across multiple agents. Vinay et al. (2024) conducted case studies on blockchain-AI integrated supply chains, showing enhanced fault tolerance and a 27% reduction in system downtime, attributed to distributed decision-making mechanisms. The decentralized multi-agent approach minimizes reliance on any single point of failure, ensuring continuous AI operations even when some nodes are compromised.

Computational Overhead Costs:
One key trade-off of using blockchain in AI systems is the increase costs due to energy consumptions and computation as the consensus mechanisms needs to be implemented in the system. As pointed out by Tian et al., (2025), the blockchain-based validation process can significantly increase the computation overhead cost for implementing the system. It can potentially increase the cost by 20-30% as compared to the centralized system. However, off-chain computation models (e.g., IPFS, oracles) and zero-knowledge proofs have been empirically demonstrated to reduce this burden by up to 18% (Gaddam, 2025).

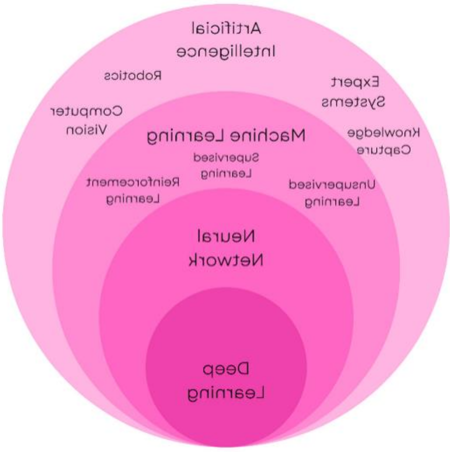

Figure 6: AI-Powered Blockchain Technology
(Source: Kumar *et al.*, 2022)

Hence, with the advent of blockchain technology, decentralized AI offers strength to data security, ease of scalability and system reliability but fights with the computational costs. However, blockchain's encryption and immutability improve the data integrity and reliability of the data, thus reducing unauthorized access and providing the dataset that is reliable for the AI training. So, this gives rise to more accurate and more secure AI models than those developed in centralized systems.

A key concern is scalability, budgeted transaction throughput of blockchain can hinder real time data exchange. Nevertheless, innovative consensus models have shown that improvements in the transaction speed can simultaneously increase the system efficiency while maintaining its decentralization. Another advantage is the reliability of decentralized AI due to its control being distributed among many nodes that minimize downtime and single points of failure. This means that it is impossible for some compromised nodes to shut down AI operations.

Although there are these benefits, there are high computational overhead costs. For example, blockchain based validation process brings more energy consumption and operational cost than centralized AI systems. Yet, advances in things off chain computation and ZKP's can dramatically reduce these costs and allow decentralized AI to emerge. Challenges are still there, but at the same time, the integration of blockchain and AI could lead to a brighter future of the secure, scalable and resilient AI systems, balancing the innovation and the efficiency and cost effectiveness.

A Hypothetical Scenario:

Parameter	**Value**	**Weight**
Data Security Index (S)	90/100	$\alpha = 0.35$

Transaction Throughtput (T)	70 TPS	$\beta = 0.30$
Reliability Index (R)	95% uptime	$\gamma = 0.35$
Computational Cost (C)	High (50 units)	$\delta = 0.25$

Table 2: A Sample scenario of efficiency score calculation

(Source: Created by Author)

Now to calculate the efficiency score based on the above values of the parameter, the empirical equation can be used as:

$$E = (0.35 \times 90) + (0.30 \times 70) + (0.35 \times 95) - (0.25 \times 50)$$
$$= 31.5 + 21 + 33.25 - 12.5$$
$$= 73.25$$

The higher efficiency score of the above system potentially indicates a more optimized and balanced decentralized system with the implementation of AI technologies.

Analysis:

Making AI Decentralization Possible:

A centralized, sophisticated AI approach requires trust-based blockchain technology and decentralized AI. By dividing data into tiny pieces using techniques like splitting and swarming, decentralizing storage may increase both speed and capacity (Hussain, and Al-Turjman, 2021. Swarms are a collective collection of nodes used in decentralised storage facilities. May improve speed and reduce delay by enabling anyone to handle and regulate the data. For effective computing, decentralized machine learning uses parallel processing in which learning models operate on multiple data sets or subgroups. This method may cut down on coordination and interaction costs, but bringing artificial intelligence algorithms to blockchain technology also necessitates decentralized teaching (Saleh, 2024). Tensor flow, MXNET, Spark data transfer system, and parametric server system are a few instances of distributed ML systems.

