A Framework for Blockchain-Based Augmented Reality to Ensure Content Integrity in Tanzanian STEM Education

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Abstract: **As Augmented Reality (AR) in Science, Technology, Engineering, and Mathematics (STEM) education is emerging, the problem of securing and verifying digital content is becoming a central challenge. This study proposes a blockchain-based augmented reality framework to improve the authenticity and security of educational content in Tanzania's STEM education system. The framework consists of five main components: a content submission portal, a blockchain ledger, a digital certificate of authenticity issuance system, a content verification system, an integrity check, and an access control system. Together, the system ensures that the content remains authentic. Moreover, algorithms are developed to hash the AR content and compare it against the hash of the content stored on the blockchain to verify the content before access is given. A set of experts was invited to validate the technical soundness, feasibility, and alignment with the centre's educational standards. Future work aims to improve the decentralization level of the framework and test the impacts of the platform on the academic outcomes of users in real-world settings.**

***Keywords*: Augmented Reality, STEM Education, technology Integration, Educational Innovation, Learning Outcomes**

I. Introduction

In Tanzania, the achievements in technological development, provision of educational services and sustainable production of goods and services are strongly linked to education in Science, Technology, Engineering and Mathematics (STEM) fields [1], [2]. Due to this fact, government has realized the importance of STEM field and various initiatives have been taken to encourage students for taking up STEM subjects [3]. Conversely, during the last decades students interest in STEM fields as well as their scientific literacy has been on a decline [4]. This low payoff risks the future economic development and technological progress of the country. STEM education is the core of a powerful, though nescient initiative in terms of educational interventions that are necessary to rejuvenate and fortify national standards as outlined by [5].

Augmented Reality (AR) manages to extend various benefits that learners associated with science, technology, engineering and math educational experiences [6]. AR can get scientific concepts from the abstract to the visual in a narrative way that imparts understanding. In a more specific example, AR can enable students to interact with 3D models of biomolecular structures in the case of proteins that cannot be seen in other ways and is an otherwise abstract concept given context[7]. These experiences can assits visual and spatial dimensions to learning, either in a lab or at home via the computer screen (or even an immersive space), creating collaborative, experiential environments that may boost student excitement about content areas.

Educational platforms, especially those using AR , stand to be challenged in a great deal if this kind of data becomes falsified or slanted to promote misinformation. Educational content must stand up to scrutiny, follow correct standards of education, and not mislead learners. The proliferation of AR-related educational platforms in recent years has made such environments vulnerable to unauthorized, incorrect content being inserted into these platforms, thus reducing the overall educational quality and reliability of these platforms and products [11,12].

Given the growing prospects of using AR applications to foster Tanzanian STEM education, the likelihood of encountering false or tampered content becomes more dire. This has the potential to compromise the educational value of AR by delivering false information to students, educators and other individuals who leverage AR for learning purposes. Along with the development of content, a practical and verifiable mechanism to authenticate AR content is needed to promote its reliability. This ability to verify the security of AR content is crucial in building confidence among students and educators to rely on the educational resource of choice to yield its desired educational outcomes.

Misleading educational content disseminated via AR could have detrimental effects on students. Recently, there has been growing research on the technical and pedagogical benefits of AR, and how it can foster effective learning through interactive and immersive experiences [6-10]. Yet, few of the studies put the spotlight on verifying the content of AR, thereby making it prone to unauthorized changes of content, manipulation of data, and missing proper mechanisms to validate information.

Also, apart from the fact that blockchain technology is widely introduced as an approach for creating immutable records [13-15], the case studies on AR content validation using blockchain for educational purposes have not yet fully explored. Although some studies have briefly introduced this application into specific emerging sectors in the digital era such as finance and supply chain [16, 17], there are few studies that have specifically investigated the use of blockchain to integrate with AR platforms to verify the validity of the educational content and its conformity with national education standards. This calls for the need of systematic framework to integrate AR and blockchain to ensure the validity of the AR based educational resources.

The study's objectives is to address the following research questions.

1. What are the critical design components for developing a blockchain-based augmented reality (AR) platform for STEM education in Tanzania?
2. How can a blockchain-based algorithm be designed to ensure the integrity and verification of AR content in Tanzanian STEM education?
3. To what extent does the proposed blockchain-AR platform guarantee content integrity and educational outcomes?

