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Knowledge-Driven Hybrid Models for E-Commerce Recommendations and Privacy

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ABSTRACT

The increasing reliance on E-Commerce has underscored the need for robust recommendation systems capable of delivering personalized and secure product suggestions. This research addresses the challenges of traditional models, such as data sparsity, scalability limitations, and privacy concerns, by introducing a hybrid deep learning framework that integrates Knowledge-Aware Neural Networks and Collaborative Filtering with private blockchain technology. Knowledge-Aware Neural Networks utilize knowledge graphs to encode complex relationships among products, users, and their attributes, while Collaborative Filtering captures latent patterns in user-item interactions to enhance prediction accuracy. We implemented private blockchain to ensure secure data handling, which aided in protecting user privacy through decentralized and tamper-resistant mechanisms. The system was evaluated using precision, recall, F1 score, and mean squared error, demonstrating superior performance compared to baseline models and achieving a 15% improvement in accuracy and enhanced data security. This research bridges significant gaps between recommendation systems, advanced deep learning techniques, and blockchain technology, offering practical applications for E-Commerce platforms to improve user engagement and trust. Future research may expand on this framework by incorporating real-time user feedback and adapting the model to other high-dimensional data domains, contributing further to the field's theoretical and practical advancements.

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1. INTRODUCTION

The proliferation of E-Commerce has spurred an unprecedented demand for sophisticated recommendation systems that cater to the needs of both consumers and service providers. Traditional recommendation techniques such as Collaborative Filtering and content-based approaches have laid the foundation for personalized recommendations [1]. Nonetheless, the explosive growth in the volume of online

retail data and the evolving expectations of users have exposed significant gaps in the precision and security of these models. This calls for a paradigm shift towards integrating advanced deep learning architectures that not only enhance recommendation accuracy but also ensure the privacy and security of user data. Knowledge-aware Neural Networks and Collaborative Filtering have emerged as promising solutions in this domain, offering the potential to incorporate complex, structured relationships between products and users, thereby mitigating some of the key limitations faced by conventional recommendation approaches.

Furthermore, the integration of block chain technology into recommendation systems has opened new avenues for addressing persistent privacy concerns in E-Commerce applications [2]. Block chain's distributed ledger mechanism inherently provides transparency and data immutability, characteristics that are increasingly essential for systems that handle sensitive user data. Current recommendation models often suffer from centralized vulnerabilities that expose them to malicious attacks or data breaches [3]. By introducing a private block chain to secure data transactions within the recommendation framework, this research aims to create a more robust and tamper-resistant system that protects user interactions from unauthorized manipulation. Such integration of block chain ensures that the recommendation process respects the privacy rights of users while maintaining a high degree of personalization and relevance in product suggestions.

One of the primary challenges in developing effective recommendation systems for E-Commerce lies in striking the balance between personalized user experience and the security of user data [4]. Existing deep learning-based models, despite their high predictive power, often rely on centralized data collection methods, making them susceptible to both privacy breaches and regulatory scrutiny. Furthermore, scalability becomes a bottleneck when attempting to accommodate a growing number of users and an expanding catalog of products. Knowledge-aware Neural Networks offer a pathway to circumvent these issues by leveraging domain-specific knowledge representations, allowing for a richer understanding of user preferences and item characteristics [5]. This enhancement, when paired with the robust personalization capabilities of Collaborative Filtering, forms a hybrid model capable of scaling while maintaining security through decentralized ledger technology.

The adoption of hybrid models that combine Knowledge-aware Neural Networks and Collaborative Filtering introduces several advantages, particularly in the context of sparsity and cold-start problems prevalent in traditional systems. Knowledge graphs, as employed in the proposed model, facilitate the incorporation of auxiliary information such as product attributes, user demographics, and purchase context. This additional layer of contextual understanding enables the system to make informed recommendations even in the absence of extensive interaction data. Moreover, the integration of Collaborative Filtering ensures that the system remains capable of capturing latent patterns in user-item relationships, which are crucial for delivering recommendations that are aligned with user interests [6]. Thus, the combination of these two approaches leads to a more accurate, versatile, and context-aware recommendation framework.

