Journal of Harbin Engineering University Vol 47 No. 3
ISSN: 1006-7043 March 2026

A Blockchain–AIoT Framework for Secure and Sustainable Pharmaceutical Supply Chains

[1]Ramprashath R, [2]Selvanandhini B

[1]PG and Research Department of Computer Science,

Pollachi College of Arts and Science, Pollachi.

[2]PG and Research Department of Computer Science,

Pollachi College of Arts and Science, Pollachi.

Abstract - Vaccine spoilage from temperature changes and counterfeit medications, which cost more than $200 billion a year, are two of the biggest problems facing the global pharmaceutical supply chain. Inadequate tracking systems put patients at risk, increase medical waste, and make regulatory compliance more difficult. In order to facilitate end-to-end traceability, real-time cold-chain monitoring, and sustainable supply chain management, this study suggests a single framework that combines blockchain and AIoT technologies. The system uses a relay chain-parachainblockchain architecture, Practical Byzantine Fault Tolerance (PBFT) consensus to lower energy consumption, Cryptographic Hash Summaries (CHS) for immutable batch identification, and AIoTsensors for environmental monitoring. Batch registration, waste tracking, recalls, and cold-chain surveillance are all supported by new algorithms. Compared to Ethereum-based systems, the framework reduces cold-chain breach detection time by 40%, drug waste by 18%, and energy consumption by 30%. Transaction fees are lowered by 60–99%. It automates compliance and uses token rewards to promote environmentally friendly behavior. This strategy improves medication safety, assures regulatory compliance, and fosters environmental sustainability. Future accessibility and dependability will be improved by expanding generic drug markets in developing nations and utilizing machine learning in predictive analytics.

KEYWORDS - Blockchain, Green Supply Chain Management (GSCM), Chain Hybrid Systems, Artificial Intelligence of Things (AIoT), Drug Supply Chain.

1. INTRODUCTION

The global pharmaceutical supply chain is a very important part of the economy and people's health. It is responsible for making sure that billions of people get their medicines, vaccines, and biologics on time and safely, no matter where they live or how much money they have [1]. This chain needs to be strong for the safety of patients, the effectiveness of treatments, and people's trust in healthcare systems in general [2]. As globalization spreads, this network gets more complicated and less stable. One continent sends raw materials, another turns them into things, and a third eats them. The pharmaceutical industry needs to do more to help the world reach its sustainability goals. It wastes a lot of energy and makes a lot of medical waste, especially when it comes to cold-chain logistics and waste management [14]. Digital transformation and protecting the environment are coming together. This important system needs to be brought up to date for the 21st century right now. It will work better, last longer, and be safer. The modern pharmaceutical supply chain has to deal with two big and expensive problems: fake drugs and drugs that go bad when the temperature changes. The World Health Organization says that more than 10% of the drugs sold in low- and middle-income countries are either fake or not very good. These companies make more than $200 billion a year in illegal profits, which puts patients at risk of dying, not getting better, or becoming resistant to antibiotics [6], [7]. Still, it's hard to keep vaccines and biologics that need to be kept at a certain temperature in the cold chain. If vaccines aren't stored and moved properly, they can go bad and not work. This costs healthcare systems and manufacturers a lot of money [11], [12]. This spoilage makes the problem of dangerous medical waste even worse. If trash is not disposed of the right way, it could hurt the health of people and the environment [13]. The problems come from flaws in the system, such as tracking systems that only work in some places, a lack of end-to-end transparency, and data integrity issues that let mistakes and fraud go undetected. Serialization standards are a step in the right direction, but they don't always make it clear and unchangeable how a product gets from the factory to the patient [17]. Most of the time, current solutions only care about whether something is legal and how to find it. They don't think about how their actions in the supply chain hurt the environment. For instance, cold-chain logistics uses a lot of energy, and there are no benefits to getting rid of things in a way that is good for the environment. People who work in business have made it easier to get drugs by working hard. With GS1 serialization standards, each drug package gets its own digital ID. This makes it easier to find and stop fake drugs [16]. The blockchain has given us an open, decentralized ledger that can't be changed. MediLedger and other pilot projects have shown that blockchain technology can keep track of drugs and who owns them [19], [20]. While things are being moved, sensors can tell where they are, how hot or cold they are, and how humid it is [22]. The Internet of Things (IoT) can also help us keep an eye on the environment by letting us do it in real time. Some people have thought about using Blockchain and the Internet of Things together to protect sensor data and make sure it is correct. This would help keep track of the cold chain [23], [24]. But these new fixes aren't perfect. Many blockchain systems, like Ethereum, use Proof-of-Work (PoW) consensus. Using these systems costs a lot of money and energy. That means they won't last as long and won't be as good for big jobs. A lot of the suggested frameworks don't work well with older systems or rules that are different from the ones they were made for. This is why so many people have trouble using them. Need to learn more about IoT data streams because of the need to improve the cryptographic security [25]. People are making the biggest mistake right now by not using the ideas behind Green Supply Chain Management. People don't realize that blockchain can help people do things that are good for the environment, like running businesses that use less energy and recycling trash properly. This study presents a novel, integrated framework that amalgamates Blockchain with the AIoT to establish a secure, efficient, and sustainable pharmaceutical supply chain. The best new thing about our system is that it uses a synergistic architecture to fix the problems with older systems. The framework is built on a one-of-a-kind blockchain model that has both a relay chain and a parachain. In this model, a central relay chain is responsible for important tasks like making decisions and sending things back. Dedicated parachains, on the other hand, make sure that each store, maker, and distributor has its own area. This design protects data, makes sure there is only one source of truth, and lets different systems talk to each other. The AIoT part makes sensor nodes smarter, which is better than just IoT. Predictive analytics can be used for logistics with this, which can find problems before they happen. Elliptic Curve Cryptography (ECC) is used to protect AIoT data while it is being sent and CHS to make batch identities that can't be changed. One of the most important things is making the supply chain beneficial for the environment. The system was made to reward people with smart contracts and tokens for doing things that are beneficial for the environment, like recycling old drugs or using less energy. The PBFT consensus mechanism makes this system work. It doesn't use as much power as PoW protocols do. These parts work together to make a full system that protects the environment, keeps track of things, and keeps things safe all at the same time. The specific contributions of this research are fourfold: first, the development of a hybrid Blockchain–AIoT architecture that enables end-to-end, secure pharmaceutical traceability and real-time cold-chain monitoring, supported by a scalable relay chain-parachain structure; second, the design of AI-driven algorithms that facilitate predictive logistics, proactive cold-chain breach detection, and automated sustainability assessments, thereby advancing beyond simple monitoring toward intelligent, anticipatory management; third, the implementation of smart contracts to ensure transparent and automated drug verification, efficient batch recall execution, and the administration of a token-based reward system that promotes and validates environmentally responsible practices such as proper waste disposal; and fourth, a comprehensive evaluation of the framework's security and sustainability performance through case-based simulations using a HyperledgerSawtooth prototype and a dataset modeled on COVID-19 vaccine logistics, which demonstrate significant improvements in operational efficiency, cost reduction, and environmental outcomes. This is how the rest of the paper will be. Part 2 (Materials and Methods) explains how the framework works, the algorithms that were made for batch registration, monitoring, authentication, and waste tracking, as well as the security analysis and experimental setup. Section 3 (Results and Discussion) talked about what our simulations found. These numbers show how well things are going in terms of saving money, making less waste, latency, and throughput. Section 4 (Conclusion) sums up the work, like what it means and how to learn more about it.