This study contributes to the emerging area of educational technology that adopts innovative technologies such as blockchain to drive positive change in education. It proposes and validates a generalizable framework combining the capabilities of blockchain technology with those of AR to improve the authenticity and security of information in STEM educational content in Tanzania. This happens in the context of increasing concerns raised regarding the trustworthiness of digital learning materials that are being increasingly used in classroom teaching, especially in developing countries. Such a solution offers a practical, scalable means for leveraging blockchain's immutability to protect AR content from intentional alteration. The study contributes to the gap in the literature by providing integration of AR and blockchain in an educational context, which offers a generalizable and practical approach to increasing the trustworthiness of digital educational content.

The rest of the paper is structured as follows: Section 2 provides an overview of augmented reality and blockchain technology. Section 3 presents the methodology used in the study. Section 4 presents the proposed framework. Section 5 discusses the findings of the expert validation. Section 6, and the study concludes with a conclusion and future work in Section 7.

II. AUGMENTED REALITY AND BLOCKCHAIN TECHNOLOGY

2.1 Augmented Reality

Augmented Reality (AR) enables students to truly grasp complex concepts by virtually bringing them to life. AR technology has become an indispensable tool in education, especially in the STEM fields, as it is helping children understand concepts through interactive and immersive learning experiences [2,3]. AR overlay or mixed reality is a technology that superimposes digital information, like images, videos and 3D models, over real-world environments to create a blended learning experience that engages students [4].

AR has been shown to be highly effective in teaching abstract concepts to students [18] provides an excellent summary of the current landscape of AR applications in educational contexts across several disciplines and in the domain of science. AR has been shown to make scientific phenomena more transparent and more effective by visualizing abstract concepts [19]. For instance, it has been used to understand better different biological structures – from cellular structures to structural systems of anatomical systems [20]. Researchers such as [21] have demonstrated that using AR can support students' spatiotemporal reasoning and conceptual understanding through interacting with 3D models in an AR environment.

The AR makes it easier for studies to be more interactive with students at the same time maintaining their interest and enjoyment [7]. AR can keep interest and motivation by offering students with engaging environments [22]. Augmented reality adds a real-time component with features gamification elements. In simple terms, AR has the power of turning passive learning into active, participatory ones. Applications of AR in physics education also help in improving motivation of students and their problem-solving skills showing that students interact with abstract physical concepts. Another example is the AR computer-mediated touchable simulations in Physics [23], which showed how students can interact with abstract physics phenomena yet visible and tangible.

AR can support collaborative learning by allowing an entire team to work in shared virtual spaces by adding virtual objects into the physical environment, and they can act collectively by interacting with these in an immersive and naturalistic way. For example, [24] found that AR applications can facilitate group activities and that students can collectively interact with a shared visualization of the real world, sharing problems or searching for pieces of information together.

An important area for exploration is content authenticity. It's important to consider the content that AR provides. Given the inevitability of AR in education, the chances of education being influenced by false or inaccurate AR content are notable. The chances of such things happening are likely to be more than once in a lifetime. How researchers deal with the question of content authenticity needs to not be as good as up spreading AR content that false, which will not of content authenticity should be considered in AR. What mechanisms of providing content authenticity must be developed to avoid content that is misinformed or simply false?

2.2 Blockchain Technology

Blockchain is a decentralized digital ledger, which tracks transactions grouped in a block, chained and secured by cryptographic hashes - which are each a unique digital signature that can be produced by hashing the contents of every block – including its reference to the hash of the previous block [25]. Since you can't reference the preceding block without knowing its hash, the immutability of any previous block assures the immutability of the entire chain.

The lack of centralization is maintained by means of a consensus mechanism used to validate and confirm transactions. In proof-of-work, for example, miners are incentivized to validate and add a new block to the chain by competing to solve complex cryptographic problems [26]. A miner that solves the problem first and adds their block to the chain is then rewarded by the network participants (i.e., the other miners). Once validated, the blockchain is updated with the new information. Verification of the consensus process is achieved through means of decentralization, eliminating the need for a central authority [27].

