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A Blockchain-based smart waste management system framework for used cooking oil collection process

Kullanılmış yemeklik yağ toplama süreci için blokzincir tabanlı akıllı atık yönetim sistemi çerçevesi

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Abstract

Used Cooking Oil (UCO) has significant potential for biodiesel production recycling; however, its recycling is limited by the absence of smart waste management systems specifically designed for UCO. This article proposes a blockchain-based smart UCO collection platform aimed at UCO collection with real-time tracking. The platform features system architecture, UCO detection and classification modules, and a fuzzy inference system (FIS)--based decision support module for estimating UCO collection potential and calculating collection thresholds for smart garbage bins (SGBs). The proposed platform integrates various technologies and tools, including blockchain, IoT sensors, smart bins, cryptocurrency micropayments, gamification elements, and machine learning. A case study from Antalya is presented to showcase the FIS-based decision support module and the computation of collection thresholds. To the best of the authors' knowledge, this platform is the most comprehensive smart recycling solution presented in the literature for UCO, enhancing public awareness, increasing interaction, and motivating recycling through financial incentives.

Keywords: Sustainable biodiesel feedstock, IoT-enabled smart waste solutions, Cryptocurrency incentives, Fuzzy inference systems, Used Cooking Oil (UCO) collection, Blockchain, real-time tracking, smart garbage bin (SGB), smart waste management systems.

Özet

Kullanılmış Yemeklik Yağ (UCO), biyodizel üretimi için geri dönüşüm açısından önemli bir potansiyele sahiptir; ancak, UCO'ya özel tasarlanmış akıllı atık yönetim sistemlerinin olmaması, geri dönüşümünü sınırlamaktadır. Bu makale, UCO'nun toplanmasına yönelik gerçek zamanlı takip imkânı sağlayan blokzincir tabanlı bir akıllı UCO toplama platformu önermektedir. Platform, sistem mimarisi, UCO tespit ve sınıflandırma modülleri ile akıllı çöp kutuları (SGB'ler) için UCO toplama potansiyelini tahmin eden ve toplama eşiklerini hesaplayan bulanık çıkarım sistemi (FIS) tabanlı karar destek modülünü içermektedir. Önerilen platform, blokzincir, IoT sensörleri, akıllı çöp kutuları, kripto para mikro ödemeleri, oyunlaştırma unsurları ve makine öğrenimi gibi çeşitli teknoloji ve araçları bir araya getirmektedir. Antalya'dan bir vaka çalışması, FIS tabanlı karar destek modülü ve toplama eşiği hesaplamalarını göstermek için sunulmaktadır. Yazarların bilgisine göre, bu platform, literatürde sunulan en kapsamlı akıllı UCO geri dönüşüm çözümü olup, kamu farkındalığını artırmakta, etkileşimi güçlendirmekte ve geri dönüşümü finansal teşviklerle motive etmektedir.

Anahtar Kelimeler: Sürdürülebilir biyodizel ham maddesi, IoT destekli akıllı atık çözümleri, Kripto para teşvikleri, bulanık çıkarım sistemleri, Kullanılmış Yemeklik Yağ (UCO) toplama, Blokzincir, gerçek zamanlı takip, akıllı çöp kutusu (SGB).

1 Introduction

Fast-paced consumption culture is depleting the world's natural resources and causing environmental pollution by emiting hazardous waste and byproducts. Among these waste streams, used cooking oil (UCO) is a prominent one produced by households, restaurants, and other food service establishments. Just like petroleum-based oils and animal fats, vegetable oils can also carry toxic properties and have negative impacts on the environment by coating animals and plants causing oxygen depletion, destroying food supplies, and triggering fires [1]. Pouring UCO into the sewage system can pollute drinking water supplies and endanger human health. It is estimated that one liter of UCO contaminates 1 million liters of drinking water [2].

Over the past 10 years, there has been a consistent increase in global vegetable oil consumption. It is predicted that global vegetable oil consumption was approximately 160 Mton in 2013, while in 2023, it is projected to exceed 210 Mton [3]. Concurrently, the International Energy Agency predicts that demand for biofuels that can be made from UCO will increase by 41 billion liters, or 28%, between 2021 and 2026 [4]. Although UCO can supply a considerable share of biofuel production feedstock, worldwide UCO collection values have not yet reached the anticipated levels. The projected annual UCO collection volumes in the EU and

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UK range between 0.7 and 1.2 Mton/yr, while only 18.5% of the biodiesel produced in the EU is derived from UCO [5].

UCO possesses inherent chemical properties that make its recycling a beneficial practice. When properly recycled, UCO can be utilized as a main feedstock for biodiesel production, one of the most common green energies. Biodiesel currently accounts for 90% of the renewable energy utilized in transportation in the EU, making it a prominent clean energy source used in many areas, including aviation [5]. Biodiesel is being utilized in various blends with diesel worldwide, as its substitute with lower greenhouse gas emissions [6].

In addition to biofuel production, UCO can also produce various other goods such as soaps, detergents, lubricants, and other industrial products. UCO can help decrease the dependency on fossil fuels by providing a clean alternative. The recycling of UCO also reduces the environmental impact associated with its disposal.

Nevertheless, there are various challenges associated with the recycling of UCO. One of the primary challenges is the lack of public awareness regarding the proper disposal of oil and the unavailability of a collection service in some areas. The absence of safe storage containers and transportation options can result in oil spills and leaks that may lead to environmental damage. Another major challenge is related to financial incentives, as the benefits of collecting UCO may not be evident to some individuals or companies. Thus, addressing these challenges requires raising public awareness, providing safe storage and transportation options, and creating effective economic incentives to promote the collection and recycling of UCO.

To achieve this goal, today, there are many active initiatives around the world between local communities and the government, leading to nationwide assisted UCO recycling processes. For effective collaboration within this context, new sustainable business models are necessary to bring together stakeholders, along with the development of infrastructures and platforms to standardize and simplify UCO recycling processes.

Several companies and partnerships are implementing UCO collection systems to recycle this valuable resource and promote sustainability. Henkel, a German chemical and consumer goods company, has developed the Fat Box, a container that collects UCO and ensures it is transported safely for recycling [7] Bio Oil Energy in the Netherlands collects UCO and transforms it into biodiesel and other products for different industries [8]. Neste, a Finnish renewable fuels and oil refining company, has acquired the UCO collection and aggregation business of Crimson Renewable Energy in the United States [9]. Italian energy company Eni has partnered with Renoils to boost the collection of used food oil and UCO in Italy, which is then transformed into biodiesel [10]. Austrian hypermarket chain Interspar has implemented a unique UCO collection system in its stores, allowing customers to bring their UCO for recycling [11]. These companies and partnerships' UCO collection and recycling initiatives contribute to the circular economy and promote sustainable energy sources.

