Exploring Fairness in Ethereum PoS: The Impact of Protocol Design and MEV

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Abstract

This paper analyzes fairness in the Ethereum Proof-of-Stake (PoS) protocol using a Python-based simulation framework. Our model enables flexible modifications to protocol parameters, allowing us to assess fairness across different settings. We investigate how reward distribution aligns with stake proportionality and explore the effects of various protocol adjustments on fairness outcomes. Additionally, we examine the role of MEV in influencing reward variance and its potential impact on fairness. Our findings provide insights into the mechanisms driving fairness in PoS Ethereum, offering guidance for improving protocol design to ensure more equitable reward distribution.

Keywords

Ethereum, Proof of Stake, MEV-boost, analysis

1. Introduction

Blockchain technology enables secure, decentralized, and transparent peer-to-peer transactions without intermediaries. By leveraging cryptographic techniques and consensus mechanisms, blockchains ensure tamper-resistant records of digital assets and transactions. Over the years, blockchain applications have expanded beyond cryptocurrencies—such as Bitcoin [1]—to include smart contracts on Ethereum [2], decentralized finance (DeFi) [3], supply chain traceability [4], and secure voting systems [5].

Early blockchains like Nakamoto's [1] used Proof of Work (PoW), where nodes solve puzzles to validate transactions. Due to PoW's energy demands [6], many systems now adopt Proof of Stake (PoS), which selects validators by stake, cutting energy use while preserving security.

Fairness in PoS, especially in reward distribution and stake growth, is a key challenge. Ideally, rewards should scale with stake without promoting wealth concentration. However, factors like protocol design and external incentives (e.g., Maximal Extractable Value or MEV) can disrupt this balance. Understanding these effects is essential for building fair and sustainable networks. We define fairness as stake-proportional reward allocation: validators should earn rewards in line with their stake over time, despite randomness in block proposals. This reflects economic fairness, where returns match contributions—i.e., staked tokens—rather than factors like timing, position, or access to MEV.

We analyze fairness in Ethereum's PoS protocol using a Python-based simulation framework. Unlike prior works that rely on formal modeling tools like PRISM [7, 8, 9, 10], our approach allows for greater flexibility in modifying protocol parameters and assessing their impact on fairness. We examine the relationship between stake and reward distribution under different protocol settings, including the presence and absence of MEV Boost. Our simulations reveal how validator rewards deviate from expected stake-proportional outcomes and highlight the extent to which MEV influences fairness in Ethereum's PoS system. This flexibility is key, as existing state-of-the-art tools often require rigid specifications and struggle to scale with complex blockchain scenarios. They're also typically tied to fixed protocol assumptions, limiting exploration of how design tweaks, like reward schemes or validator selection, impact fairness. Our simulation framework fills this gap, enabling rapid testing across diverse protocol setups and adversarial behaviors—vital in Ethereum's evolving landscape, where features

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like MEV Boost and dynamic staking are under active debate. This work is motivated by ongoing questions about whether Ethereum's shift to PoS ensures fair participation. We investigate how protocol structures shape long-term wealth distribution and whether MEV opportunities worsen inequality. Our flexible simulation environment enables empirical exploration of these issues, helping inform future protocol design.

The structure of this paper is as follows: Section 2 provides background on Ethereum's PoS protocol and fairness considerations. Section 3 introduces our simulation model and its key design choices. Section 4 presents our experimental results, analyzing stake distribution, reward fairness, and the impact of MEV. Section 5 discusses related work on PoS fairness analysis. Finally, Section 6 summarizes our findings and outlines directions for future research.

2. Background

The transition of the Ethereum blockchain to a Proof-of-Stake (PoS) consensus mechanism, known as the Merge, marked a significant evolution in its architecture. This shift replaced the energy-intensive Proof-of-Work (PoW) system with a more sustainable and efficient model based on validator staking. Understanding the fundamentals of Ethereum's PoS, particularly the role of validators and the emergence of Maximal Extractable Value (MEV) and its mitigation through MEV-Boost, is crucial for contextualizing the simulations presented in this paper.