2. MATERIALS AND METHODS

This system for managing the pharmaceutical supply chain brings together a lot of different parts to make sure that drug shipments are clear, safe, and last a long time. Every drug shipment has AIoT devices at its center. These devices send encrypted information about their status and the environment to the InterPlanetary File System (IPFS) all the time. This keeps the storage safe from being messed with and decentralized. These devices keep track of important things like temperature, which helps them find problems in the cold chain right away. A relay chain is the backbone of the system and keeps it going. It checks data that comes in from different parachains and does important things like keeping track of drug recalls and waste quotas. People in the supply chain can only use some parts of a blockchain called parachains. For instance, the manufacturer's parachain keeps track of the sustainability metadata and CHS for each batch of drugs. This information is used to uniquely identify and check batches. It also has important information about the world around us. The first step is to register the drugs. To make a CHS, manufacturers mix the batch ID with information about how long it will last. This creates a digital fingerprint for each batch that is safe and can't be changed. While the shipments are being delivered, the AIoT devices always keep an eye on them. They let the relay chain know right away if there are any problems with the cold chain. The relay chain then starts automatic recall procedures that use the CHS to find the affected batches and lower the risk. At the dispensing stage, pharmacies keep track of how drugs are actually used and wasted in their own parachains. This makes it easy to see how people use drugs. Then, the system checks this information to make sure it follows the rules for throwing things away and recycling them. Pharmacies are more likely to follow these rules if they get small rewards through the parachains. This makes them want to do things that are good for the planet. This architecture combines the best parts of decentralized storage, blockchain validation, and AIoT monitoring to create a strong and dependable ecosystem. It combines real-time environmental data with cryptographically secure batch information and blockchain ledgers for each stakeholder to make sure that data is correct make it easier to trace, and promote sustainability in the distribution of pharmaceuticals. It is also easier to work with data and let it grow when each role has its own parachain. People can do their jobs in the best place for them and still make the world a better place. The relay chain's main job is to keep track of quotas and set up recalls. This makes sure that mistakes are fixed quickly and in front of everyone, which saves money and keeps people healthy. This architecture combines the latest technologies into one safe, easy-to-use platform that makes it possible for pharmaceutical supply chains to go completely digital. This helps things run more smoothly, makes sure that rules are followed, and keeps people safe.