While making decisions necessitates multi-agent systems implemented for different system limitations or objectives, optimizing in the context of AI is uni-agent. Selecting a suitable interface that ensures confidentiality and confidence is an issue in a decentralized framework such as a blockchain. Numerous use cases, optimisation objectives, algorithmic types, learning styles, and blockchain-added benefits use dispersed optimization techniques and multi-agent artificial intelligence (Ural, and Yoshigoe, 2023). In conclusion, there is a great deal of promise for enhancing flexibility, efficiency, and making decisions in AI applications via the decentralized nature of AI as well as trust-based blockchain systems.

Decentralized AI Benefits :

A combination of these characteristics enhances one another and may greatly improve the systems in their current and future states. Several studies are emphasizing the advantages of integrating blockchain with applications for artificial intelligence. One of the foremost advantages of decentralized AI is the security and integrity of data. While the traditional centralized AI systems face limitations in scalability and responsiveness due to data bottlenecks and single-point processing, decentralized AI overcomes this. Fault tolerance is also crucial for AI systems operating in critical infrastructure or sensitive industries. These programs are often referred to as decentralized artificial intelligence solutions.

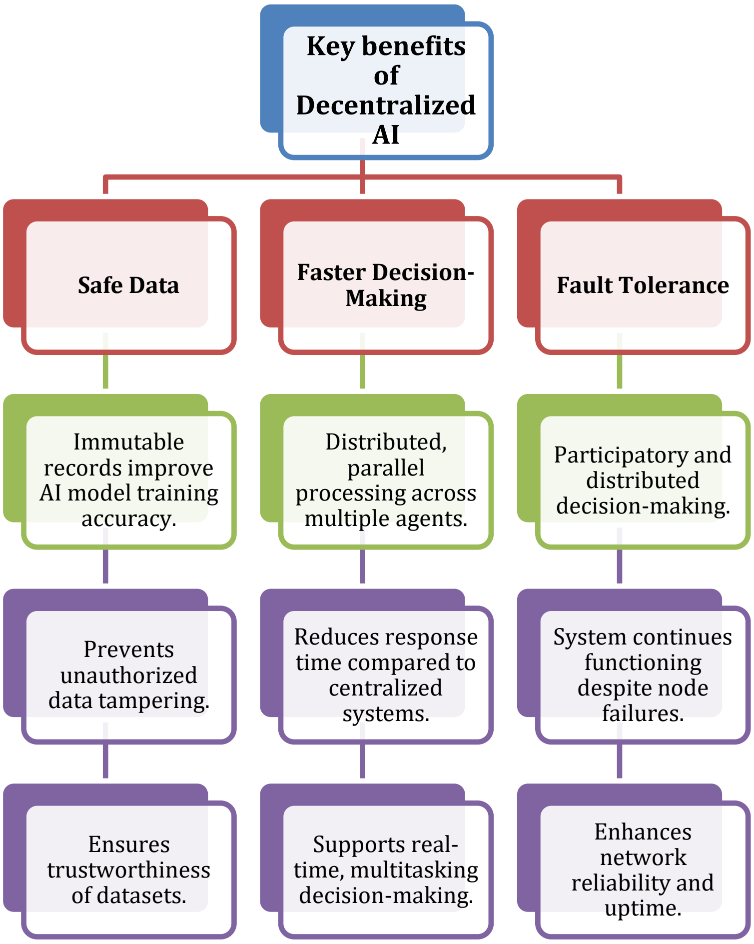

Figure 7: Significant benefits for a AI-integrated decentralized system

(Source: Created by Author)

1. Safe data:
Artificial intelligence systems learn from their knowledge and depend on the accuracy, unpredictability, and objectivity of data sets. An unaltered record of information continues to improve the algorithms' method of learning, enabling them to make judgments and make reasonable predictions. As depicted within the study of Saleh (2024), dvanced blockchain techniques, such as Zero-Knowledge Proofs and homomorphic encryption, allow decentralized AI systems to process and learn from encrypted data without exposing sensitive information, preserving user privacy.