The first block in a blockchain is called the genesis block since it is the very first one in the chain, there is no previous block that it references. This seed block then allows a chain to be built on top of it. All other blocks reference the block that came before them through the block's block header. The block header is an essential part of a block, and it contains a lot of fields that are vital for keeping the chain secure and unbroken. One of those fields is the version number, which represents the current version of the blockchain protocol being used. It's so crucial that implementations or upgrades of the blockchain protocol must keep them compatible. One of the most critical of those fields is the previous block's hash, which is created by cryptographically hashing the previous block's header to create a chain of blocks that prevents modification of a single block. If a block is modified, all subsequent blocks would need to be changed, which would entail the use of different (newer) hashes [28].

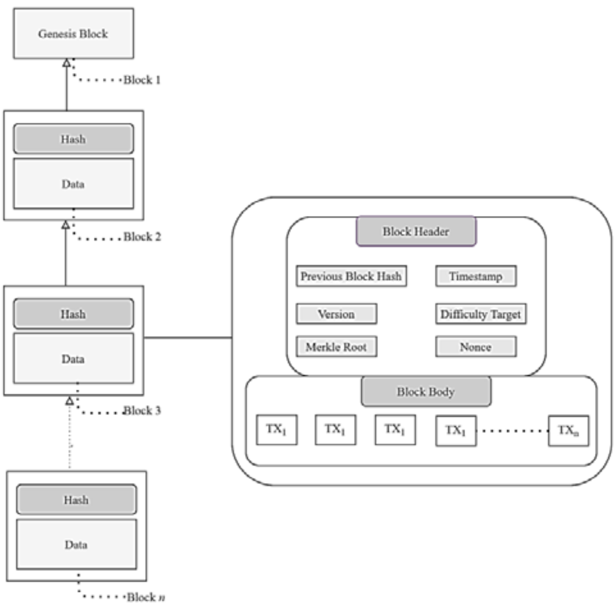

Fig. 1. Blockchain Technology

The hash of all transactions in the block (which is called a Merkle root) is provided in the block header as well. The Merkle root is derived from a Merkle tree, in which transaction hashes are paired and then hashed iteratively until a single hash remains. The Merkle tree makes verifications efficient and secure. The next piece of data is the timestamp of when the block was created. The temporal information maintains the chronological order of the blocks in the chain. The difficulty target is a parameter that determines how difficult or costly it is for the necessary proof of work to arrive. The fields in the block header are varied to compute the hash –-coin. These are just systems that might vary one or over again until valid.

Blockchain technology can provide more innovative solutions in the educational field. For example, it can securely record educational qualifications, degrees and certificates to enhance credential verification, minimize fraud and simplify the verification process for employers and institutions [29]. Blockchain can also be used to manage academic records such as grades and transcripts and authenticate their validity while making it impossible for anyone to modify them.

III. METHODOLOGY

The study follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2015 checklist to ensure the methodological quality and process transparency of the review [30]. In the review, all the data were guided by the inclusion of peer-reviewed articles, conference proceedings, and books published between 2014-August 2024 that were on educational technology adoption in Tanzania, blockchain technology, and AR for education, as long as the information is written in the English language. It is essential to mention that any other sources of non-peer-reviewed works, outdated works, and written materials not in the English language were excluded from this systematic literature review.

A search was made in major electronic databases, including Scopus, Web of Science and IEEE Xplore, using a set of keywords consisting of synonyms and controlled vocabulary terms connected by Boolean operators. The search terms included 'blockchain', 'augmented reality', 'content integrity', 'STEM education' and 'educational technology'.

Two reviewers evaluated the titles and abstracts according to the inclusion and exclusion criteria described previously and retrieved the full texts of all possibly eligible articles and resolved any disagreements through discussion. The data were extracted from the studies according to preset criteria so that they could be archived and analysed.