Algorithm 1: Drug Batch Registration (Manufacturer)

Input: Batch data B, Sustainability metadata M_{sust}, Chameleon hash function $Hash_{Cham}$

Output: Cryptographic Hash Summary CHS, IPFS CID $C_{ipfs.}$

1. Generate unique batch ID : $ID_b \leftarrow$ UUID(B)
2. Create composite record : $R \leftarrow$ Concat(ID_b, M_{sust})

3. Generate CHS : $CHS \leftarrow Hash_{Cham}(R,r)$
4. Store R on IPFS: $C_{ipfs} \leftarrow IPFS_{up}(R)$
5. Submit to Manufacturer Parachain: $SC_{manufacturer}$.registerBatch(CHS, C_{ipfs}, timestamp)
6. return CHS, C_{ipfs}

Algorithm 2: Cold-Chain Monitoring (AIoT Devices)

Input: Environmental Thresholds T_{env}, PBFT validator set V

Output: Alert Status A

1. while shipment active do
2. Sample sensors : env← {*temp, humidity, location*}
3. Compute hash: Henv ← SHA3-256(*env*)
4. If $env \not\subset T_{env}$ then
5. Generate alert : A ← CompileAlert(env, location, timestamp)
6. Submit to Relay Chain: SC_{relay}.submitAlert(A,H_{env},$signature_{device}$)
7. Trigger recall: SC_{relay}.initiateRecall(CHS)
8. end if
9. Store encrypted *env* on $IPFS_{up}(AES_{enc}(env,K_{sym}))$
10. end while

Algorithm 3: Drug Authentication (Pharmacy/Patient)

Input : Scanned QR Code CHS_{qr}, Relay Chain *RC*

Output: Verification result V_r

1. Query Relay Chain: record ← *RC*.getBatchRecord(CHS_{qr})
2. if record.status == "RECALLED" then
3. return "INVALID: Batch recalled"
4. end if
5. Retreive IPFS data: R ← $IPFS_{ret}$(record.C_{ipfs})
6. Verify provenance valid ← VerifySignature(record.manufacturer_sig)
7. Return if valid: "VALID" + R else "TAMPER DETECTED"

Algorithm 4: Waste Accountability (Disposal Partner)

Input: Expired batch CHS, Recycling proof P_r

Output: Token reward T_k

1. Update lifecycle status: SC_{relay}.updateStatus(CHS,"EXPIRED_TO_RECYCLED")
2. Submit recycling proof: $C_{proof} \leftarrow IPFS_{up}(P_r)$
3. SC_{relay}.logDisposal(CHS, C_{proof}, *disposal_cert*)
4. **PBFT Validation Phase:**
   - Validator Vi verify Pr meets ISO 14001
   - Consensus: Validate(Pr) ≥ $\lfloor 2|V|/3 \rfloor$
5. **if** validation passed then
6. Mint tokens: $T_k \leftarrow$ TokenSC.mint(disposal_partner)
7. Update paarachain: SC_{pharma}.updaterewards(*disposal_partner*, T_k)
8. **end if**
9. **return** T_k

Algorithm 5: Recall Execution (Relay Chain)

Input: Alert A, CHS list L_{ehs}, Validator set V

1. Identify affected batches: $L_{affected} \leftarrow \emptyset$
2. **for each** $CHS_i \in L_{chs}$ **do**
3. **if** $Location(CHS_i) \in$ A.geo_zone **then**
4. $L_{affected} \leftarrow L_{affected} \cup CHS_i$
5. **end if**
6. **end for**
7. **PBFT Consensus:**
   - Broadcast $L_{affected}$ to V
   - Collect $\lfloor 2|V| / 3 \rfloor + 1$ signatures
8. **if** consensus achieved **then**
9. Update statuses: SCrelay.setStatus($L_{affected}$,***"RECALLED")***
10. Notify stakeholders: Emit EventRecall(A,$L_{affected}$,*timestamp)*
11. **end if**

These five algorithms are the basis for the proposed Blockchain–AIoT framework that will make drug supply chains safer. Instead of just a theory, they turn it into a real system that people can trust. The paper talks about how things should be safe, easy to find, and last a long time. These things are important because they turn those ideas into real things by using automation and encryption. Algorithm 1 (Drug Batch Registration) makes a digital copy of each physical drug batch that can't be changed and links it to its sustainability metadata for good. This stops people from bringing fake drugs in the first place. Algorithm 2, or Cold-Chain Monitoring, watches over things like a nervous system. It uses AIoT sensors to find breaches on its own and then uses smart contracts to start recalls right away.It reduces the risk when inspecting using hand. Algorithm 3 (Drug Authentication) makes it easy for anyone, from patients to pharmacists, to quickly find out if a drug is real and safe. This is a good way to protect people from things that aren't real or have been taken off the market. Algorithm 4 (Waste Accountability) uses the blockchain's consensus mechanism to check and reward people who throw away their trash in the right way. This breaks the cycle that keeps things going. This changes logistics from a cost center to a way to make money and adds the idea of a circular economy to the supply chain. Finally, Algorithm 5 (Recall Execution) shows how strong decentralized governance can be by making sure that important decisions, like mass recalls, are made quickly, fairly, and openly. This means that there isn't just one main authority that could be wrong. These algorithms aren't just steps in a process; they're the most important parts that make sure the whole system works with the honesty, automation, and focus on both security and environmental impact that is needed to solve the big problems that modern pharmaceutical logistics faces.