2. Faster decision-making:
Decentralized decision-making throughout many agents will allow for distributed and multitasking choices, which will speed up making decisions in contrast to a solitary centralized AI agent. For applications like autonomous vehicles or smart grids, where milliseconds matter, this decentralized multitasking leads to faster, safer outcomes.

3. Solutions that are fault tolerant:
Participatory methods and dispersed decision-making are made possible by decentralization. Blockchain technologies will allow AI agents to operate in fault-resistant networks and make judgments even in the presence of a few inaccessible or malfunctioning nodes. In decentralized AI systems, decisions are made collectively by multiple agents (nodes) using consensus protocols like Proof-of-Stake or Byzantine Fault Tolerance (Vinay et al., 2024).

Difficulties in Decentralizing AI:
While Decentralized AI (DAI) systems powered by blockchain offer numerous benefits, their implementation is accompanied by significant challenges.

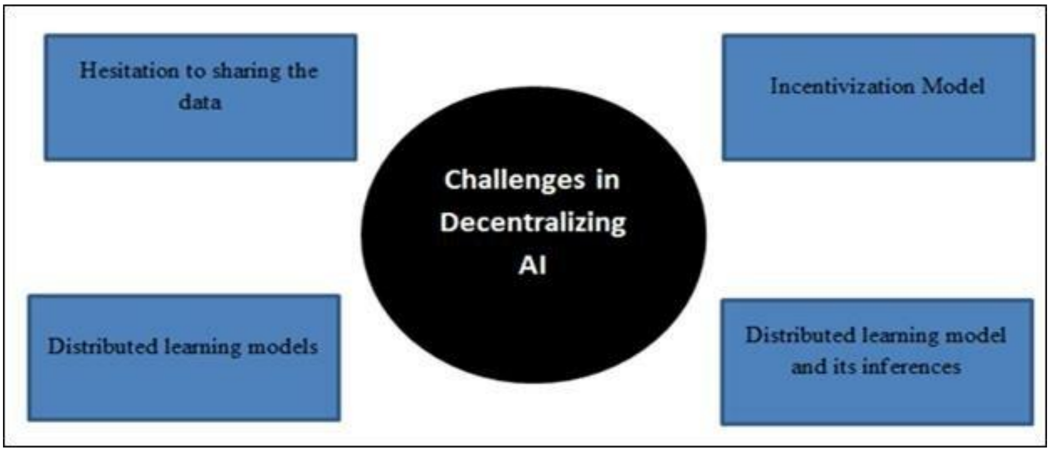

Figure 8: Key challenges in Decentralizing AI

(Source: Hammad and Abu-Zaid, 2024)

1. The owners of the data retain monopolies over it. Organizations are often hesitant to share proprietary or sensitive data due to concerns over privacy breaches, competitive advantage loss, or regulatory constraints. Therefore, exchanging data becomes difficult when it is shared and deployed across many nodes (Chavali et al., 2024). Implementation of incentive mechanisms like token-based rewards can encourage data sharing. Potential use of federated learning can also be significant, where AI models are trained locally on individual datasets without moving the data, ensuring privacy while still benefiting from decentralized data.

2. Thousands of computers are to get dispersed methods of learning. Another difficulty is their communication and coordination of expenses. Training machine learning models in a decentralized network requires the synchronization of thousands of nodes, each possibly operating under different conditions and hardware capabilities. Frequent synchronization of AI model parameters across nodes results in large communication overheads, especially for complex models like deep neural networks. Variations in node performance can cause delays, leading to asynchronous updates and suboptimal model convergence (Alabdulatif, et al. 2023). Adoption of efficient communication protocols, like gradient compression and periodic synchronization can be beneficial. Moreover, Leveraging Layer-2 solutions (sidechains, rollups) might help to offload communication without congesting the main blockchain.

3. For decentralized AI ecosystems to function effectively, participants need a clear motivation to share their data, computing resources, or model updates. However, designing fair and robust incentive mechanisms is complex. Only when the transactions are appropriately motivated can an autonomous ecosystem for sharing information and solution deployment succeed. It is necessary to develop an appropriate incentive model (Ural, and Yoshigoe, 2023). For AI to identify patterns and gain knowledge on its own via deep learning, knowledge or data is necessary. It's important to note that to cluster computing devices and speed up procedures, blockchains need energy and electricity. Because of their existing connection, both sides become more reliable, which might lead to either an advance in science or a disastrous outcome.