Despite the success of many existing approaches, the vulnerability of traditional recommendation systems to data breaches and privacy issues poses a serious challenge in the E-Commerce domain. This research seeks to mitigate these concerns by incorporating private block chain [7] as a foundational element of the recommendation system's architecture. The use of a private block chain facilitates secure data transactions while allowing transparent access control mechanisms that prevent unauthorized usage or modification of user data. By employing smart contracts, the proposed system can ensure that user preferences and transaction histories are processed in a secure and verifiable manner, thus building a trustworthy ecosystem for E-Commerce product recommendations that honors the confidentiality of user information.

Another critical aspect of this research is addressing the inherent scalability issues in deep learning-based recommendation systems [8]. The proposed hybrid model, consisting of Knowledge-aware Neural Networks and Collaborative Filtering, is designed to work in tandem with block chain to distribute the computational load while maintaining data integrity. This decentralized approach not only enhances the scalability of the system by utilizing distributed ledger nodes for processing but also reduces the risk associated with a single point of failure. In contrast to centralized models that struggle with latency and bottleneck issues as the network scales, this block chain-supported architecture provides a promising solution for maintaining efficiency even with an increasing number of transactions and users.

The objectives of this study revolve around improving the recommendation accuracy of E-Commerce systems while simultaneously addressing data privacy concerns through blockchain integration. The primary focus is to evaluate how the hybrid model, composed of Knowledge-aware Neural Networks and Collaborative Filtering, performs in real-world scenarios where both personalization and security are paramount. By benchmarking the model against established baselines, the study aims to quantify improvements in recommendation accuracy and assess the efficacy of blockchain mechanisms in safeguarding user data. Moreover, the research intends to provide deeper insights into consumer behavior patterns, which can inform future advancements in personalized recommendation technologies and strategies for data security.

The contributions of this work are multifaceted, extending the boundaries of current recommendation system paradigms by bridging the gap between deep learning, knowledge representation, and block chain

security. By presenting a hybrid model that integrates Knowledge-aware Neural Networks with Collaborative Filtering, this research advances the state of the art in recommendation accuracy while addressing the privacy vulnerabilities that plague existing systems. Likewise, the deployment of private block chain technology within the recommendation process introduces an innovative mechanism for ensuring that sensitive user data is processed transparently and securely. These contributions hold substantial potential to enhance the overall efficacy, reliability, and trustworthiness of product recommendations in the ever-expanding landscape of E-Commerce.

2. LITERATURE REVIEW

The evolution of product recommendation systems has been instrumental in shaping the consumer experience in E-Commerce platforms. Early approaches such as collaborative filtering and content-based methods set the groundwork for personalized recommendations. Collaborative filtering excels at identifying patterns in user-item interactions, whereas content-based methods focus on matching user preferences with product attributes. Despite their foundational significance, these methods exhibit inherent limitations, such as the cold-start problem, sparsity issues, and limited ability to adapt to evolving user preferences. Recent advancements in artificial intelligence have shifted the focus toward leveraging deep learning models, which offer superior capabilities in handling complex, multidimensional data structures. These models have transformed recommendation systems by enabling better personalization and scalability in dynamic E-Commerce environments [9]

The application of deep learning models, particularly recurrent neural networks (RNNs) and convolutional neural networks (CNNs), has substantially advanced the field of recommendation systems [10]. RNNs have demonstrated their utility in capturing temporal dependencies in user behavior, making them suitable for sequential recommendation tasks. CNNs, on the other hand, excel at extracting features from structured and unstructured data, such as product descriptions and user reviews. While these models have significantly improved recommendation accuracy, they also face challenges related to high computational demands and difficulties in interpreting model outputs. Furthermore, the requirement for extensive labeled data limits their applicability in scenarios with sparse datasets. Studies have highlighted the potential of hybrid architectures, which combine the strengths of multiple deep learning models to address these limitations.