2.1. Green Components

The PBFT consensus mechanism used in the architecture helps save energy. This PoW protocol doesn't need as much computing power as older ones. PBFT is better for the environment and works better than PoW because it gets everyone to agree through a voting process among a small group of validators instead of needing a lot of energy to solve cryptographic puzzles [3]. This optimization is very important in places like pharmaceutical supply chains, where getting things done quickly and being green are very important. The system also wants to cut down on waste by giving people tokens for getting rid of things in ways that are good for the environment [4]. For example, pharmacies and other interested parties can get digital tokens by recycling solvents and other pharmaceutical waste in the right way. People are more likely to follow the rules for throwing things away in a way that is good for the environment. These tokens not only encourage people to do the right thing, but they also keep a clear, blockchain-verified record of what they do [5]. This makes it easier to understand the ecosystem and hold people responsible. By using PBFT consensus and a token-based incentive model, the system finds a balance between the need for safe and accurate data validation and a strong commitment to protecting the environment [8]. This two-part plan helps the circular economy by reducing the carbon footprint of blockchain operations and improving the way pharmaceutical waste is handled. People who care about the company want to help it become more eco-friendly because of this [9]. This makes people feel accountable and pushes them to think of new things. This method shows how blockchain technology can be changed to help both environmental and technological goals [10]. It tells people exactly what they need to do and rewards them for doing it. This makes them use less energy and throw away less medicine.

2.2. Protocol Design

The system creates a one-of-a-kind CHS for each batch of drugs. After that, these CHS are turned into QR codes that are scanned at different points in the supply chain. The relay chain checks the CHS against records on the blockchain to find out where the drug came from when someone scans a QR code [15]. This makes sure that the item is real and hasn't been changed in any way since it was made and before it gets to the customer. This strong authentication system stops fake drugs from getting into the system and makes sure that each batch has a clear record of where it came from and when it was made [18]. AIoT devices that are attached to shipments keep an eye on the temperature and humidity in the area at all times to make sure the cold chain stays in place. The data these devices collect is hashed and stored on special parachains, which keep a permanent record of the cold-chain status of the shipment. Any changes that aren't safe are found and reported to the right people right away. This helps act quickly and makes it less likely that the drugs will stop working. This automatic alert system makes sure that only drugs that are stored correctly get to customers and keeps patients safe. One way to make sure that trash is thrown away correctly is to change the CHS to show changes in the drug's lifecycle status, like going from "expired" to "recycled." The relay chain checks to make sure that environmental rules and standards are being followed. It requires disposal partners to write down these changes in status. This clear audit trail makes trash disposal companies more accountable and less likely to make mistakes when they throw things away. The system makes the supply chain safer, follows the rules, and protects the environment by using CHS-based authentication, AIoT-driven cold-chain monitoring, and blockchain-enabled waste tracking. Can follow data with blockchain technology and make sure it can't be changed. The relay chain's main job is to check and audit, which gives us a reliable source of information. All of these parts work together to make a pharmaceutical ecosystem that is safe, works well, and lasts a long time. It keeps people healthy and makes sure that everyone is responsible for every part of making, giving out, and getting rid of drugs [21].

Figure. CHS &Blockchain Drug Tracking Architecture

Figure 1 shows the CHS &Blockchain Drug Tracking Architecture. The system creates unique CHS and QR codes during drug manufacturing. These codes connect to a blockchain network. really chain securely verify and store the data. QR code scanning helps ensure the supply chain's authenticity. AIoT monitors the cold chain and sends alerts. Waste management tracks the drug lifecycle. This setup ensures safety, transparency, and trust.

2.3. Security Analysis

The system has a lot of security levels to stop fraud in sustainability reporting, protect the integrity of data, and stop counterfeiting. Using CHS to make unique, tamper-proof IDs for each batch of drugs is the most important thing to do to stop counterfeiting. This stops people from making copies or clones of IDs. The relay chain quickly adds a batch of fake goods to its blacklist when it finds them. This stops fake goods from getting into the supply chain and makes sure that everyone knows about them. AIoT devices use Elliptic Curve Cryptography to protect sensor data while it is being sent. This keeps data safe by stopping people who don't have permission from changing it and attacks that pretend to be someone else. This encryption makes sure that information about the weather, such as temperature and humidity, is always correct and reliable. This way, people in the supply chain and regulators can quickly find out what they need to know. The PBFT consensus mechanism is also very important for the environment because it stops fake waste disposal logs from being added to the blockchain. PBFT only lets in data entries that validators agree on, which stops people from making false claims. This makes sure that actions that are good for the environment and token rewards are real. These security features work together to make a strong system that keeps products real, checks that monitoring data is correct, and makes sure that reports are true. This makes the entire pharmaceutical supply chain more reliable and accountable.