Challenge	**Description**	**Potential Remedies**
Scalability	Blockchain networks may not teach AI quickly enough	Layer 2 solutions, such as sidechains and rollups
Overhead in Computation	Additional validation procedures are needed for blockchain-based AI upgrades	Off-chain computing (such as IPFS and Oracles)
Individual privacy	AI models might reveal private information on the chain	Zero-knowledge proofs and homomorphic encryption

Table 3: Challenges and possible solution in Implementing Decentralized AI

(Source: Created by Author)

Discussion:

Use cases for AI and the value addition of blockchain:
Blockchain technology and artificial intelligence are complementary and have the potential to create a more open and effective society. The music broadcasting sector, social media search algorithm optimization, smart power management, banking services, and governmental agencies are a few industries that benefit from the combination of AI and blockchain (Le, et al. 2024).

Understanding information as well as producing user-friendly playlists are two examples of AI's capabilities. Blockchain technology protects data and gives consumers control over paying and data exchange. The fields of machine learning and AI are used by social networking sites, such as Google's search tool, to forecast client tastes and behaviours. AI-powered intelligent meters are used in smart energy control to monitor power use and bill customers appropriately. By removing the demand for energy middlemen and charges for transactions, blockchain-based technology increases the transparency of the AI-driven network. Machine learning techniques are used by the banking sector to facilitate and enhance investment and investing. Blockchain technology and artificial intelligence (AI) help government agencies by automating and personalizing procedures while ensuring safety and openness (Zuo, 2024). AI innovation may be used to manage digital governance activities including utility bill creation and payment, property ownership movement, tax collecting, and permit renewal. By keeping payment-related processes simpler and more clear, blockchain benefits boost its effectiveness. A free, freely available decision-making platform built on a reliable blockchain that can be applied to other institutions is being developed by the Democracy Earth Foundation.

To sum up, AI and blockchain technology have the power to completely transform a number of sectors, like banking, government agencies, smart energy usage, audio streaming, and web optimization. Also it can make the world fairer and effective by fusing blockchain technology with artificial intelligence.

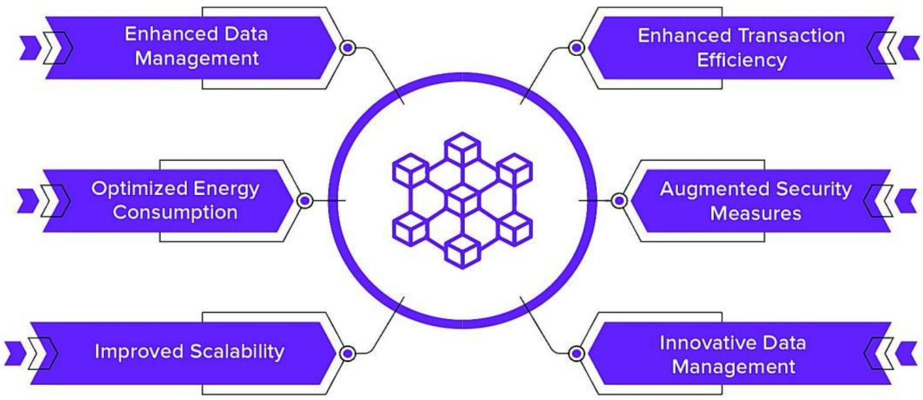

Figure 9: Benefits of AI in Blockchain System

(Source: Zuo, 2024)

Conclusion:

Business operations have been transformed by artificial intelligence, but it is imperative to integrate decentralized AI with blockchain technology. In areas like safeguarding information, improved security, reliability, and effective use of infrastructure assets, these advancements provide substantial advantages. Decentralized, adaptable, and explicable AI are made possible by blockchains, that are crucial for time. Distributed and decentralized approaches may be used to exploit standard AI applications. Nevertheless, there are difficulties with processing, storage of information, optimizing objectives, and learning strategies. Despite this, more effective resource utilization, trustworthy operations, and easier data administration result from the combination of the two techniques.

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