Ethereum Proof-of-Stake (Consensus Layer). Following the Merge [11], Ethereum transitioned to a Proof-of-Stake (PoS) consensus governed by the Beacon Chain [12]. The Beacon Chain organizes time into epochs, each composed of 32 slots lasting 12 seconds. In every slot, a validator is pseudo-randomly selected to propose a block, while a committee of validators is tasked with attesting to its validity. To participate, validators must stake 32 ETH and operate validator software. They receive rewards for proposing and attesting to blocks correctly, and can be penalized or slashed for malicious or negligent behavior. Validator selection relies on a pseudo-random mechanism (RANDAO) based on staked ETH. Block finality is achieved through justification and finalization: a checkpoint (first block of an epoch) becomes justified when attested by more than two-thirds of the total stake, and is finalized once another justified checkpoint builds upon it.

Maximal Extractable Value (MEV). In parallel to the base consensus mechanism, a phenomenon known as Maximal Extractable Value (MEV) has emerged within blockchain networks, including Ethereum. MEV refers to the maximum value that can be extracted from transaction ordering and inclusion within a block, beyond the standard block reward and transaction fees. This can involve various strategies, such as front-running user transactions on decentralized exchanges (DEXs), back-running profitable arbitrage opportunities, or liquidating undercollateralized positions in lending protocols.

While MEV can incentivize efficient transaction processing and arbitrage, it also presents potential risks. Uncontrolled MEV extraction can lead to increased gas prices, network instability due to priority gas auctions, and concerns about fairness and censorship if block proposers prioritize MEV-maximizing transactions over standard user transactions.

MEV-Boost. To mitigate the negative impacts of MEV and broaden its benefits, Ethereum introduced MEV-Boost: a relay middleware that connects validators with external "builders". Builders optimize blocks for MEV opportunities and submit bids to proposers via the relay. When selected, a validator's client fetches the highest-paying valid block and broadcasts it, allowing validators to benefit from MEV without specialized expertise.

By separating transaction bundling from block proposing, MEV-Boost fosters a more competitive and transparent block market. It can improve validator rewards, reduce centralization risk, and improve censorship resistance by encouraging diverse transaction inclusion. These dynamics are relevant to our PoS model simulations, which may reflect efficiency gains and incentive effects similar to those introduced by MEV-Boost.

Fairness. A central challenge in Proof-of-Stake (PoS) protocols, including Ethereum's, is ensuring a fair and attack-resistant allocation of block proposal opportunities among validators. Attacks such as the *nothing-at-stake* problem [13] and the *branching process* attack [14] exploit weaknesses in block selection fairness. In Ethereum's current PoS mechanism, the chance of being selected as a block proposer is directly proportional to a validator's staked ETH. This means that validators with larger stakes are more likely to propose blocks and earn rewards, which in turn increases their stake even further. Over time, this dynamic can lead to increasing centralization, as wealthier validators gain a compounding advantage, making it harder for those with smaller stakes to participate in block production.

3. Proof of Stake Simulation Model

In this section, we present a Python-based simulation model for the Ethereum Proof of Stake (PoS) protocol. The model focuses on token distribution among peers in the network, validator selection, and the consequences of corrupted validators. It mimics a decentralized blockchain network where validators are selected based on their stake, rewarded for their actions, and penalized if they are corrupted.

```python
def pos_simulation():
    corrupted_peers = np.sort(np.random.choice(range(1, number_of_peers + 1), number_of_corrupted_peers, replace=False))
    token_distribution = np.sort(np.random.randint(min_tokens_per_peer, max_tokens_per_peer + 1, number_of_peers))

    for iteration in range(1, number_of_iterations + 1):
        stakeable_tokens = np.floor((stakeable_percentage / 100) * token_distribution).astype(int)
        stakeable_total = np.sum(stakeable_tokens)
        stake = np.zeros(number_of_peers, dtype=int)
        validators = np.zeros(number_of_validators, dtype=int)

        for i in range(number_of_validators):
            r = np.random.randint(1, stakeable_total + 1)
            s, j = 0, 0
            while s <= r:
                s += stakeable_tokens[j]
                j += 1
            j -= 1
            if stake[j] == 0:
                validators[i] = j
                stake[j] = stakeable_tokens[j]

        corrupted_validators = np.intersect1d(validators, corrupted_peers)
        token_distribution -= stake
        stake += reward_tokens
        for v in corrupted_validators:
            stake[v] -= reward_tokens
            stake[v] = np.floor(stake[v] * (penalty_percentage / 100)).astype(int)
        token_distribution += stake