Integrating blockchain technology for UCO waste management system is relatively new. According to a recent literature review, only 4 papers have contributed to modeling such platforms and none of the articles tackled UCO recycling processes [12]. To the best of the authors' knowledge, the only existing system for UCO collection with smart capabilities was developed for the Island of Crete, Greece, by the Technical University of Crete in partnership with the Municipality of Rethymno and local stakeholders in 2018. The smart UCO collection system has multiple collection points and bins and integrates sensors, GSM technology, and a web-based platform. The software enables the optimization of collection routes and real-time monitoring of bin-filling levels. While decreasing operational expenses, fuel consumption, and greenhouse gas emissions, this technology improves collection efficiency [13]. Our work differs significantly from the established platform and achieves contributions in the following areas. Firstly, our platform is incentive-based and supports crypto payments. Secondly, our platform incorporates a detection and classification module for UCO. Lastly, our platform is blockchain-based and facilitates the UCO recycling process.

The article proposes a new smart garbage bin (SGB) system that offers various contributions to the waste management process. Firstly, the system is designed with blockchain technology in a novel way to support operations of stakeholders and enable efficient collection of UCO from consumers. Secondly, the system integrates advanced sensor technologies to assess the quality of the collected cooking oil, which allows for more accurate sorting and processing. Moreover, a sophisticated oil quality detection module is suggested to detect UCO and classify it with concerning to its characteristics. Furthermore, a secure and efficient transaction system that utilizes smart contracts is implemented to facilitate payments and incentivize recycling. Lastly, the system offers real-time tracking and monitoring of garbage bin status, ensuring efficient and timely waste collection. Overall, our article presents a promising solution for facilitating the collection and recycling of UCO, while promoting sustainable and eco-friendly waste management practices.

The proposed blockchain-based Smart UCO collection platform makes the following contributions:

- A novel system that incorporates several modules based on machine learning and smart contracts
- Providing an SGB for efficient collection of UCO
- Supporting cryptocurrency micropayments as incentives
- Real-time tracking of SGB status
- Supporting gamification via NFTs, leadership boards, personalization to boost user engagement
- Preventing fraud and enhancing security in UCO collection via a UCO detection module
- Implementing multiple Fuzzy Inference Systems (FIS) to estimate the UCO collection potential and the threshold level

Table 1. Summary of the literature review

Waste Management Platform	Type of Waste	Blockchain Adoption	Gamification and Social Elements	Incentive	Incentive Approach	Real-Time Monitoring	Multiple Collectors	Optimized Vehicle Routing	Threshold Estimation	Threshold Estimation Approach
***Mamun* et al., 2016** [15]	Solid Waste					✓		✓		
Baby et al., 2017 [16]	Solid Waste					✓			✓	Machine Learning
Al-Jabi and Diab, 2017 [17]	Solid Waste					✓	✓			
Dua et al., 2020 [18]	E-Waste	✓		✓	Payment based on Smart Contracts		✓			
França et al., 2020 [19]	Solid Waste	✓		✓	Payment by coin transfer					
Akter, 2021 [20]	Solid Waste	✓		✓	Payment by coin transfer					
Sen Gupta et al., 2022 [14]	Solid Waste	✓		✓	Payment based on Smart Contracts	✓		✓		
Ramos et al., 2013 [21]	UCO							✓		
Winpol, 2019 [13]	UCO					✓				
Proposed Platform	UCO	✓	✓	✓	Micro Payment based on Smart Contracts, NFTs	✓	✓		✓	Fuzzy Inference System

2 Theoretical foundation

2.1 Literature review: SGBs and waste management systems

The main application areas in smart waste management systems can be classified into three categories: 1. Waste collection and segregation, 2. Real-time bin monitoring and disposal, 3. Optimized vehicle routing [14]. Researchers have been designing and implementing waste management systems that automate and integrate few or all categories of the application areas. The literature does not include any smart systems or platforms developed to boost the recycling process of UCO [12], therefore we have performed a brief literature review on smart waste management systems and platforms designed by implementing blockchain technology.

One of the earliest examples of smart systems for real time bin monitoring and disposal for solid waste management is developed in [15]. They have introduced a novel model, framework, and intelligent sensing algorithm that operates and enables data transactions via GPRS. The proposed methodology tracks bin status in real-time and provides information to the solid waste collector on which bin to collect and when. [16] also developed a smart waste bin for real-time bin monitoring and disposal that utilizes basic ultrasonic and IR sensors and microcontrollers, which alert the authorities when the bin is full and ready to be collected. The system will predict possible future generation amount via machine learning by using previous collected data.

Another waste management system to boost waste collection and segregation was proposed by [17] that aims to measure citizen engagement with the bin by leveraging IoT devices, RFID tags, weight sensors, and ultrasonic sensors. The process evaluates each citizen's interaction with the waste management system and awards them with marks.

More recent studies involve decentralized approaches to waste management and integrating blockchain into the proposed platforms. For instance, [18] presented a waste management technique to deal with electronic waste (e-waste) by using blockchain in the 5G scenario for waste segregation and collection. A public-private partnership model was developed for effective implementation of the methodology and an incentive-based system to encourage recycling was suggested. Ethereum's blockchain digital architecture is used by [19] for solid waste management in a small municipality in Sao Paulo, Brazil. The proposed system facilitates the economic management of waste collection and segregation by replacing the current paper-based system with crypto coins.

A blockchain-based smart garbage management system for developing countries is presented in [20] which motivates citizens to recycle more waste. The cost-efficient waste collection and segregation methodology runs on an app and includes an incentive mechanism based on cryptocurrency and a proximity sensor is embedded in each garbage bin to open the lid when an individual is detected nearby. [14] suggested an end-to-end smart waste management system based on blockchain using smart contracts. The methodology combines multiple functionalities of waste management systems in one platform. It contributes to the field by offering incentives through tokens for waste segregation, monitoring real-time waste collection, detecting full garbage bins and providing optimum routes to vehicles for waste transfer and disposal.

Research in smart waste management systems for UCO is currently limited. [21] presented a mixed integer linear programming model to optimize the vehicle routes in a waste cooking oil collection system. The only known smart UCO collection system, developed in 2018 for the Island of Crete, Greece, incorporates sensors, GSM technology, and a web-based platform. It optimizes collection routes and provides real-time monitoring of bin filling levels, improving efficiency and reducing expenses and emissions [13].

The related literature is summarized in Table 1 concerning the adoption of several characteristics and technologies. These elements are types of waste targeted, implementation of blockchain, usage of gamification elements, integration of incentives, the types of incentive approach used, compatibility with multiple collectors, enabling optimized vehicle routing, the existence of threshold estimation tools, and the threshold estimation approach used.