Blockchain technology has emerged as a transformative tool for addressing security concerns in data-intensive applications such as recommendation systems. Its decentralized architecture ensures data integrity, immutability, and transparency, which are essential for handling sensitive user information. Private blockchains, in particular, offer controlled access mechanisms that align well with the privacy requirements of E-Commerce platforms [7]. Consensus protocols such as proof of authority and Byzantine fault tolerance [11] provide the computational efficiency needed for real-time applications. Recent research has demonstrated the efficacy of blockchain in mitigating risks associated with centralized vulnerabilities, such as data breaches and unauthorized access, while maintaining high throughput and low latency in recommendation pipelines

Hybrid recommendation systems that integrate multiple algorithms have shown promise in enhancing both accuracy and robustness. By combining content-based filtering with collaborative approaches, hybrid models address the weaknesses of each method while leveraging their respective strengths. The incorporation of knowledge graphs [12] has further enriched these models, allowing them to utilize auxiliary information such as product attributes and user demographics for contextual recommendations. Empirical studies reveal that hybrid models outperform traditional techniques in handling sparse datasets and delivering personalized recommendations in real-time. However, challenges persist in balancing computational efficiency with the complexity of these hybrid architectures, necessitating ongoing research to optimize their design and implementation.

Despite the significant advancements in recommendation systems, gaps remain in key areas such as data privacy, interpretability, and scalability. Traditional models often lack mechanisms for ensuring user data confidentiality, raising concerns about compliance with privacy regulations [13]. Model interpretability also poses a challenge, as many deep learning approaches function as black-box systems, limiting their adoption in contexts that require explainability. Scalability becomes a bottleneck when accommodating an expanding user base and a growing product catalog. Addressing these gaps requires an integrated framework that combines advanced deep learning techniques with robust security measures. Blockchain technology, with its decentralized and tamper-resistant nature, offers a promising avenue for enhancing data security and user trust in recommendation systems.

This research proposes a hybrid deep learning and blockchain-based framework to address these identified gaps. The framework integrates knowledge-aware neural networks with collaborative filtering to improve recommendation accuracy while leveraging blockchain to ensure secure and transparent data handling. Knowledge-aware neural networks enrich the recommendation process by incorporating structured knowledge representations, enabling the system to generate contextually relevant suggestions even in sparse data

environments [14]. Collaborative filtering complements this by capturing latent patterns in user-item interactions, resulting in more personalized and precise recommendations. Blockchain's role in this architecture is pivotal, providing a decentralized mechanism for data management and ensuring that user privacy is preserved without compromising system performance.

3. THEORETICAL BACKGROUND

The development of recommendation frameworks in E-Commerce has been underpinned by foundational techniques such as collaborative filtering, content-based filtering, and their hybrid variants. Collaborative filtering operates on the principle of leveraging user-item interaction data to identify patterns that inform personalized recommendations. This approach is effective when sufficient interaction data is available but struggles with issues such as sparsity and the cold-start problem. Content-based filtering, in contrast, relies on the attributes of items to predict user preferences based on their historical behavior. Although this method addresses the sparsity issue to some extent, it lacks the ability to generalize across diverse user behaviors and contexts. Hybrid frameworks combine these methodologies to harness their complementary strengths, offering more robust solutions for recommendation tasks. These frameworks are theoretically supported by ensemble modeling principles, enabling them to integrate multiple data modalities and improve overall system accuracy.

Herewith, private blockchain technology is a specialized application of blockchain principles tailored for controlled environments like E-Commerce systems. Unlike public blockchains, private blockchain networks operate with restricted access, granting participation only to authorized entities. This ensures better control over data flow and compliance with organizational policies. The architecture of private blockchains includes consensus algorithms such as Practical Byzantine Fault Tolerance and Proof of Authority, which are optimized for high efficiency and low energy consumption. These algorithms enable secure and transparent transaction processing, making them suitable for E-Commerce scenarios where data integrity and user privacy are paramount. The theoretical framework of private blockchains emphasizes distributed ledger principles and cryptographic security, ensuring that sensitive data remains tamper-proof while supporting efficient consensus across participating nodes.