```

Listing 1: Proof of Stake Simulation Model

Though inspired by Ethereum's PoS, our model adopts simplifying assumptions to support controlled experiments and clearer analysis of fairness. We bound initial token allocations using `min_tokens_per_peer` and `max_tokens_per_peer` to explore both equal and unequal wealth distributions. While Ethereum imposes no such caps, this design lets us simulate a range of starting conditions, essential for studying wealth centralization under protocol rules. We also introduce a tunable parameter, `stakeable_percentage`, to define what fraction of a peer's tokens are staked. While Ethereum validators stake exactly 32 ETH per validator, real users vary their stake based on factors like liquidity needs or risk tolerance. This flexibility lets us model a range of validator behaviors—from cautious to fully committed—and assess fairness under diverse strategies. Finally, our simulation includes a fixed block reward and a penalty for malicious behavior, reflecting Ethereum's reward–punishment model in simplified form. Instead of fully modeling slashing or complex incentives, we apply deterministic penalties to corrupted validators, enabling repeatable and focused fairness evaluations.

The simulation is controlled by key parameters defining the network. `number_of_peers` sets the total number of peers, each holding a random token amount between `min_tokens_per_peer` and `max_tokens_per_peer`. A portion, defined by `stakeable_percentage`, is used for staking. The parameter `number_of_corrupted_peers` defines how many peers act maliciously when selected as validators, attempting to exploit the system, while `number_of_validators` sets how many validators are chosen per round to validate blocks, a core part of PoS. The fixed reward per validator is controlled with the parameter `reward_tokens`, while `penalty_percentage` reduces rewards for corrupted validators. Finally, `number_of_iterations` determines how many rounds of validator selection, staking, and reward distribution the simulation runs.

The simulation, presented in Listing 1, begins by defining the peer network, where each peer is assigned a random number of tokens within the specified range. However, only a portion of these tokens, determined by the `stakeable_percentage`, is available for staking. These staked tokens are used to participate in the validator selection process. In the first step, the simulation randomly selects a set of corrupted peers. These corrupted peers will attempt to manipulate the validation process by reducing their rewards, simulating malicious behavior within the network.

The initial token distribution is created by randomly assigning tokens to each peer. The simulation then outputs various statistics on this initial distribution, including the total number of tokens, the mean number of tokens per peer, and the standard deviation. Next, the validator selection process begins. Validators are chosen randomly, with selection probability weighted by each peer's stake—those with more tokens are more likely to be picked. Selected validators receive a fixed reward for validating blocks. If a corrupted peer is selected, their reward is reduced based on the `penalty_percentage`, simulating the impact of malicious behavior. After rewards are applied, token balances are updated: staked tokens are subtracted, and rewards are added. Corrupted validators receive reduced rewards to reflect penalties. At the end of each iteration, updated token distributions and statistics are displayed. This process repeats for the specified number of iterations, modeling how rewards, stake, and corruption affect fairness over time.

This model is not intended to mirror Ethereum's protocol line-for-line, but rather to offer a parameterized environment where protocol dynamics can be isolated, manipulated, and studied with respect to fairness. By enabling control over variables that are fixed or emergent in real-world settings, we provide a framework for empirical exploration of reward distribution under different assumptions and adversarial conditions.

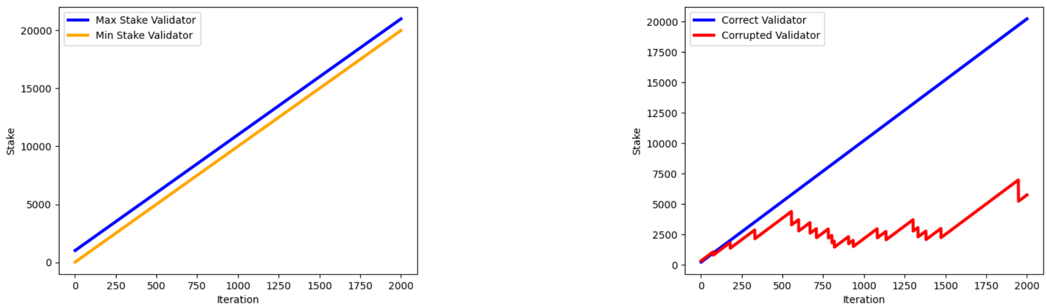
4. Simulations

This section presents simulation experiments to evaluate fairness in Ethereum's Proof-of-Stake protocol. The goals are to understand how stake evolves under varying conditions and to assess the impact of external factors—particularly MEV Boost—on reward distribution and validator selection. Each experiment isolates key mechanisms influencing fairness.