While previous research has predominantly focused on solid waste management, our framework targets the underexplored domain of UCO. Unlike existing systems that primarily address solid or e-waste, such as [15-17], our approach is designed specifically for UCO management. The only comparable UCO-related works [13, 21] lack critical features such as secure transactions, gamification, incentives, and threshold estimation tools, which are integral to our proposed system.

Moreover, while systems like [14,18-20] incorporate blockchain for solid waste management, our platform uniquely integrates these elements with micropayments based on smart contracts, gamification elements and NFTs, specifically for UCO collection. It also combines real-time monitoring, multi-collector support, and FIS-based threshold estimation, addressing gaps identified in these works. Similarly, the systems [14, 20] provided optimized vehicle routing but did not address threshold estimation for UCO collection or gamification tailored to incentivize recycling behavior.

The proposed blockchain-based smart UCO collection framework integrates unique features absent in prior research.

By integrating and automating these multiple processes, our proposed platform combines secure transactions, incentives, real-time SGB tracking, and Fuzzy Inference Systems (FIS) to estimate UCO collection potential and support multiple collectors simultaneously. This comprehensive approach addresses gaps in the literature, offering a secure, efficient, and engaging solution for UCO recycling.

2.2 Technical background

This section explores the diverse applications of blockchain technology. Subsection 1 focuses on the core components of blockchain and smart contracts. Subsection 2 discusses the potential of NFTs and gamification in incentivizing social and environmental benefits. Finally, subsection 3 explores the potential of micropayments and the emerging consensus algorithms to facilitate low-cost transactions in various fields.

2.2.1 Blockchain and smart contracts

A blockchain is a decentralized, immutable digital ledger that securely and transparently records transactions and data. The term “blockchain” was first coined by Satoshi Nakamato [22]. Its primary objective was to solve the double-spending problem. This was achieved by utilizing a network of nodes, or miners, to validate transactions and establish ownership records of assets owned by individuals on the network. This secure and traceable system encourages research to find new use cases beyond being only a cash system. Over time, Blockchain technology has been studied on numerous potential uses, such as supply chain management [23], voting systems [24], real estate transactions [25], inexpensive and efficient financial transactions [26, 27], digital identity management [28], healthcare data management [29], smart cities [30], [31], sustainability and social responsibility [32, 33] and many more.

Blockchain technology has gained widespread recognition and adoption due to its key characteristics. These include decentralization, ensuring that no single entity controls the network; immutability, making data tamper-evident; transparency and traceability, enabling public auditing and tracking of transactions; security, achieved through cryptographic methods; and consensus, requiring agreement among network nodes to validate new blocks. These features have made blockchain a potential technology across various fields.

The concept of smart contracts was first introduced by computer scientist and cryptographer Nick Szabo in 1997 [34]. However, the technology was limited and it didn’t gain attention until the emergence of Bitcoin and especially Ethereum [35].

Smart contracts are self-executing contracts (or computer programs) with the terms of the agreement between sides directly written into lines of code. They are designed to execute when the predefined conditions are met. These contracts run on blockchain technology, which ensures that they are transparent, immutable, and tamper-proof without the need for any intermediaries.

2.2.2 NFT-gamification

NFTs, or non-fungible tokens, are digital assets that represent unique ownership (partially or whole) of items such as art, music, real estate, in-game items, and more. Unlike cryptocurrencies, NFTs cannot be fungible and replicated. For this reason, NFTs are gaining mainstream attention among collectors [36, 37].

Gamification is widely recognized as one of the most effective ways to motivate people by turning a dull system into a game. A gamified system may help the stakeholders to contribute to beneficial causes like increased recycling [38-40]. NFTs work as part of the incentive mechanisms to increase the recycling rate within households. In our proposed system, certain NFTs can provide discounts, act like a pass card or indicate achievements like a milestone for recycled amounts, and the number of visits to SGB.

2.2.3 Micropayments

Existing payment methods for international transfers in traditional financing usually operate with high fees and require time to finalize the transfer. Although it varies from bank to bank, these fees range from $25 to $50 [41]. The emergence of Bitcoin has made the transfer of assets secure, inexpensive, traceable, and anonymous way. As of August 23, 2022, the typical fee for a Bitcoin transaction is 0.000044 BTC, which is equivalent to $0,957. Over the past year, the fee has varied from under $1 to almost $5. Nevertheless, during its highest point in April 2021, the average fee for a transaction was over $60 [42]. Often in many practices, transaction amounts are small, sometimes even higher than the transaction fee [43]. For instance, in Japan, the sale price of UCO is around $0,38 while there is a demand average price $1,21 from Singapore [44]. Therefore, these kinds of applications require a low transaction fee environment to function properly, which has driven researchers to develop a new consensus mechanism to reduce costs amid volatility and high fees. Many blockchains using new consensus algorithms, such as Solana, Polygon, and Astar, have been commercially released throughout the years. Even, some of them have practically near to zero fees. These advancements have revealed new use cases for micropayments with blockchain.

3 Research methodology

In our research paper, a structured methodology is employed to guide the design and formulation of our proposal's solution (see Figure 1). The process begins with setting clear research goals and objectives, followed by a comprehensive literature review aimed at identifying gaps in existing smart waste management systems. In particular, the review explores the lack of studied systems for UCO collection and recycling, which ultimately informs the conceptual framework of the study. Building on this foundation, we then examine the technical background by exploring relevant technologies such as blockchain, NFTs, micropayments, gamification, and fuzzy inference systems (FIS). The roles of these technologies are detailed, emphasizing their significance in enhancing the proposed platform. Using these insights, we design a collaborative framework that facilitates communication among stakeholders, including municipalities, waste collectors, SGB organizer, and consumers. This framework integrates smart garbage bins (SGBs) equipped with IoT sensors and a blockchain-enabled incentive system.

The development of the waste management system follows, structured around three key steps: defining the architecture of the SGB system, including user registration and operational processes; designing detection and classification modules for UCO using machine learning algorithms; and implementing a fuzzy inference system within a decision support system to estimate UCO collection potential and determine threshold levels for SGBs.

To demonstrate the practical benefits of our system, we present a case study. This phase begins with the collection of data on population, food service points, distances to recycling facilities, and historical UCO data. This information is then utilized to predict UCO collection and establish threshold levels through the decision support system.

Finally, the methodology concludes with an analysis of the study's results, highlighting key findings, limitations, and suggestions for future work. This systematic approach ensures the design and validation of a robust blockchain-based UCO management platform.