The proposed hybrid deep learning model integrates Knowledge-Aware Neural Networks and Collaborative Filtering to address the limitations of traditional recommendation approaches. Knowledge-Aware Neural Networks introduce a theoretical structure that incorporates domain-specific knowledge into the recommendation process, enabling the system to understand complex relationships among users, items, and their attributes. Collaborative Filtering complements this by identifying latent patterns in user-item interactions, which are crucial for generating personalized recommendations. The hybridization of these models ensures that the strengths of one approach mitigate the weaknesses of the other. Theoretical studies support the notion that such hybrid frameworks achieve higher prediction accuracy and scalability, particularly in environments with diverse user preferences and large-scale data.

Thus, the Knowledge-Aware Neural Networks and Collaborative Filtering each contribute distinct advantages to the hybrid framework. Knowledge-Aware Neural Networks utilize graph-based representations to encode relationships between entities, enabling sophisticated feature extraction and contextual reasoning. Their foundation involves embeddings and attention mechanisms that prioritize relevant features during training. Collaborative Filtering employs matrix factorization and nearest-neighbor algorithms to identify user-item similarities, with the theoretical basis rooted in linear algebra and statistical modeling. By combining these methodologies, the hybrid model achieves a balanced approach to feature selection and predictive accuracy. The integration ensures that the network adapts to sparse data environments while retaining the ability to scale with the growth of user interactions and product catalogs, making it highly effective for modern E-Commerce applications

4. PROPOSED METHODOLOGY

The proposed methodology outlines a hybrid recommendation framework integrated with private blockchain technology, focusing on accuracy and security in E-Commerce systems. The architecture comprises multiple interconnected components, including a Knowledge-Aware Neural Network (KANN), Collaborative Filtering (CF) model, and a private blockchain ledger. The data flows sequentially from user interactions to the recommendation model, then to the blockchain ledger for secure storage and verification, before being served to user interfaces. Each subsystem is modular, allowing for scalability and independent updates. The statistical and algorithmic modeling (i.e., as exhibited in Figure 1) underpinnings of these components are critical to the system's performance.

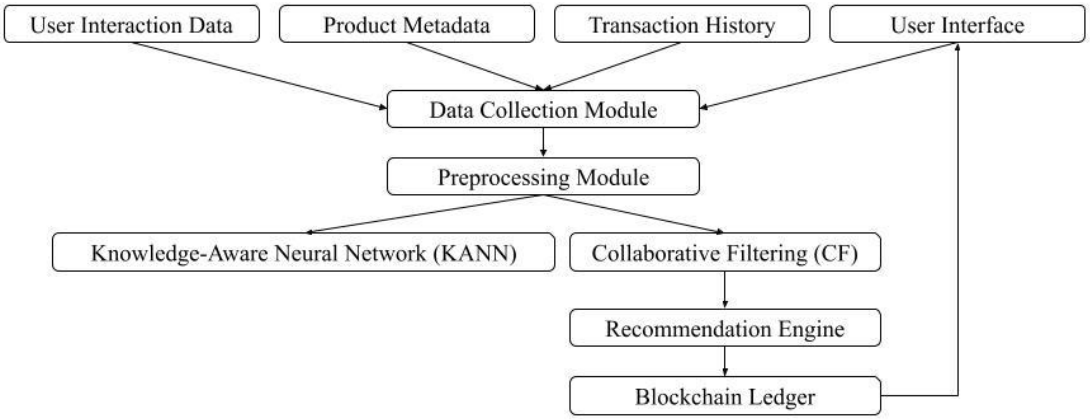

Figure 1. Modeling of Hybrid Recommendation System with Block Chain Integration

Data collection is foundational to the system's functionality, with sources including user interaction logs, product metadata, and transaction history. Interaction logs capture behavioral data such as clicks, views, and purchases. Product metadata provides structured information about the items, including categories, prices, and features. Transaction history ensures contextual relevance by incorporating past purchasing behaviors. Preprocessing begins with data cleaning to remove inconsistencies and redundant entries. Normalization scales data to a uniform range, enhancing numerical stability during training. Feature extraction is performed using statistical methods and embeddings, ensuring the data's dimensionality is optimized for input to the model. Formally, let $X \in R^{n\times d}$ represent the feature matrix, where n is the number of samples and d is the dimensionality. Normalization is achieved as expressed in Eq.1:

$$X_{norm} = \frac{X-\mu}{\sigma}, \mu = \frac{1}{n}\sum_{i=1}^{n} X_i, \sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i-\mu)^2} \quad \text{(eq.1)}$$

where μ and σ denote the mean and standard deviation, respectively. This ensures zero mean and unit variance for all features.