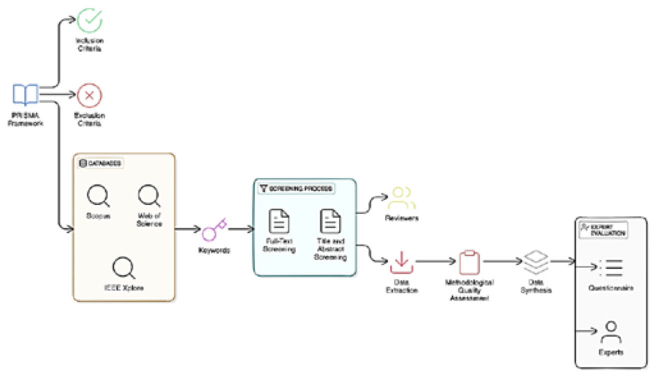

Fig. 2. Methodology employed in this study

Methodological quality was appraised. For qualitative studies, the assessment of critical indicators was the precision and clarity of the research questions, the appropriateness of the data collection methods in achieving the research objectives, and the extent to which data analysis was conducted. For quantitative studies, the methodological appraisal included the rigor and strength of the study design, the transparency in the selection of the participants' sample size, and the suitability of the statistical methods of data analysis.

Thematic analysis was used to synthesise data that involved systematically identifying and interpreting key findings across the included studies. NVivo software was used as a tool to code data and organize data extracted from full texts and abstracts of the selected studies. The thematic synthesis helped identify themes and patterns related to the integration of blockchain and augmented reality in enhancing content integrity in Tanzanian STEM education.

A panel was formed to review and validate the proposed framework to integrate blockchain technology with augmented reality to develop reliable content for STEM education in Tanzania. The panel members were selected based on their specialization and relevance to the various elements of the framework for the proposed project (Table 1).

The steps of the validation process were as follows:

1. Expert Selection: An expert panel was formed, including experts with specialized expertise pertinent to the different components of the framework (Table 1).

2. Presentation of the Framework: Each expert was presented with the framework, including its components and underlying algorithm.

3. Framework evaluation: Experts judged the framework on criteria that included technical robustness and feasibility, as well as compliance with local and national standards and the likelihood of implementation.

4. Feedback: Feedback was gathered, followed by discussions to clarify the feedback and address any doubts.

Table 1: Experts used in framework validation

Expert	Role	Organisation	Location
1	Educational Technology Specialist	Institute of Rural Development Planning (IRDP)	Dodoma, Tanzania
2	AR and Blockchain Integration Specialist	Tech Innovators Ltd.	Mwanza, Tanzania
3	STEM Education Consultant	Growth Solutions Inc.	Arusha, Tanzania
4	Industrial Technology Researcher	Tanzania Investment Center	Dar es Salaam, Tanzania
5	Educational Policy Advisor	Tanzania Chamber of Commerce, Industry and Agriculture	Dar es Salaam, Tanzania
6	ICT Policy and Regulation Analyst	Ministry of Information, Communication, and Information Technology	Dodoma, Tanzania
7	STEM Education Researcher	The University of Dodoma	Dodoma, Tanzania
8	Blockchain Technology Analyst	The University of Dodoma	Dodoma, Tanzania
9	Technology-Enhanced Education Specialist	The University of Dar es Salaam	Dar es Salaam, Tanzania
10	STEM Educator	The University of Iringa	Iringa. Tanzania

IV. THE PROPOSED FRAMEWORK

The proposed framework is designed to provide a cycle of assurance for AR educational assurance content to ensure the integrity of such content in educational spaces by leveraging blockchain technology. It includes five components: Content Submission Portal for a first-level content review and metadata collection; Blockchain Ledger for immutable recording; Digital Certificate Issuance System for the registration and validating registration of such certificate; Content Verification System for integrity verification; and Integrity Check and Access Control System for content accessing controlling for the verification results of the Content Verification System.