We begin by investigating the influence of initial stake on validator rewards and how the protocol's design reinforces or mitigates inequalities. This is followed by a comparative analysis of different initial stake distributions to explore the emergence of wealth concentration. The section concludes with an assessment of the impact of MEV-like strategies on both block production efficiency and fairness.

4.1. Stake Growth and Validator Behavior

To examine how the amount of initial stake influences long-term reward accumulation, we track two validators: one starting with the highest number of tokens and one with the lowest. As shown in Figure 1a, the validator with the larger initial stake consistently earns more rewards and grows its wealth at a faster pace. This divergence remains stable across iterations, suggesting that the protocol maintains consistency over time while allowing initial inequalities to persist, if not intensify. This



(a) (b)

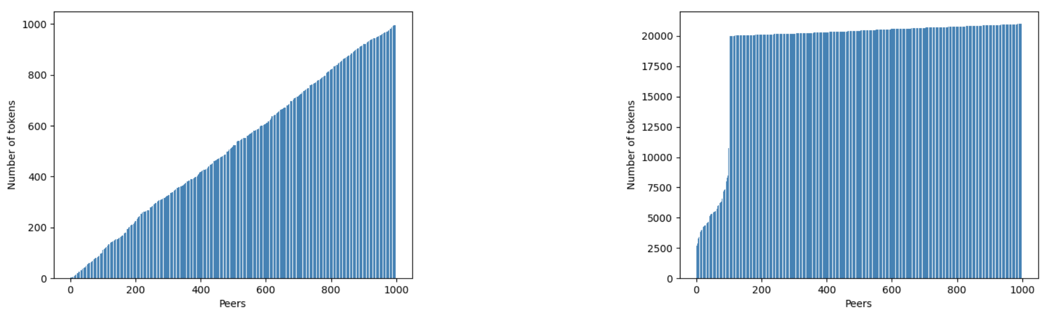
Figure 1: Stake growth for the maximum and minimum initial stake holders (left) and for a honest and a corrupted validator (right)

observation raises fairness concerns, as it indicates a compounding advantage for early or wealthy participants. Such effects, if unchecked, may lead to increasing centralization of power within the validator set.

In parallel, we analyze how validator behavior—specifically, honest versus malicious activity—affects stake evolution. Figure 1b compares an honest validator with a corrupted one. While both start with similar initial conditions, the corrupted validator exhibits stagnating or declining stake levels due to penalties applied for dishonest behavior. This contrast highlights the protocol's effectiveness in discouraging attacks and maintaining network integrity, though it does not resolve the broader issue of wealth accumulation among honest yet already advantaged actors.

4.2. Distributional Effects and Wealth Inequality

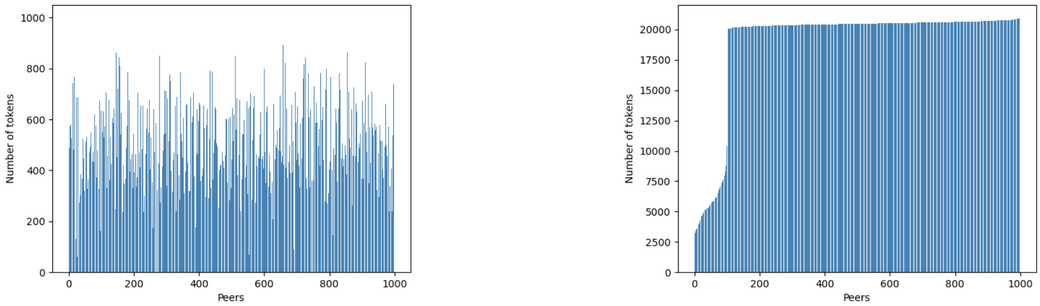
To further explore fairness, we evaluate how the initial distribution of stake affects long-term outcomes. Figures 2a and 2b present the system before and after simulation under a uniform distribution of tokens. Although the initial allocation is nearly linear and equitable, the final distribution reveals a striking increase in inequality, with some peers amassing significantly greater wealth than others. This emergent disparity is a direct consequence of the proportional validator selection mechanism, which favors those with more staked assets.