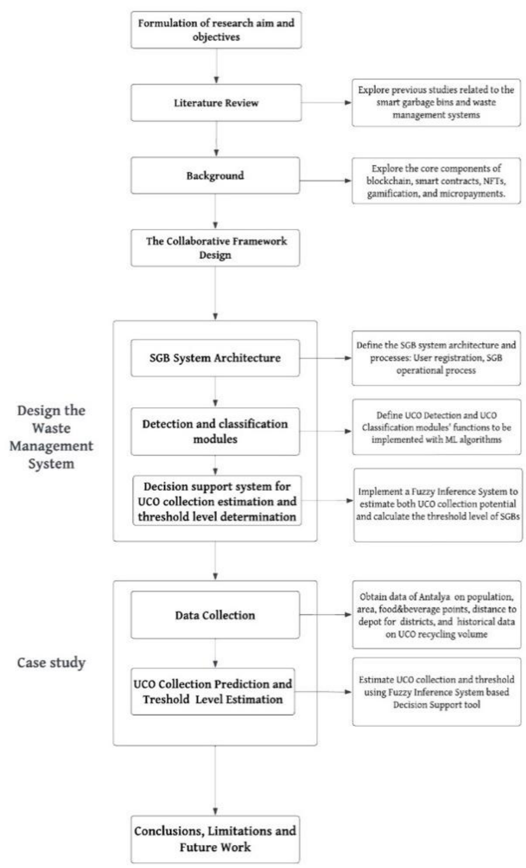

Figure 1. Research methodology

4 Our proposed UCO waste management system

4.1 Proposed framework for UCO collection system

The platform supports collaboration among shareholders by facilitating decentralized communication and provides the base framework for parties to prolong their activities using predetermined smart contracts (see Figure 2).

The main shareholders in the developed UCO recycling system can be listed as the municipality, consumers, UCO waste collector companies, and the SGB organizer. The proposed platform contributes to shareholder by different means. Through the platform consumers can receive incentives in return of collected UCO, in terms of cryptocurrency which makes micropayments available, NFTs and other gamification tools. Moreover, consumers can also donate their earnings to charities and support social causes. Discounts or promotions can be made available via the platform as an incentive to their recycling efforts. UCO SGBs will also increase public awareness by its display and availability in neighborhoods.

Traditionally, municipalities play an intermediary role in collecting UCO from the consumers and aim to increase recycling through regulations and social campaigns. In this setting, municipalities only rent out the space for the SGBs and charge a rental fee for the area where SGBs are established.

The platform offers significant benefits to UCO collectors. First and foremost, it aims to boost the UCO recycling by facilitating and simplifying the process. The recycling quality is improved by determining whether collected liquids are UCO or not. Then, UCO is classified based on its composition, and an incentive value is computed with respect to its amount and quality.

UCO waste collector firms act as a bridge between UCO recyclers and consumers, ensuring that collected UCO reaches the biodiesel production plants. Funds flow from biodiesel production plants to UCO collectors and from UCO collectors to consumers in the proposed system. It should be noted that data transfer between biodiesel production facilities and UCO collectors does not occur via this platform, hence biodiesel production plants are not included in the system. In addition, the fullness of SGBs is monitored and collected using real-time data flow and unnecessary trips to the SGBs are minimized.

The SGB organizer is responsible for designing, operating, and updating the platform and receives a percentage of the users' incentive in return. The platform serves a set of stakeholders mentioned above and is upgraded in response to changes in technology, market demands, or received user feedback. The SGB will also provide a team of employees for the installation and maintenance of the SGBs.

4.2 The UCO waste management system

This section explains the UCO Waste Management System, by providing its functionalities and processes and further describes three main components namely: SGB System Architecture, UCO Detection and Classification Modules and Decision Support tool for UCO collection threshold level.

4.2.1 SGB system architecture

Figure 3 visualizes the proposed smart and incentive-based system for UCO collection process. The system provides users with a convenient way to register themselves using a dedicated mobile application. This application operates on a private blockchain infrastructure, and a trusted third-party entity responsible for user registration generates a unique set of public-private keys. The private key is kept confidential and known only to the user, while the public key can be shared with others and stored within the blockchain network.

During the registration process, the user creates a password and a username. These, along with the encrypted password and additional data generated by the application, are linked to the corresponding public key and securely stored within the blockchain ledger. This ensures that all user data stored within the private blockchain is in advance, providing a secure and reliable method for authenticating users to Internet of Things (IoT) devices, without the need for a centralized database. At a conceptual level, the authentication procedure involves the user providing their username and password to initiate the login process. The application then uses one of the secure cryptographic authentication algorithms to verify the user's identity during the login phase.

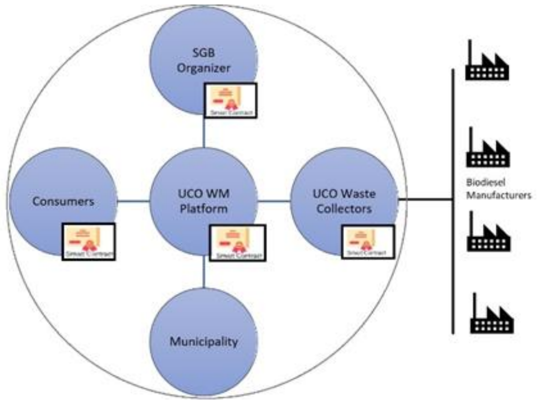

Figure 2. Proposed framework for UCO collection system

SGB operational processes. Figure 4 depicts the SGB operational process followed in the platform. Upon completion of the authentication, the SGB will grant the user access by opening its lid. Subsequently, the user deposits a bottle of UCO into the bin. Oils are collected in standardized bottles, specifically designed for the SGB for UCO collection purposes. To prevent fraud and user mistakes, the SGB initially runs an oil detection module. The UCO detection module will utilize machine learning methods trained with the physical parameters of UCO samples to accurately identify UCO during the collection phase in an SGB. To overcome the lack of comprehensive datasets, the machine learning model will be trained using data obtained from a local UCO recycling company, including previously measured physical and chemical characteristics of UCO samples. Integrated sensors such as density, viscosity, pH, odor, and level sensors in the SGB enable the measurement of various physical and chemical properties of the newly received UCO sample, which are then used as input for the machine learning model to predict whether the liquid supplied by the consumer is UCO or not. If the module does not detect oil content in the bottle, access will be denied.