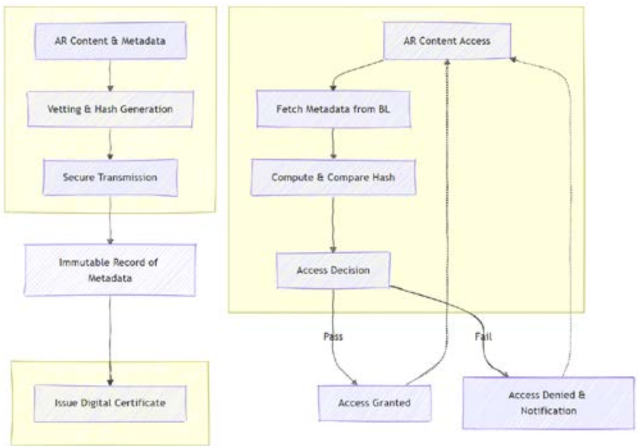

Fig. 3. The proposed framework

1. *Content Submission Portal (CSP)*: This component receives uploaded AR content along with associated metadata. It initially attempts to vet the quality and educational standards of the object and generates a unique identifier along with a cryptographic hash for the content using a hashing algorithm. The portal ensures secure transmission to the blockchain ledger. The CSP is the point of entry for all AR content and enforces quality and educational standards in this way. Every time the hash of the content is recalculated, it will match the one generated when the content was first uploaded to the blockchain. This is important because the

object is not stored on the blockchain. It is just referred to.

2. *Blockchain Ledger (BL)*: Records the metadata bundles of AR content. Each metadata bundle includes an identifier (which could serve as an indicator to identify a specific asset), the cryptographic hash of the content, and other related metadata. The records stored in the blockchain ledger are immutable and cannot be changed or removed without permission. The blockchain ledger ensures the integrity of the metadata in a tamper-proof environment. The recorded metadata of AR content will be unchangeable or erasable in the future, which will help to ensure the authenticity of the AR content.

3. *Digital Certificate Issuance System (DCIS):* After successful registration of AR content on the blockchain, it issues a digital certificate or token to the content creator, which includes the AR content identifier, content hash, and timestamp of registration. Digital certificate serves as proof that registration successfully took place for content creators, and end-users accessing content services can use certificates to verify content authorship, adding a layer of trust and validation to both content creators and end-users.

4. *Content Verification System (CVS):* When a piece of AR content is accessed, the CVS fetches the pertinent metadata from the blockchain. The hash of the current version of the content is then computed and compared with the stored hash, thus proving the integrity of the content. Without the CVS, anyone could easily modify the original piece, injecting their stuff and creating confusion.

5. *Integrity Check and Access Control (ICAC) System:* The ICAC system decides whether to allow or not allow access to AR based on the integrity check results. Contents that pass the integrity check can be accessed, and the ones that fail are flagged or reported, and users can be notified. The ICAC system is the access management component of the content distribution system, which makes decisions for access based on content integrity. It plays a vital role in the trust-building mechanism of the content distribution system.

V. PROPOSED ALGORITHM

4.1 Proposed Algorithm

The algorithm that accompanies the submitted AR content and verifies the integrity check and authenticity is explained in detail below. Content creators submit the AR content, which consists of multimedia elements and metadata, to the centralized portal. The portal subjects it to an initial review and states the form of compliance with domain-specific quality control and educational relevance standards. The portal then generates a unique identifier and a cryptographic hash; together, they form a metadata bundle. These are recorded on a blockchain ledger, which is immutable and protects the reference content from any future tampering. This automatically generates a digital certificate that the content creator/controller receives.

The system uses the hash and metadata of AR content stored on the blockchain to verify it when access is requested. The system computes a hash of the accessed object to be checked against the hash stored in the blockchain. If these checksums match, the authenticity of the AR content can be verified by users, and the content can be accessed. If these checksums do not match, the content can be flagged and reviewed, and access can be denied to users who are informed of potential integrity problems. This ensures, in turn, that the integrity of AR content is systematically guaranteed during content distribution by using the tamper-proof qualities of blockchain to prevent fake or unauthorized content from being disseminated.

1. **Content Submission:**

   - **Step 1.1:** The content creator composes the AR content, which consists of multimedia components such as 3D models and animations, as well as supplementary metadata, including educational descriptions and author credentials. Let C denote the AR content and M the associated metadata.

   - **Step 1.2:** The content creator transmits C and M to a centralised submission portal, denoted as P, for an initial evaluation.

2. **Initial Review and Metadata Collection:**

   - **Step 2.1:** The portal PPP performs an initial assessment of C based on predefined quality standards Q and educational relevance criteria R. Let $Q(C)$ represent the evaluation function for quality and $R(C)$ the evaluation function for significance.

   - **Step 2.2:** Following the review, P generates a unique identifier ID and computes a cryptographic hash H of C. The metadata M is augmented with ID and H, forming a metadata bundle M'. This metadata bundle M' is then prepared for registration on the blockchain.