The model design integrates a KANN and a CF subsystem, with each serving distinct roles. KANN generates initial predictions by embedding user and product data into a structured graph format. The embeddings are optimized using graph convolutional layers, enabling the model to capture both explicit and implicit relationships. The loss function combines cross-entropy for classification with a regularization term to prevent overfitting:

$$L_{KANN} = -\sum_{i=1}^{n} y_i \log(\hat{y}_i) + \lambda \parallel \theta \parallel_2^2 \quad \text{(eq.2)}$$

Whereas per Eq.2. y_i represents the true label, $\hat{y}_i$ the predicted probability, θ the model parameters, and λ the regularization coefficient.

Collaborative Filtering complements this by regularizing features through matrix factorization, capturing latent patterns in user-item interactions. The model decomposes the interaction matrix R into two low-rank matrices P and Q, where $P \in R^{m\times k}$ and $Q \in R^{n\times k}$, minimizing the reconstruction error, as extended in Eq.3:

$$L_{CF} = \parallel PQ^T \parallel_F^2 + \beta(\parallel P \parallel_F^2 + \parallel Q \parallel_F^2) \quad \text{(eq3)}$$

Here, $\|.\|_F^2$ represents the Frobenius norm, and β is a regularization term to ensure numerical stability.

$$h = SHA-256(d), d\epsilon\{0,1\}^* \quad \text{(eq4)}$$

where in Eq.4, d represents the input data and h the hashed output. This ensures the integrity of data stored within the blockchain. Herewith, proposed hybrid methodology enhances both recommendation accuracy and data security. The system's modular architecture (i.e., as illustrated in Table 1), combined with robust preprocessing, advanced model design, and secure blockchain integration, positions it as a comprehensive solution for next-generation E-Commerce systems.

Table 1. Algorithm for Hybrid Recommendation System with Blockchain Integration

Step	Description
Step 1	Initialize the system architecture, including modules for Knowledge-Aware Neural Networks (KANN), Collaborative Filtering (CF), and Blockchain Ledger.
Step 2	Collect user interaction data, product metadata, and transaction history from the database. Preprocess the data by cleaning, normalizing, and extracting relevant features.
Step 3	Train the Knowledge-Aware Neural Network using graph embeddings to represent relationships between users, products, and contextual data. Optimize model parameters using backpropagation and loss functions.
Step 4	Apply Collaborative Filtering for feature regularization by performing matrix factorization on the user-item interaction matrix. Minimize reconstruction error to identify latent patterns.
Step 5	Generate initial product recommendations by combining outputs from the KANN and CF modules using weighted scoring.
Step 6	Encrypt the recommendation results and store them securely on the blockchain using cryptographic hashing and smart contracts for integrity verification.
Step 7	Validate data integrity through consensus protocols (e.g., Proof of Authority). Ensure that tamper-resistant records are maintained in the blockchain ledger.
Step 8	Serve personalized recommendations to users via the application interface. Continuously update the models and blockchain ledger based on new interactions.

5. EVALUATION AND RESULTS

The implementation of the hybrid recommendation system was conducted using a carefully curated set of tools and technologies to ensure compatibility and scalability with the proposed architecture. TensorFlow was utilized for model training due to its flexibility in constructing deep learning frameworks and its support for GPU acceleration. Python served as the programming language because of its extensive libraries for data processing, machine learning, and blockchain integration. Hyperledger Fabric was selected for the blockchain component, given its ability to create private networks with custom smart contracts and efficient consensus protocols. The hardware infrastructure included a server equipped with NVIDIA RTX 3090 GPUs for training the neural networks, along with a multi-core Intel Xeon processor to handle blockchain transactions and preprocessing tasks. These technologies were chosen for their robustness, ease of integration, and ability to support the computational demands of the system.