(a) (b)

Figure 2: Comparison of initial (left) and final (right) token distributions with uniform distributed initial stakes

To model more realistic starting conditions, we repeat the experiment using a normally distributed token allocation (Figures 3a and 3b). Even with moderate initial inequality, the protocol produces sharper divergence over time. Validators with above-average stake benefit from increased selection probability, leading to faster compounding of rewards. These results align with economic patterns of wealth concentration, demonstrating that PoS systems may inherently amplify even modest disparities.



(a)

(b)

Figure 3: Comparison of initial (left) and final (right) token distributions with normal distributed initial stakes

A broader view of this dynamic is captured in Figure 4, which displays the net change in stake for each validator. While many honest participants see positive gains, a substantial portion—especially those flagged as corrupted—experience losses. This underscores the dual role of stake as both an incentive and a mechanism of differentiation, reinforcing merit-based growth while preserving initial advantages.

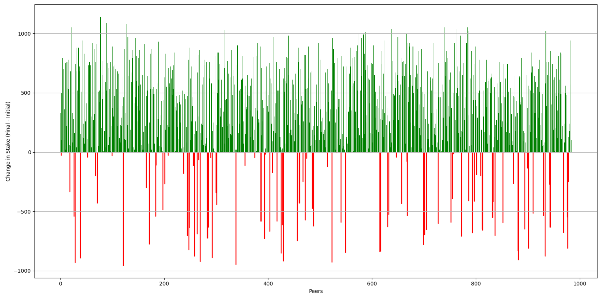


Figure 4: Difference in Stake (Final - Initial) for all validators

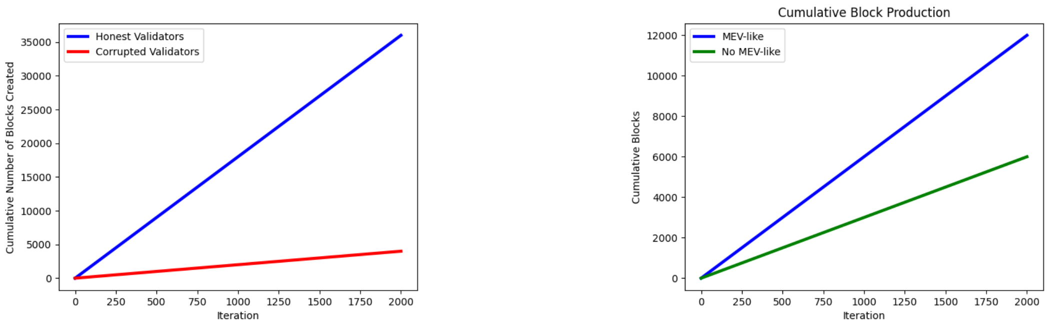
4.3. Block Production and Validator Participation

Validator participation over time is another key dimension of fairness. Figure 5a compares the cumulative number of blocks produced by honest and corrupted validators. As expected, honest validators dominate block production, owing both to their larger stake and to the protocol's penalization of misbehavior. This result affirms the protocol's resilience to manipulation, but also hints at a deeper pattern: honest validators with more frequent selections continue to grow their dominance, potentially skewing long-term participation rates.

To assess how additional incentives alter this dynamic, we introduce MEV-like strategies into the simulation. Figure 5b reveals a dramatic increase in total block production when MEV Boost is enabled. This outcome suggests improved network efficiency—but also introduces new concerns about the distribution of these additional rewards.

4.4. Fairness Under MEV Boost

The final set of experiments isolates the effect of MEV Boost on fairness. Figure 6 compares the initial stake of each validator to the total rewards they accumulate when MEV Boost is active. While a general trend of proportionality is observable, a number of outliers deviate sharply from it—most notably, validators with modest initial stake who achieve disproportionately high rewards. These anomalies



(a) (b)

Figure 5: Cumulative number of blocks created by honest and corrupted validators (left) and with and without MEV-like strategies (right)

indicate that MEV opportunities, though potentially rare, can significantly distort reward distribution by introducing variance unrelated to stake size.