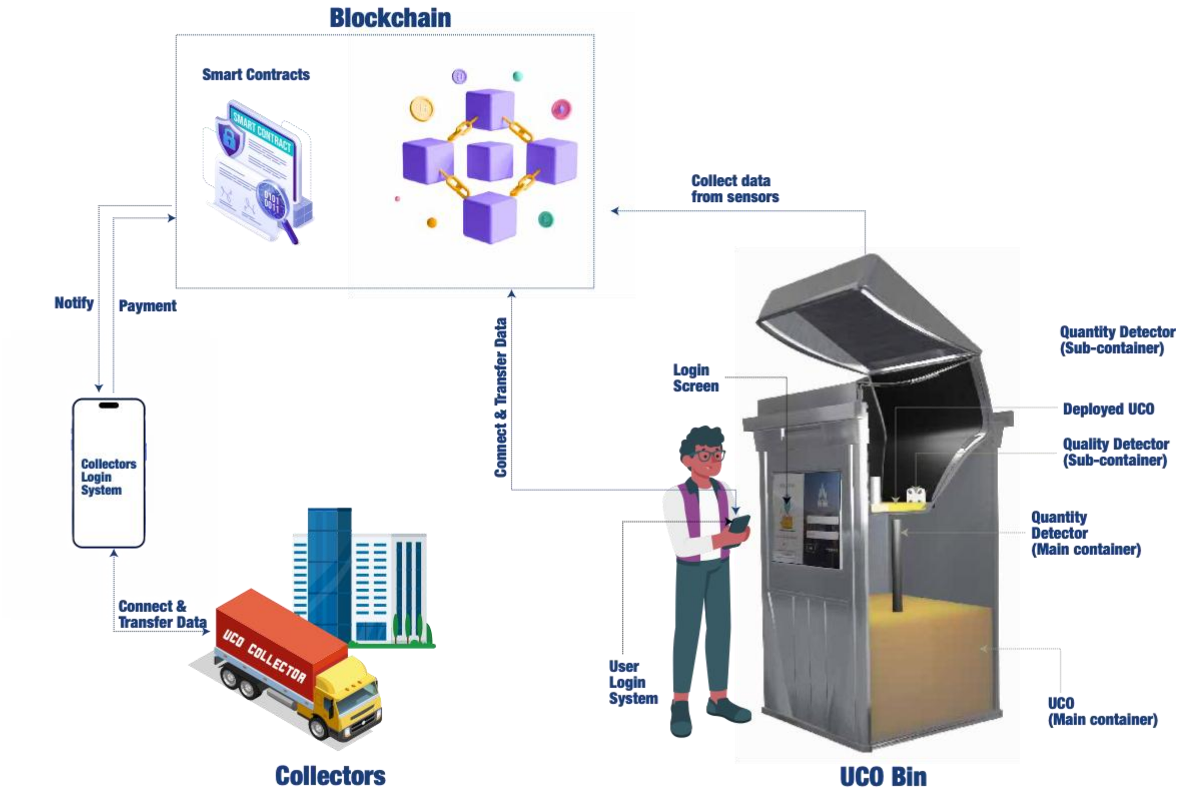

Figure 3. Visualization of the proposed smart and incentive-based system for UCO collection process

Once the UCO is approved, the UCO classification module based on machine learning tools and algorithms will evaluate UCO quality. The SGB will measure the amount of UCO deposited by the user. Both the quality and quantity of the UCO are essential in evaluating the user's total contribution. Section 4.2.2 provides a more detailed explanation of the UCO detection and UCO classification modules.

The proposed UCO waste management system offers two types of incentives to reward UCO disposal: cryptocurrency and non-fungible tokens (NFTs). The system utilizes a smart contract to automatically transfer cryptocurrency to the respective user via blockchain's micropayment solutions upon receiving payment from the waste collector.

However, the NFTs are automatically transferred to the user's digital wallet upon meeting certain predefined criteria at the time of UCO disposal. The type of NFT earned by the user can be determined using a set of predefined rules, such as number of times the user contributed to an SGB, or the quality of UCO they have deposited.

The proposed system incorporates a notification mechanism that informs registered UCO waste collectors when an SGB reaches a predefined level of UCO. This functionality is achieved by employing the level sensor to track the UCO level after each deposit. The SGB retrieves the current status of the bin and verifies if it has exceeded the predetermined threshold. Once the threshold is reached, the system promptly sends notifications to the registered waste collectors, indicating the need for emptying the bin.

The waste collector registers and signs in to the SGB in the analogous way as a regular user, using their unique collector's name and password. The payment for the waste collected will be transferred from the waste collector's wallet to the wallets of all contributing users, along with the SGB organizer's share. The amount transferred to each user's wallet will depend on the incentive amount agreed upon and written previously in the smart contract. After the waste collector empties the SGB, the status of the bin will be set as "Empty".

The waste management system incorporates various gamification strategies to enhance user engagement and motivation. As discussed in [38], gamification revolves around concepts such as fun, engagement, motivation, purpose, and social collaboration/competition. In line with these principles, the system implements a reward system utilizing NFTs and virtual medals based on users' recycling performance. A smart contract embedded within the system evaluates the overall recycling performance of each user, following the payment process, and mints additional NFTs that are sent to the respective user's wallet. The performance criteria for earning these rewards include the total number of tokens earned, the number of payments received, the reduction in particulate matter exposed to the environment, and the prevention of carbon monoxide emissions [45]. Additionally, fostering a sense of neighborhood and community competition, the system emphasizes the value of recycling and personalization. However, social media announcements of winners and leaderboard statistics will only be provided if users explicitly provide their consent.