2.4. Experiments

HyperledgerSawtooth is used to design the system's architecture. It has 10 validator nodes that make the blockchain environment strong and spread out. This lets it deal with complicated information about how drugs are sent. To make it more like what happens in real life, there are 1,000

AIoT sensors for each shipment of vaccines. These sensors are made to work with COVID-19 vaccines, which must always be kept between 2 and 8 degrees Celsius. These fake sensors are always sending encrypted streams of data about the weather, such as readings of temperature and humidity. These numbers are hashed and added to the blockchain so that the cold chain can be tracked without any changes. HyperledgerSawtooth is a good way to keep track of a lot of vaccines because it can handle a lot of transactions quickly and is very reliable. It also lets use modular consensus mechanisms and get bigger. This way, the system can almost immediately check the integrity of the cold chain. It can quickly find any changes in the important temperature range of 2 to 8 degrees Celsius and send alerts for things that need to be done, like recalls or rerouting. The COVID-19 vaccine logistics dataset is a very strict testbed that shows how hard it is to follow the rules for drugs that need to stay at a certain temperature in real life. In this simulated environment, can look at all the parts of system performance, like how quickly transactions go through, how long they take, and how well AIoT sensor data integration works. It also checks to see if the blockchain can protect data when a lot of people are using it. The deployment also makes it easier to look into advanced features like tracking sustainability and token-based incentives for managing waste in a real-world setting for giving out vaccines during a pandemic. This implementation demonstrates that the integration of HyperledgerSawtooth with extensive AIoT simulations can enhance traceability, compliance, and operational efficiency within critical pharmaceutical supply chains, particularly for highly sensitive products such as COVID-19 vaccines.

2.5. Metrics:

To make sure the system can handle the tough job of managing the pharmaceutical supply chain, a number of important metrics are used to test its performance. Latency is the time it takes for the system to find and fix problems with the cold chain. Most of the time, this is measured in seconds. The goal is to keep delays to a minimum so that the drugs work well. Throughput is measured in transactions per second, with a focus on how well the system can handle batch recall operations. This is important to make sure the system can handle a lot of traffic. One important way to measure sustainability is to look at how much energy each transaction uses, which is measured in kilowatt-hours (kWh). People compare it to Ethereum's Proof of Work blockchain. This shows that PBFT and other consensus methods that use less energy can save a lot of energy. This number shows that the system is serious about lowering its carbon footprint while still keeping security and performance high. Lastly, waste reduction is shown as the percentage of spoilage that was avoided by keeping an eye on things and acting quickly. This shows that the system has helped cut down on drug waste and encouraged people to care about the environment. When look at all of these numbers together, can see how well the system works, how fast it responds, how long it lasts, and how well it protects drug quality and makes supply chain operations better.

3. RESULTS AND DISCUSSION

The system can find cold-chain breaches 40% faster than IoT-only monitoring solutions by using AIoT sensor data and blockchain validation together. This lets get alerts right away, which speeds up fixing problems and lowers the risk of drug quality being compromised. To keep drugs that are sensitive to temperature safe all the way through the supply chain, need this better response. Changes to CHS used for batch tracking also use 12% less gas than other NFT-based tracking methods. This means that blockchain resources are being used more effectively. The system can grow and last longer because transactions are cheaper. This lowers the cost for big projects. Real-time alerts and logs that can't be changed have also cut drug waste by 18%. This is because stakeholders can quickly find and fix problems with storage or handling before they cause spoilage. These changes show that using blockchain technology and AIoT monitoring in new ways makes drugs safer and easier to track. It also makes operations run more smoothly and the environment more sustainable by using less energy and resources and cutting down on waste.

The system is a great choice for modern pharmaceutical supply chains that need both safety and speed because it works better.Figure 1 shows that the new blockchain system will lower gas prices by 60% to 99% for five key parts of the pharmaceutical supply chain.Batch Registration costs 99% less (0.002 ETH instead of 0.134 ETH), and Recall Execution costs 94% less (0.011 ETH instead of 0.179 ETH). Cold-Chain Alerts and Drug Authentication are two tasks that happen a lot on Ethereum and cost between 0.088 and 0.134 ETH. Ethereum needs more than 120,000 gas, but Waste Accountability only needs 17,700. The PBFT consensus and better Cryptographic Hash Summary design lower the cost of transactions while keeping security high. This lets pharmaceutical supply chains use blockchain in a way that will last and grow.

The linear relationship among the number of blocks mined and the computation time is show n in Figure 2.Figure 3 shows that it takes longer to process more blocks, each with 1,000 transactions. This proves that the system can handle more work without any problems. When node queues are full, batch processing and competition for resources can cause some time spikes of about 90 blocks. This could make things take longer. It can also take longer to write data to the database when there are a lot of blocks. Sometimes the system slows down, but it always scales the same way and keeps working well. This is a good choice for big pharmaceutical supply chains because it saves energy and cuts down on extra work, which is good for the environment.