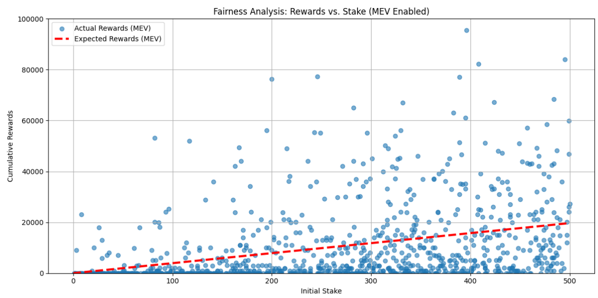


Figure 6: Fairness Analysis: Rewards vs. Stake with MEV Enabled

By contrast, when MEV Boost is disabled (Figure 7), the reward distribution more closely mirrors the initial stake, with fewer extreme deviations. This reinforces the idea that MEV introduces an element of randomness that, while beneficial to overall throughput, may undermine the fairness guarantees typically associated with stake-based systems.

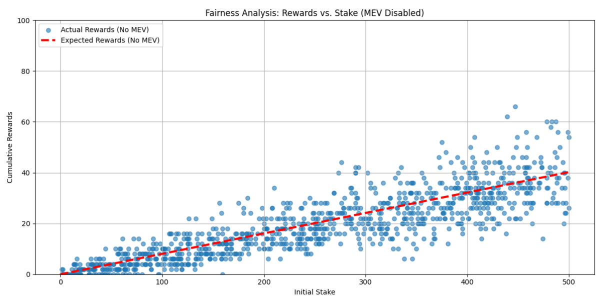


Figure 7: Fairness Analysis: Rewards vs. Stake with MEV Disabled

4.5. Discussion

Taken together, these results illustrate a nuanced trade-off at the heart of Ethereum's PoS design. On one hand, the protocol effectively discourages malicious activity and maintains consistent validator selection mechanics. On the other hand, it amplifies pre-existing inequalities and, when combined with MEV, introduces further distortions in reward distribution. These findings underscore the importance of protocol-level safeguards to prevent excessive centralization and suggest a need for fairness-enhancing mechanisms—particularly in the context of MEV reward extraction.

5. Related Works

In blockchain systems, fairness is closely tied to wealth distribution among nodes. Analyzing validator rewards offers insight into the trade-off between investment power and equal opportunity.

Several works study wealth distribution in PoW and PoS systems [15, 16, 17]. For example, [18] discusses preferential attachment, where top Bitcoin holders accumulate wealth faster than others.

A broader analysis in [19] compares leading accounts across platforms, showing that tokens tend to centralize more than native coins, based on evolving statistical indicators.

In contrast, [20] takes a theoretical approach, defining fairness as selection probability proportional to stake. It studies scenarios with 1% and 40% corrupted nodes. In the first, wealth grows proportionally even for the rich, raising fairness concerns; in the second, penalties eventually eliminate malicious nodes, potentially restoring balance.

To mitigate fairness issues, some propose protocol changes. e-PoS [21] enhances fairness via blind-block auctions in smart contracts to widen participation. Similarly, RPoS [22] selects validators by coin ownership but caps coinage, countering accumulation attacks and Nothing-at-Stake vulnerabilities.

6. Conclusions

We analyzed fairness in Ethereum's Proof-of-Stake using a Python-based simulation, exploring how stake distribution and protocol design affect reward allocation, including the impact of MEV Boost.

Our results show that wealthier validators consistently earn more, reinforcing stake inequality. While the protocol penalizes malicious behavior effectively, honest validators still face uneven reward outcomes. Notably, MEV Boost disrupts stake-proportionality, enabling some low-stake actors to gain outsized rewards and amplifying reward variance.

Though MEV Boost improves efficiency, it introduces fairness trade-offs. These findings point to a need for mechanisms like reward redistribution or MEV mitigation to ensure more equitable outcomes. Future work should explore protocol adjustments—such as changes to validator incentives or staking rules—to support long-term fairness and sustainability.

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Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT in order to: Grammar and spelling check, Paraphrase and reword. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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