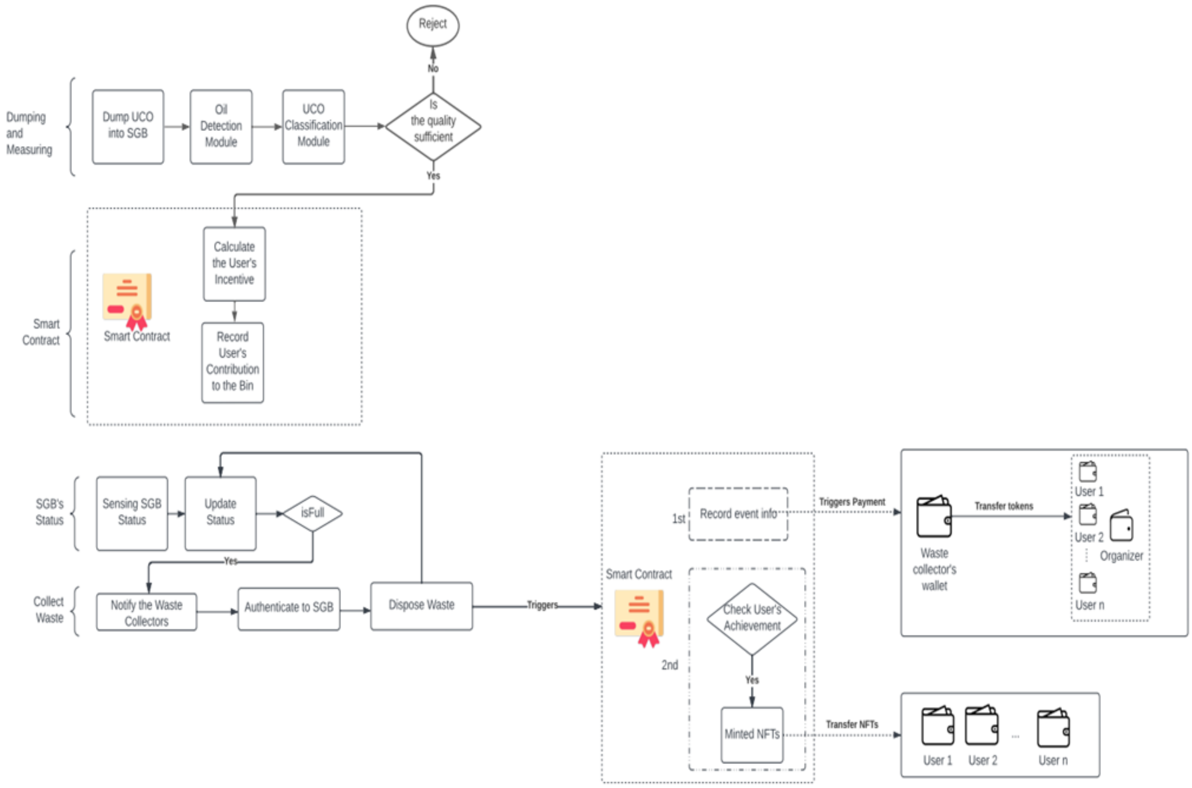

Figure 4. SGB operational process

4.2.2 UCO detection and classification modules

Within the SGB framework, two modules with machine learning algorithms will be employed for enhanced functionality: UCO Detection and UCO Classification.

The UCO detection module detects whether the liquid provided by the consumer is UCO based on ML-based methods trained with the physical parameters of UCO samples. The detection of UCO in an SGB is crucial to prevent fraud. Some individuals or businesses may attempt to dispose of non-UCO substances as UCO to take advantage of recycling incentives or regulations. By accurately identifying UCO, the system can detect and prevent such fraudulent attempts, ensuring that the recycling process remains legitimate and reliable. Moreover, improper disposal of non-UCO substances in UCO recycling bins can have adverse environmental impacts. By detecting UCO, the system can ensure that only genuine UCO is collected, preventing the contamination of the recycling process with substances that may harm the environment.

The module aims to identify UCO during collection, but the lack of datasets on UCO's physical properties limits the use of ML techniques. To overcome this, the ML model will use data from a local UCO recycling company, including physical and chemical characteristics of UCO samples. Table 2 provides the ranges for the key properties observed in UCO samples [6].

Table 2. Physical and chemical properties of waste cooking oil collected

Property	Units	Value
Density	g/cm3	0.910 - 0.924
Kinematic viscosity (40 °C)	mm2/s	36.4 - 42.0
Saponification value	mgKOH/g	188.2- 207.0
Acid value	mgKOH/g	1.32 - 3.60
Iodine number	gI2/100g	83.0 -141.5

Once the ML-model is built, the module can identify if a fresh sample obtained from a consumer is UCO or not. For this purpose, the SGB incorporates integrated sensors such as density, viscosity, pH, odor, and level sensors, enabling the measurement of various physical and chemical properties of the newly received UCO sample. These sensors facilitate the detection process by capturing the associated characteristics of the sample.

The UCO classification module is designed to categorize UCO samples based on their recycling potential, with a particular focus on the FFA ratio to enhance biodiesel production efficiency. Since UCO typically contains a higher percentage of FFAs than vegetable oil, this concentration plays a critical role in selecting the appropriate catalyst for the transesterification process [46], and managing the limitations it poses for large-scale biodiesel production. By accurately classifying UCO samples, the module ensures that essential transesterification parameters—such as reaction temperature, time, catalyst concentration, and the molar ratio of oil to alcohol—are optimally adjusted for each sample. This approach maximizes biodiesel yield and overall production efficiency. Leveraging ML tools and algorithms, the module will improve the classification accuracy and adaptability of the system, driving further optimization.

4.2.3 Decision support tool for UCO collection threshold level

A decision support tool is also developed to predict UCO collection potential and compute SGB threshold levels. The module first clusters districts by K-means clustering. Then these clustered are used in a FIS based model to predict UCO collection potential of each district. Then the associated threshold levels are estimated by considering the collection process and its assumptions. Figure 5 provides an overview of the decision support tool designed. The following section provides an application of the decision support tool through a pilot study from Antalya, Türkiye.

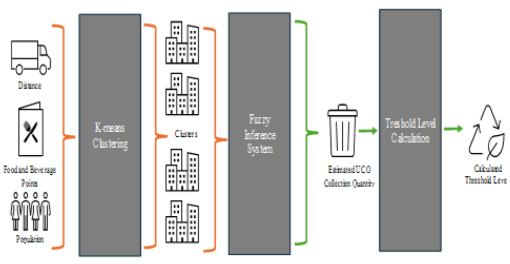

Figure 5. Proposed framework for UCO collection system

5 A case study: Antalya, Türkiye

To demonstrate the application of the UCO WM system, Antalya, a city in Türkiye, is taken as a case study. Antalya is not only a crowded city with 2.688.004 inhabitants, but also a very touristic zone that receives more than 10 million foreigners per year. Therefore, a practical UCO SGB system will benefit the city tremendously. The proposed system will collect UCO from hotels, food service points, and especially from households.

5.1 The UCO waste management system

Antalya is composed of 17 municipalities spread over a large geographical area with significant distances (see Figure 6). These districts differ from each other in population and number of food service points. A summary of the data on municipalities can be seen in Table 3 (District Kale is also commonly known as Demre).

Figure 6. Antalya districts

Table 3. Data on Antalya districts

District (of Antalya)	Population (2022)	Total Area (km^2)	Road Distance to Depot
Kepez	608 675	403.76	21.9
Muratpaşa	526 293	88.84	30.2
Alanya	364 180	1582	153
Manavgat	252 941	2283	94.9
Konyaaltı	204 795	562.4	24.2
Serik	139 545	1550	57.8
Döşemealtı	79 495	673.1	0
Aksu	77 623	440	34.7
Kumluca	73 496	1253	108
Kaş	62 866	2231	194
Korkuteli	56 285	2471	48.7
Gazipaşa	53 702	921	198
Finike	49 720	653	125
Kemer	49 383	471	57.5
Elmalı	40 774	1647	97.6
Demre	27 691	471.4	153
Akseki	10 477	2390	151
Gündoğmuş	7 188	1323	160
İbradı	2 875	1267	128

5.2 UCO collection estimation

The annual UCO collection potential for Türkiye is estimated to be around 976,000 tons (EMRA, 2016), however, private conversation with an industry professional revealed that the current amount of UCO collected is around 35,000 tons per year. Therefore, the data on UCO collection potential for each municipality is unavailable.