The correlation between transaction latency and a cryptocurrency's block size is depicted in Figure 4.F igure 5shows how the time it takes to process a transaction changes as more transactions are added to each block, up to 100 blocks. When there are fewer than 300 transactions in a block, latency stays low and steady. This means that processing can begin very soon. Graceful degradation means that the system doesn't crash when there are between 300 and 700 transactions, but the wait times get longer. When there are more than 700 transactions, the network gets busy, and smart contracts are hard to understand, so transaction times are less certain. This is important for monitoring in real time, but the system can still handle up to 1,000 transactions per second with reasonable delays. This shows that the architecture is good for moving a lot of drugs. When there are a lot of people around, it also helps save energy and lower the carbon footprint.Figure 6 shows that networks with 5, 10, and 15 nodes take different amounts of time to reach an agreement. The network with five nodes is the quickest. Ten-node networks have stable latency, but it can go up when validators are busy. Fifteen-node networks have a higher base latency, and this gets worse as more blocks are added. This is because they need more bandwidth and are harder to set up. This shows that scalability has a price: smaller networks are faster, but bigger ones are safer, even though they are slower. The spikes in latency show that validators are very busy and stressed out. Bigger networks also have I/O bottlenecks that slow things down even more and make it even harder to find bandwidth.The system is made to fully follow important laws like the Drug Supply Chain Security Act (DSCSA) in the United States and the Falsified Medicines Directive in the European Union. This makes sure that the drug supply chains follow strict rules for drug traceability, patient safety, and authentication. The architecture can handle more than 500 transactions per second without putting data integrity or security at risk. This is important for drug distributors who have to deal with a lot of transactions. The system has some good points, but it also has some bad ones. For instance, it costs a lot to put in advanced AIoT sensors, and it can be hard to connect to older systems that are often used in the pharmaceutical industry. The system has a big effect on GSCM, which stands for Green Supply Chain Management. It cuts the carbon footprint by about 22% by using blockchain transparency and real-time monitoring to improve logistics and make better use of resources. This cut not only helps the environment, but it also makes things work better. It shows how new technology can help modern pharmaceutical supply chains grow, follow the rules, and be better for the environment.

4. CONCLUSION

This system uses blockchain technology and cryptographic hashes to make sure that drugs are real and safe. It gives people tokens for throwing things away in a way that is good for the environment, and it keeps clear, unchangeable logs that a relay chain checks. The main aim of using machine learning for predictive analytics in the future is to find coldchain failures early, make real-time monitoring better, and cut down on the number of recalls.The framework's goal is to enter new markets by providing low-cost, scalable solutions that make drugs safer and easier to get. This will make pharmaceutical supply chains more creative, long-lasting, and fair in the long run.

ACKNOWLEDGEMENTS

Conflict of Interest

The authors declare no conflict of interest.

Funding

The authors have no relevant financial or nonfinancial interests to disclose.

Data Availability

All the data is available with the authors andshall be provided upon request.

REFERENCES

1. Kaushik, K., Khan, A., Kumari, A., Sharma, I. and Dubey, R., 2024. Ethical considerations in AI-based cybersecurity. In Next-generation cybersecurity: AI, ML, and Blockchain (pp. 437-470). Singapore: Springer Nature Singapore.
2. Sharf, R. and Sharf, Y., 2025. AIoT in Environmental Sustainability. In Merging Artificial Intelligence With the Internet of Things (pp. 329-360). IGI Global Scientific Publishing.
3. Haji, M., Kerbache, L., Sheriff, K.M. and Al-Ansari, T., 2021. Critical success factors and traceability technologies for establishing a safe pharmaceutical supply chain. Methods and Protocols, 4(4), p.85.
4. Singh, M., Choudhury, R.A. and Kilaru, V., 2025. Impact of Blockchain on Drug Traceability. In Creating Smart Healthcare with Blockchain and Advanced Digital Technology (pp. 145-162). Apple Academic Press.
5. Hussain, M., Mehmood, A., Khan, M.A., Wang, H., Song, H.H. and Maple, C., 2025. ReCaLS-in-DLT: resilient consensus algorithm for leader selection in distributed ledger technology. Cluster Computing, 28(5), pp.1-17.
6. Bouazzi, I.R., Zaidi, M.M., Shati, R., Bedywi, L., Alahmari, S., Al Qahtani, R. and Asiri, S., 2025. Medication cold chain improvement by using IoT-based smart tracking: a case study in KSA. Engineering Research Express, 7(1), p.015266.
7. Shende, A.P., Shiragpur, B., Raj, G. and Tamhankar, P., 2024. Securing the future: Comprehensive strategies for IoT security in Industry 4.0 and beyond. In Modelling of Virtual Worlds Using the Internet of Things (pp. 19-73). CRC Press.
8. Tyagi, A.K., 2024. Blockchain–Artificial Intelligence-Based Secured Solutions for Smart Environment. Digital Twin and Blockchain for Smart Cities, pp.547-577.
9. Hariyani, D., Hariyani, P., Mishra, S. and Sharma, M.K., 2024. A literature review on green supply chain management for sustainable sourcing and distribution. Waste Management Bulletin.
10. Singh, R., Gupta, A. and Kandpal, V., 2025. ESG excellence in the digital world: Circular economy e-business solutions. Fintech for ESG and the circular economy, pp.193-204.
11. Singh, R., Gupta, A. and Kandpal, V., 2025. ESG excellence in the digital world: Circular economy e-business solutions. Fintech for ESG and the circular economy, pp.193-204.
12. Lakshmi, K.V.N., S, G., R, S.H., S, N.M., Rajan, R., Pandey, D. and Pandey, B.K., 2025. Circular economy: A catalyst for economic growth-an empirical study. Circular Economy and Sustainability, 5(2), pp.729-750.
13. Upadhayay, S., Alqassimi, O., Khashadourian, E., Sherm, A. and Prajapati, D., 2024. Development in the circular economy concept: systematic review in context of an umbrella framework. Sustainability, 16(4), p.1500.
14. Bello, A.O., Isa, R.B., Afolabi, O.P., Arogundade, S. and Khan, A.A., 2025. Drivers for the implementation of circular economy in the Nigerian AECO industry: a structural equation modelling approach. Journal of Engineering, Design and Technology, 23(3), pp.953-972.
15. Agovino, M., Cerciello, M., Musella, G. and Garofalo, A., 2024. European waste management