3. **Blockchain Registration:**

   - **Step 3.1:** The metadata bundle M', containing ID and H, is recorded onto the blockchain ledger B. The entry $E = (ID, H)$ serves as an immutable reference to C. The blockchain operation is denoted as $B.Record(E)$, where B is the blockchain, and E is the metadata entry.

- **Step 3.2:** The content creator is issued a digital certificate σ or token confirming the successful registration of C on B. The certificate σ includes ID, H, and a timestamp T, indicating the registration time.

4. Content Verification:

- **Step 4.1:** When C is accessed, the system retrieves the metadata M' from the blockchain ledger B. The system extracts ID and H from M' and uses them for verification.

- **Step 4.2:** The system calculates a new hash $H_{current}$ of the accessed version of C. It compares $H_{current}$ with the stored hash H retrieved from M'. The verification function is denoted as $V(C, H)$, where V compares $H_{current}$ with H.

Figure 4 below depicts the algorithm pseudocode.

```
Algorithm ContentSubmissionVerificationIntegrityCheck

Input: ContentCreator, ARContent, Metadata

Output: VerificationStatus


// Step 1: Content Submission

SubmitContent(ContentCreator, ARContent)

GenerateMetadata(ARContent) -> Metadata

RegisterMetadataOnBlockchain(Metadata)


// Step 2: Blockchain Registration

Function RegisterMetadataOnBlockchain(Metadata):

    BlockchainRecord =
CreateBlockchainRecord(Metadata)

    Blockchain.Add(BlockchainRecord)

    Certificate = IssueDigitalCertificate(Metadata)

    Return Certificate
```

Fig. 4. The algorithm pseudocode

5. Integrity Check and Access:

- **Step 5.1:** If $H_{current} = H$, the content C is confirmed to be authentic. The system grants access to users based on the verification result. This decision process can be described as:

$$Access = \begin{cases} Granted, & H_{current} = H \\ Denied, & otherwise \end{cases}$$

- **Step 5.2:** If $H_{current} \neq H$, the content C is flagged for review. Users are notified of potential integrity issues through a notification system.

VI. FRAMEWORK VALIDATION

As summarized in Table 2, the expert panel provided the ratings on the proposed framework based on the four metrics namely: Technical robustness, feasibility, alignment with national standards, and implementability.

The framework scored well on *technical robustness*, which considered the technology (including the use of the blockchain) and whether it could ensure integrity of the content. Most experts rated this as good and scored it between 4 and 5. However, several experts did highlight the need for this aspect to be further scaled to allow for more content and users.

Table 2: Expert validation results

Expert	Technical Robustness	Feasibility	Compliance with Educational Standards	Implementation Potential
Expert 1	4/5	4/5	5/5	4/5
Expert 2	5/5	3/5	4/5	4/5
Expert 3	4/5	4/5	5/5	4/5
Expert 4	4/5	4/5	4/5	3/5
Expert 5	3/5	5/5	4/5	4/5
Expert 6	5/5	3/5	5/5	4/5
Expert 7	4/5	4/5	5/5	5/5
Expert 8	5/5	4/5	5/5	5/5
Expert 9	4/5	5/5	4/5	4/5
Expert 10	4/5	5/5	4/5	3/5

Feasibility scores were more varied, but essentially, it was a consensus that while they were feasible and 'applicable, ' there were some improvements to be made. Some comments pointed out that while the framework is generally achievable, 'there is still room for improving the user interface design as well as system integration to make the system more usable'.

Regarding educational standards, the responses generally indicated that their high rankings were consistent with the specific requirements and standards outside the classroom for STEM education topics and content. The framework was noted for its ability to meet these standards.

The *implementation potential* also received strong endorsements, with scores indicating confidence in the use of the framework in real-world settings.

VII. DISCUSSION

The proposed framework is designed to allow the possibility of blockchain-enabled AR for securing STEM content in Education. The framework consists of a process model involving content submission, blockchain registration and validation. The associated algorithm commences with the submission of AR content and metadata to a central portal. Such a step involves further initial review and generates a unique identifier and cryptographic hash, which is then fixed onto a blockchain ledger. This ledger offers immutability for every entry through timestamping and decentralized blocks. Consequently, any changes or alterations made to the content of AR can be easily detected. The framework algorithm scores the authenticity of AR by comparing hashes on access, thus maintaining integral educational materials.