To estimate the potential for UCO collection in each district of Antalya, we used a fuzzy inference system (FIS). The FIS relies on two main factors: population size and the number of food and beverage points in each district. These inputs help predict the amount of UCO that could be collected from each area. Additionally, we developed five different scenarios with varying probabilities to improve the accuracy of our predictions, allowing for more reliable estimates under different conditions.

An FIS is an expert system that is composed of input and output parameters, fuzzy rules, fuzzy sets and defuzzification schemes. Based on fuzzy sets and a fuzzy rule system, the fuzzy output function f1(p1, p2) is computed, and transformed into a crisp value. A Mamdani FIS is a straightforward way to include logical reasoning to inputs that are hard to relate with outputs. The FIS approach is particularly suitable for this application due to its ability to handle the inherent uncertainty and imprecision in such real-world data. The model is implemented on MATLAB, Fuzzy Logic Toolbox.

The probability of occurrence for each scenario is represented by *P(x)*:

- No increase in UCO collection, *P(1)= 0.10*
- 50% increase in UCO collection, *P(2)= 0.20*
- 80% increase in UCO collection, *P(3)= 0.30*
- 200% increase in UCO collection, *P(4)= 0.20*
- 300% increase in UCO collection, *P(5)= 0.20*

While the input values for each scenario are the same, the output functions are created coherent with the UCO collection values. Note that the scenarios and the associated probabilities were decided after consulting with experts, industry professionals, and decision-makers.

Data on population and food service points are not uniform and have outliers. For this reason, we employ K-means clustering before using FIS. K-means clustering is an algorithm which iteratively assigns data points to the nearest cluster centroid and then recalculates the centroids based on the mean of the assigned points. It aims to minimize the variance within each cluster.

In this study, the data is clustered in both dimensions (population and food service points). The districts are divided into four clusters named Small Municipality (SM), Small Medium Municipality (SMM), Medium Municipality (MM), Large Municipality (LM) based on their populations. Also, four clusters are defined as: Small Municipality (SM), Small Medium Municipality (SMM), Medium Municipality (MM), Large Municipality (LM) based on the number of food service points. Separate triangular functions were created for each cluster. Table 4 presents the parameters used for the triangular functions of the FISs based on the clusters.

Figure 7 presents the FIS, build for scenario 1 and the associated fuzzy rules. The two input parameters "Population" and "Food and Beverage points" are transformed into triangular fuzzy membership functions based on the clusters mentioned above and combined into a UCO Collection Potential" output. In order to make this transformation, we have developed 16 fuzzy rules as given in Figure 7. The triangular fuzzy membership functions for each input parameter, as presented in Appendix 1 are defined based on the statistics computed from the clusters. The parameters for the outputs are defined by intuition and scenario estimations. The outputs of each scenario and the total estimation for UCO collection as calculated by multiplying the output with scenario probabilities is presented in Appendix 2.

Table 4. Generated clusters of districts

Population Clusters	District	Population
LM	Kepez	608675
	Muratpaşa	526293
	Alanya	364180
MM	Manavgat	252941
	Konyaaltı	204795
	Serik	139545
SMM	Döşemealtı	79495
	Aksu	77623
	Kumluca	73496
	Kaş	62866
	Korkuteli	56285
	Gazipaşa	53702
	Finike	49720
	Kemer	49383
	Elmalı	40774
SM	Demre	27691
	Akseki	10477
	Gündoğmuş	7188
	İbradı	2875

F&B Clusters	District	Food and Beverage Points
SM	Gündoğmuş	0
	İbradı	2
	Akseki	3
	Döşemealtı	8
	Aksu	8
	Elmalı	13
SMM	Kumluca	26
	Gazipaşa	27
	Korkuteli	28
	Finike	35
	Konyaaltı	39
	Demre	41
MM	Muratpaşa	123
	Serik	128
	Kemer	178
	Kepez	185
	Kaş	258
LM	Manavgat	414
	Alanya	784

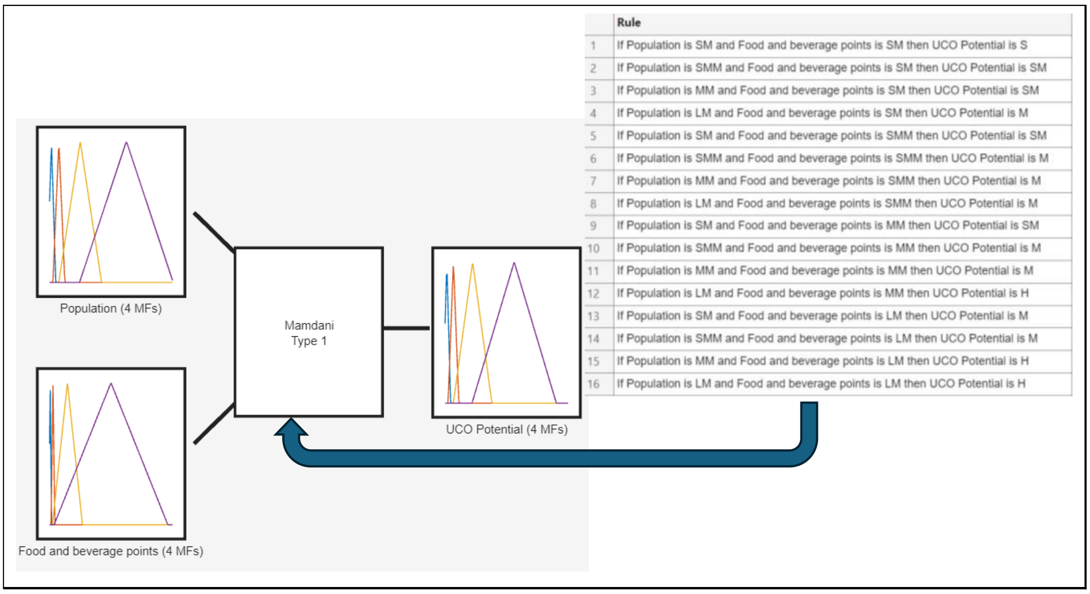

Figure 7. The FIS rules for scenario 1

5.3 Threshold level estimation

All UCO will be transported to the waste collector facility in Döşemealtı district, which is in the central zone. To simplify UCO collection and routing, the municipalities are grouped into three main clusters with respect to their locations: West region (Kaş, Demre, Elmalı, Finike, Kumluca, Kemer, Korkuteli), East region (Alanya, Aksu, Manavgat, Serik, İbradı, Akseki, Gündoğmuş, Gazipaşa), City center (Muratpaşa, Konyaaltı, Kepez, Döşemealtı). Each cluster is assigned vehicles to transport UCO from SGBs to the facility. The travel times between the waste collector facility and each SGB vary from minutes to 3hrs on average.