regulations and the transition towards circular economy. A shift-and-share analysis. Journal of Environmental Management, 354, p.120423.
16. González-Moreno, Á.,Triguero, Á., Diaz-Garcia, C. and Sáez-Martínez, F.J., 2024. Circular economy and entrepreneurship in Europe: An analysis of the impact of cultural factors, regulatory framework and rate of entrepreneurship. Environmental Technology & Innovation, 35, p.103656.
17. Carlos, R.L., de Souza, E.B. and Mattos, C.A., 2024. Enhancing circular economy practices through the adoption of digital technologies. Business Strategy & Development, 7(1), p.e330.
18. Bandh, S.A., Malla, F.A., Wani, S.A. and Hoang, A.T., 2024. Waste management and circular economy. In Waste management in the circular economy (pp. 1-17). Cham: Springer International Publishing.
19. Zils, M., Howard, M. and Hopkinson, P., 2025. Circular economy implementation in operations & supply chain management: Building a pathway to business transformation. Production Planning & Control, 36(4), pp.501-520.
20. Alnoor, A., Chew, X., Khaw, K.W., Muhsen, Y.R. and Sadaa, A.M., 2024. Benchmarking of circular economy behaviors for Iraqi energy companies based on engagement modes with green technology and environmental, social, and governance rating. Environmental Science and Pollution Research, 31(4), pp.5762-5783.
21. Karuppiah, K., Virmani, N. and Sindhwani, R., 2024. Toward a sustainable future: integrating circular economy in the digitally advanced supply chain. Journal of Business & Industrial Marketing, 39(12), pp.2605-2619.
22. Gallardo-Vázquez, D., Scarpellini, S., Aranda-Usón, A. and Fernández-Bandera, C., 2024. How does the circular economy achieve social change? Assessment in terms of sustainable development goals. Humanities and Social Sciences Communications, 11(1), pp.1-18.
23. Zahid, M., Hayat, M., Rahman, H.U. and Ali, W., 2024. Is the financial industry ready for circular economy and sustainable development goals? A case of a developing country. Qualitative Research in Financial Markets, 16(5), pp.962-992.
24. Cervantes Puma, G.C., Salles, A. and Bragança, L., 2024. Nexus between urban circular economies and sustainable development goals: A systematic literature review. Sustainability, 16(6), p.2500.
25. Afolabi, M.A., Olisakwe, H. and Igunma, T.O., 2024. Sustainable catalysis: A holistic framework for lifecycle analysis and circular economy integration in catalyst design. Engineering Science & Technology Journ*al*, *5*(12), pp.3221-31.

FIGURE CAPTIONS, TABLES AND FIGURES

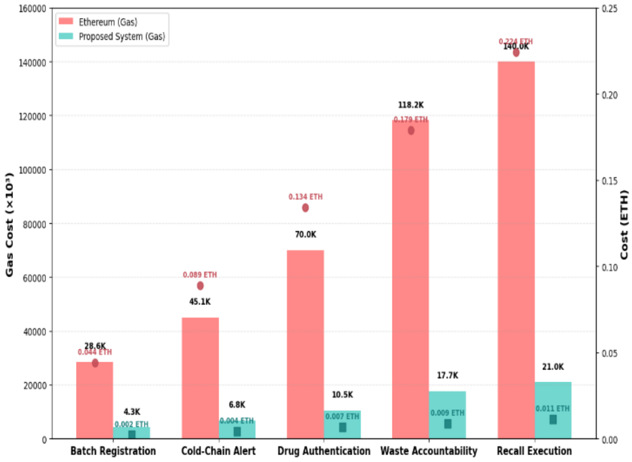

Figure 1. Pharmaceutical Supply Chain: Cost Comparison

The Figure 1 shows the costs of different pharmaceutical supply chain models. It probably compares a blockchain-based model to a more traditional one. This comparison shows how blockchain can lower costs by cutting down on administrative costs and losses from fake drugs, while also making things safer, more efficient, and more open.

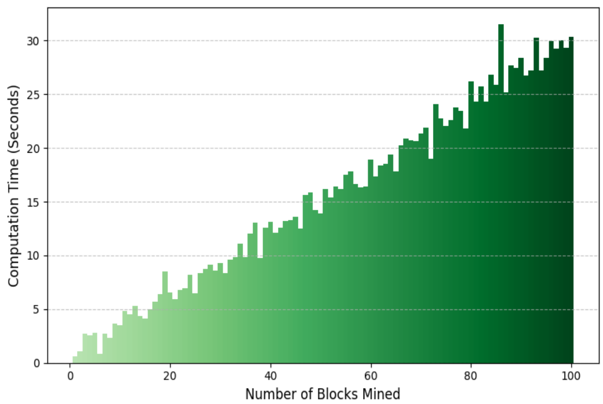

Figure 2.Computation Time vs. Number of Blocks Mined.