The integrity of the content is guaranteed largely by the blockchain-AR platform using the immutable ledger of blockchain, its hash function and cryptographic hashing. This is only possible as blockchain technology is decentralized, and after AR content is recorded in the network, it cannot be tampered with or modified. The verification of the integrity of content by comparing the hashes during the access of the AR content catches the tampering with the content immediately. So, the educational content is secure and reliable when generated and used during the life cycle of the system. However, the guarantee for educational outcomes is on the other side as it would depend on different factors, such as the quality of the content and alignment with the educational content.

The key strength of the framework developed here is the use of blockchain technology to protect AR content from tampering or permanent unauthorized changes. By keeping the metadata on a blockchain ledger which records cryptographic hashes of the AR content, we can provide a high degree of security. STEM educators can be confident that educational resources are not tampered with or corrupted in any way. However, the framework does have limitations. One significant limitation is the requirement for a centralized portal for the first-level review and metadata generation. This centralization creates a single point of failure risk for the robustness and scalability of the framework. This limitation could be alleviated by incorporating decentralized review mechanisms or additional redundancy into the framework.

In this framework, by integrating the concept of blockchain technology with AR, it develops on top of previous studies that are more abstract or less integrated. Previous research has examined the potential of blockchain in the educational context by addressing the issue of content verification. For example, Sharma et al. (2020) and Singh et al. (2021) have proposed the idea of using blockchain technology to verify content but did not fully conceptualize how this technology could be utilized alongside AR, nor did they thoroughly address the practical implementation issues of the system. The framework proposed here offers a more systematic approach to the problem of reliable educational content by the utilization of blockchain's secure ledger together with AR's add-on technology to provide an interactive experience for users. This is a distinctive contribution of this framework as it builds on previous research to fill gaps while also proposing a more robust system than earlier work.

The integration of blockchain with augmented reality in the proposed framework has policy implications for the management of educational content and the assurance of its quality. Policy-wise, the adoption of blockchain could mean that current laws and regulations would have to be adapted to include blockchain standards for the automatic verification and secure storage of content. This might consist of revised guidelines requiring the use of blockchain technology for the recording and verification of educational resources and the creation of the necessary protocols for maintaining digital certificates and managing disputes or discrepancies when certifying content. This can lead to a protocolized framework for deploying and regulating the use of blockchain technologies for educational purposes.

Practically, this framework offers a robust solution for content security and integrity in STEM educational content. Implementing the system could result in a higher level of trust and confidence in educational materials and the learning outcomes they support. For institutions, this could involve adapting to new technologies and processes to integrate blockchain and AR in a manner that ensures that educational content is being represented accurately and in line with the organization’s intended objectives. There may be a need to train staff on these new processes and potentially adapt content management workflows. However, the net benefit of increased security and integrity of content is worthwhile, because the tamper-free record of educational materials could also serve the overarching educational goal of ensuring that the learning resources being provided to students are of high quality and credibility.

VIII. CONCLUSION

The proposed blockchain-based AR framework for STEM education in Tanzania addresses an important issue in public education, which is the trustworthiness and reliability of educational content. Incorporating blockchain technology enables this platform to offer users a secure and tamper-proof approach to verifying AR content, thus preventing potential alteration of educational materials and enhancing the trustworthiness of digital educational resources. This framework also offers the potential for issuing digital certificates to content creators, which can improve the degree of trust between teachers and students. The above security framework has been implemented technically and is feasible to be deployed.

Moving forward, it is crucial to build upon this framework and enhance its scalability and decentralization to reduce the risk of a single point of failure truly. For example, the inclusion of decentralized review mechanisms or even distributed portals for submissions could help mitigate these limitations and further strengthen the framework in the future. Another important and researchable area would be the examination of the true effectiveness of the platform in improving actual learning outcomes in the classroom. Future research needs to focus on how the integration of blockchain and AR in STEM education impacts learning outcomes and engagement from students, as well as the change in academic performance brought about by this new paradigm in education. Moreover, it would be valuable to extend the proposed framework to support a wider variety of content types that differ from the current educational domain under consideration.

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