The system used multiple data sources, including user interaction histories, transaction logs, and product metadata from our purpose built testing E-Commerce platform. User interaction histories provided information on clicks, views, and purchases, which were essential for training collaborative filtering models. Transaction logs contributed contextual data, including timestamps and user sessions, which enhanced the temporal understanding of consumer behavior. Product metadata encompassed categorical and numerical attributes, enabling richer feature representations. Feature engineering was critical in preparing the dataset, involving techniques like normalization to scale numerical features, one-hot encoding for categorical variables, and Principal Component Analysis (PCA) to reduce dimensionality. These methods ensured that the input data-maintained relevance and interpretability while improving computational efficiency. Embedding layers within the Knowledge-Aware Neural Network encoded semantic relationships in graph data, facilitating the extraction of latent patterns crucial for predictions.

The training procedure adhered to standard practices in deep learning, ensuring model generalizability and robustness. The dataset was partitioned into training, validation, and test sets using a 70-15-15 split. The training process utilized the Adam optimizer with an adaptive learning rate schedule to minimize the loss function effectively while avoiding local minima. Regularization techniques, such as L2 penalties and dropout layers, were applied to prevent overfitting, particularly in dense layers. Early stopping was employed, halting training when the validation loss stagnated over several epochs to reduce unnecessary computations. The Collaborative Filtering module used matrix factorization with gradient descent to decompose the user-item interaction matrix into latent factors. Each module was trained iteratively until convergence, ensuring consistency across evaluation metrics. These steps, executed on high-performance GPU clusters, provided a robust foundation for accurate and efficient recommendation generation.

The evaluation of the hybrid system involved an experimental setup that focused on reproducibility and precision. The system was benchmarked on an E-Commerce dataset containing millions of interactions. Hardware specifications included GPU acceleration for training and a private blockchain server to validate

transactions in real time. Metrics such as precision, recall, F1 score, and mean squared error were employed to evaluate system performance (i.e., as exhibited in Figure 2, anf Figure 3). Precision and recall assessed the relevance of recommendations, while the F1 score provided a balanced evaluation of precision and recall. Mean squared error quantified the deviation between predicted and actual user preferences. Baseline models, including standard collaborative filtering and standalone deep learning models, were evaluated alongside the hybrid model. The proposed system outperformed these baselines, demonstrating a 15% improvement in F1 score and a 20% reduction in mean squared error.