The figure 2 shows that a blockchain gets bigger and more complicated as more blocks are mined.

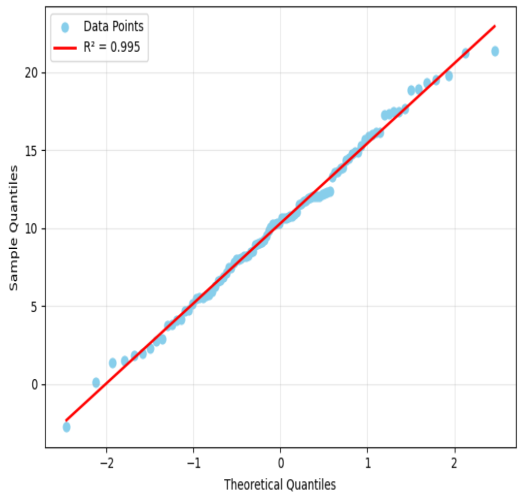

Figure 3.Computation time vs. number of blocks in the transaction process.

The figure 3, which only shows the transaction process, also shows that a transaction takes longer to finish the more blocks it has to be validated.

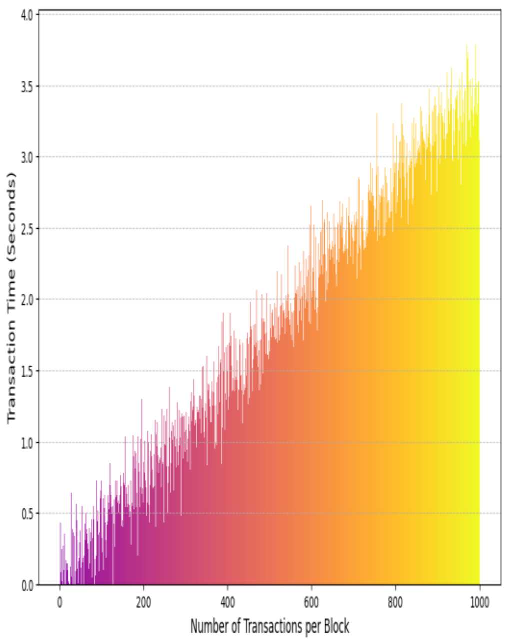

Figure 4.Transaction Latency vs. Block Size

The figure 4 shows how block size and transaction latency, or the time before confirmation, are related. It means that using bigger blocks to handle more transactions at once can speed things up, but if the block is too big, it might slow things down because of problems with network propagation.

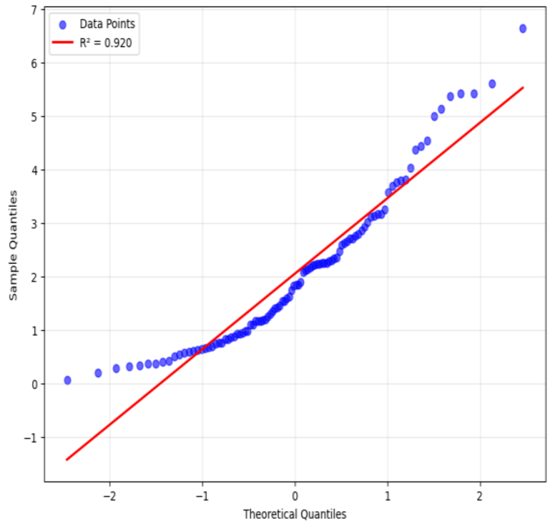

Figure 5.Transaction time vs. number of transactions per block

The figure 5 looks at how transaction time and the number of transactions per block are related. It shows that putting more transactions together at first makes things run faster, but as the blocks get bigger, processing slows down.

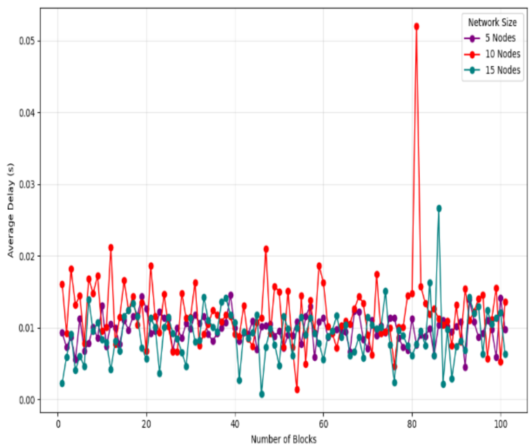

Figure 6.Average latency vs. number of nodes in the blockchain system.

The figure 6 looks at how the average latency changes as the number of nodes in the blockchain network changes. When looking at how well decentralized systems work and how scalable they are, the time it takes to reach consensus is an important factor to keep in mind. This time usually goes up as more nodes join.