Even though real-time tracking and monitoring of the SGB is made available by the system, waste collection habits and travel times are probabilistic. Therefore, another rule is set on the collection time: the SGB must notify the waste collector 3 hours before the SGB gets full. This rule will give enough time for collection.

Table 5 shows the calculated threshold levels for each SGB in different districts. Depending on the estimated daily UCO collection, either a medium SGB with a capacity of 0.5 tons or a large SGB with a capacity of 1 ton is installed. The fill rates and threshold levels are determined based on the amount of UCO collected over a 3-hour period. We assume a constant hourly collection rate throughout the day, and the UCO collected in 3 hours is subtracted from the SGB capacity to calculate the threshold level. This threshold allows vehicles to collect UCO before the SGB reaches full capacity, providing more flexibility in scheduling collections.

We calculated the SGB threshold levels for different districts based on the assumption that each SGB should notify the collector 3 hours before its expected fill time. In Alanya, the collection rate per hour is 0.045, with a fill rate during transport of 0.14, resulting in a threshold level of 0.86. In contrast, Finike has a lower collection rate per hour of 0.009, a fill rate during transport of 0.05, and a higher threshold level of 0.95. These differences highlight the variability in SGB fill rates across districts, influencing the timing of notifications for collection.

Table 5. Calculated threshold levels

District (of Antalya)	***SGB Capacity (ton)***	***UCO Collection day***	***UCO collection/hour***	***UCO Collection during transport***	***Fill Rate during transport %***	***Threshold Level Required %***
Kepez	1.0	0.797	0.033	0.100	10	90
Muratpaşa	1.0	0.704	0.029	0.088	9	91
Alanya	1.0	1.090	0.045	0.136	14	86
Manavgat	1.0	1.090	0.045	0.136	14	86
Konyaaltı	0.5	0.435	0.018	0.054	11	89
Serik	1.0	0.726	0.030	0.091	9	91
Döşemealtı	0.5	0.132	0.005	0.016	3	97
Aksu	0.5	0.132	0.005	0.016	3	97
Kumluca	0.5	0.270	0.011	0.034	7	93
Kaş	1.0	0.516	0.022	0.065	6	94
Korkuteli	0.5	0.132	0.005	0.016	3	97
Gazipaşa	0.5	0.132	0.005	0.016	3	97
Finike	0.5	0.213	0.009	0.027	5	95
Kemer	0.5	0.435	0.018	0.054	11	89
Elmalı	0.5	0.132	0.005	0.016	3	97
Demre	0.5	0.279	0.012	0.035	7	93
Akseki	0.5	0.031	0.001	0.004	1	99
Gündoğmuş	0.5	0.031	0.001	0.004	1	99
İbradı	0.5	0.031	0.001	0.004	1	99

6 Conclusions, limitations and future work

In conclusion, the increasing demand for sustainable energy sources makes UCO a vital resource for producing biofuels, which significantly contribute to reducing environmental impact and reliance on fossil fuels. Our study introduces an innovative blockchain-based smart UCO collection platform, designed to improve UCO recycling rates by leveraging advanced technologies such as machine learning, cryptocurrency micropayments, and real-time tracking. The platform incorporates gamification through NFTs and leaderboards, while also preventing fraud and enhancing security with a UCO detection module. A decision support system utilizing K-means clustering and FIS has been implemented to predict UCO collection potential and establish threshold levels for SGB units, as demonstrated in a case study conducted in Antalya.

However, several limitations have been identified in the study. The UCO data available for analysis was not specific to individual districts, and even the total amount for Turkey is uncertain. Furthermore, no comprehensive dataset on UCO specifications and characteristics existed to be used for UCO classification and detection. Consequently, the UCO collection potential was estimated based on limited and vague data, leading to a hypothetical scenario for predicting UCO collection outcomes.

Future work will focus on implementing machine learning algorithms for UCO detection and classification, using data from various UCO collectors to develop a highly accurate model. The full software implementation of the platform including the mobile application is crucial for realizing its potential benefits. Additionally, a key aspect of future development will also involve designing the hardware for the SGB units, ensuring that they are cost-effective, durable, and efficient in real-world conditions. Finally, the proposed platform can be extended to other regions in Turkey with different dynamics and could potentially be scaled into a national program through targeted advertising campaigns.

Conflict of interest

The authors declare that they have no conflicts of interest related to this work.

Similarity rate (iThenticate): 18%

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Appendix-1

Appendix 1: Triangular Fuzzy membership functions
Population triangular function parameters

F&B Triangular function parameters

Population	SM	SMM	MM	LM	SM2	SMM3	MM4	LM5
Mean	12058	60372	199094	499716	6	33	174	599
Standard Dev	9420	13001	46469	101568	4	6	49	185
Upper Limit	40317	99375	338500	804421	19	51	321	1154
Lower Limit	-16202	21368	59687	195011	-8	15	28	44

Appendix-2

istrict	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Total UCO Collection (ton/daily)**
Probabilities(x)	0.1	0.2	0.3	0.2	0.2	
Kepez	0.411	0.616	0.74	0.822	1.233	0.797
Muratpaşa	0.363	0.544	0.653	0.726	1.089	0.704
Alanya	0.562	0.843	1.012	1.124	1.686	1.09
Manavgat	0.562	0.843	1.012	1.124	1.686	1.09
Konyaaltı	0.224	0.336	0.403	0.448	0.672	0.435
Serik	0.374	0.561	0.673	0.748	1.122	0.726
Döşemealtı	0.068	0.102	0.122	0.136	0.204	0.132
Aksu	0.068	0.102	0.122	0.136	0.204	0.132
Kumluca	0.139	0.209	0.25	0.278	0.417	0.27
Kaş	0.266	0.399	0.479	0.532	0.798	0.516
Korkuteli	0.068	0.102	0.122	0.136	0.204	0.132
Gazipaşa	0.068	0.102	0.122	0.136	0.204	0.132
Finike	0.11	0.165	0.198	0.22	0.33	0.213
Kemer	0.224	0.336	0.403	0.448	0.672	0.435
Elmalı	0.068	0.102	0.122	0.136	0.204	0.132
Demre	0.144	0.216	0.259	0.288	0.432	0.279
Akseki	0.016	0.024	0.029	0.032	0.048	0.031
Gündoğmuş	0.016	0.024	0.029	0.032	0.049	0.031
İbradı	0.016	0.024	0.029	0.032	0.048	0.031