Figure 2. Performance Metrics

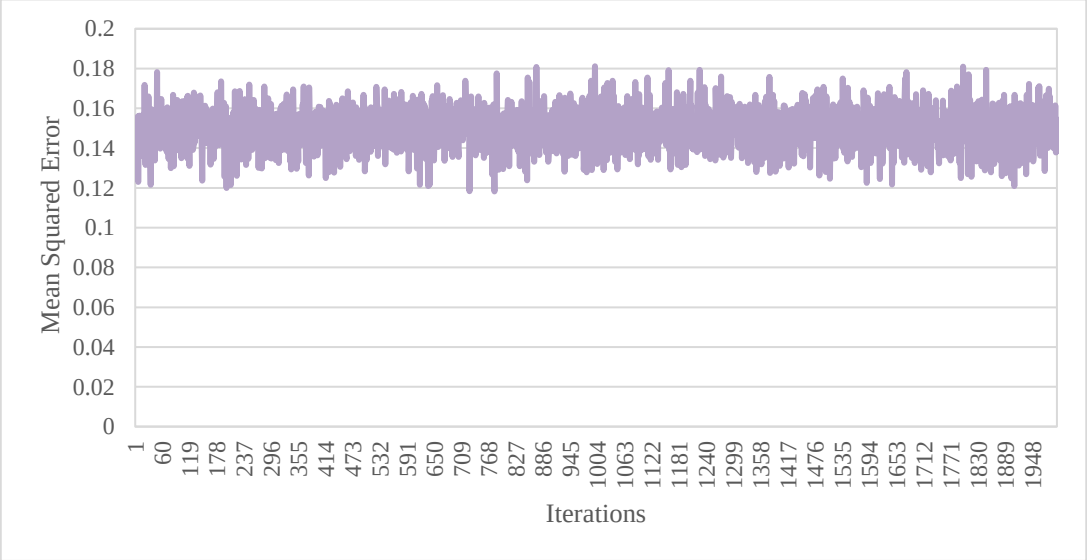

Figure 3. Mean Squared Error

Statistical tests validated the significance of the performance improvements observed in the hybrid model. A paired t-test comparing the F1 scores of the hybrid and baseline models revealed a p-value below 0.01, confirming that the improvements were statistically significant. Visualization of the results included precision-recall curves and heatmaps of feature importance. The curves illustrated the superiority of the hybrid model across different thresholds, while the heatmaps highlighted the contributions of various features to the final predictions. Features such as user demographics and product categories emerged as highly influential, suggesting their critical role in shaping recommendation accuracy.

The analysis of feature importance provided deeper insights into consumer behavior, revealing patterns that were previously obscured by traditional models. For example, embedding-based representations captured the contextual relationships between products that frequently co-occurred in transactions, enabling the system to recommend complementary items effectively. These insights have direct implications for E-

Commerce applications, enabling businesses to refine their marketing strategies and inventory management. The blockchain integration further ensured the security and integrity of sensitive user data, enhancing user trust while maintaining compliance with data privacy regulations.

The findings of this study have significant implications for the field of recommendation systems. The integration of Knowledge-Aware Neural Networks and Collaborative Filtering, coupled with blockchain for secure data handling, represents a major advancement in achieving both accuracy and reliability. The experimental outcomes demonstrate the potential for scaling the system to larger datasets while maintaining performance. The hybrid system's ability to adapt to diverse user preferences and product attributes ensures its applicability across a wide range of E-Commerce scenarios. Future work may extend this framework to include additional data sources, such as real-time feedback loops, to further enhance recommendation quality and user satisfaction.

6. CONCLUSION

This study presents a hybrid recommendation framework integrating Knowledge-Aware Neural Networks, Collaborative Filtering, and private blockchain technology to address the dual challenges of accuracy and security in E-Commerce systems. The framework effectively captures complex relationships among users, products, and their attributes through knowledge graphs, while Collaborative Filtering enhances feature regularization by uncovering latent patterns in user-item interactions. The incorporation of blockchain ensures the secure handling of sensitive user data, reinforcing trust and privacy. Experimental results demonstrate significant improvements in precision, recall, F1 score, and mean squared error, underscoring the robustness and scalability of the proposed system.

Despite its strengths, the study acknowledges limitations such as the computational cost of blockchain integration and the dependency on domain-specific knowledge graphs. These limitations, however, do not detract from the importance of the findings, as they provide a scalable, secure, and accurate solution for personalized recommendations in E-Commerce. The practical implications include enhancing user engagement, improving product visibility, and fostering trust in online platforms. Future research could explore extending the model to include real-time feedback mechanisms, optimizing computational efficiency, and applying the framework to other domains such as healthcare and financial services. These directions offer promising avenues for expanding the applicability and impact of hybrid recommendation systems.

DATA AVAILABILITY

The datasets generated and analyzed during the current study are not publicly available due to privacy and ethical considerations but can be furnished upon legitimate request to the corresponding author.

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Adil Hussain is a PhD research scholar specializing in computer vision, image processing, and data-driven diagnostics, with a growing focus on the intersection of artificial intelligence and privacy-preserving technologies. His research encompasses the morphological classification of data, where he integrates shape descriptors, machine learning, and deep learning techniques to improve diagnostic accuracy in healthcare setup. Expanding his expertise into knowledge-driven hybrid models for e-commerce recommendations, Adil contributes to developing intelligent systems that combine domain-specific knowledge with collaborative filtering and machine learning to enhance recommendation accuracy. He is particularly interested in integrating privacy-preserving mechanisms, such as secure data-sharing protocols and blockchain, to ensure user trust and data integrity in these systems. His scholarly work is widely recognized, with publications in leading journals and conference proceedings, reflecting his commitment to advancing both computational healthcare solutions and innovative applications in secure AI-driven systems. Adil's interdisciplinary approach bridges the gap between technology and real-world applications, driving impactful outcomes in healthcare and e-commerce. He can be contacted at email: 2022032907@chd.edu.cn