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Content

-Research Articles

-Review Article

Cukurova University Journal of Natural & Applied Sciences (2024) 3(2): 36-44

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Original Paper

Design and Development of a Fashion Oriented Personalized Search Engine

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Abstract
Finding the desired product in the e-commerce sector in the fastest and easiest way plays a vital role in customer satisfaction and revenue growth. Some interactive search engines have already been proposed in the literature and allow for text or visual queries. Nevertheless, these studies focus on finding items aesthetically similar to the query without considering the query personalization aspects. Query personalization allows that user preferences are provided as a user profile separately from the query and dynamically decide how this profile will affect the query results. In this study, a personalized search engine is proposed, which is fed with the product data of the e-commerce site trendyol.com operating in the fashion-oriented retailing sector. More specifically, a search engine has been developed to recognize and help online shoppers find what they are looking for and discover a broader and more relevant range of products in the trendyol.com catalog. The index, search, and data collection infrastructures and a brand-based user-segmented product listing algorithm have been designed and implemented to realize the search engine. As the outcome of the study, a fashion-oriented and personalized site search has been enabled thar successfully reveals products that have never been thought of before by directly associating the products the customers want. The results show that personalizing the search queries increase the odds of success. With the development of the personalized search engine, it is expected that Trendyol's revenues will grow in a short time through users visiting the site
Keywords: Information Retrieval, Prediction, Query Personalization, Search Engine.

1. Introduction

An online product search engine, sometimes referred to as a query response module or program, allows buyers to filter and compare products based on price, features, ratings, and other criteria. Most online product search engines in the e-commerce sector aggregate product listings from many different retailers, but they don't sell products directly themselves, instead of making money from affili-ate marketing agreements. For detailed information about the structure of product search engines, the reader is referred to the respec-tive publications. An online product search engine, sometimes referred to as a query response module or program, allows buyers to filter and compare products based on price, features, ratings, and other criteria. Most online product search engines in the e-commerce sector aggregate product listings from many different retailers, but they don't sell products directly themselves, instead of making money from affiliate marketing agreements. For detailed information about the structure of product search engines, the read-er is referred to the respective publications [1-3].

Finding the desired product in the e-commerce sector in the fastest and easiest way plays a vital role in customer satisfaction and revenue growth. Designing an interactive search engine is required for several reasons, including (a) to avoid typos and narrow the searches, (b) refine visitors' search queries and category listings, and (c) program and optimize the speed, ranking, filters, and face of the category pages.

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Some interactive search engines have already been proposed in the literature and allow for text or visual queries, as outlined in Section 2. Nevertheless, these studies focus on finding items aesthetically similar to the query without considering the query personalization aspects. Query personalization allows that user preferences are provided as a user profile separately from the query and dynamically decide how this profile will affect the query result.

Personalized search engines analyze users' past search behaviors and interests to quickly provide the most accurate results based on this analysis. These engines save users time, reduce information pollution by offering more relevant results, and enhance the user experience. They also stand out as an important tool for advertisers by providing more effective marketing strategies through targeted ads.

This study proposes a personalized search engine, which is fed with the product data of the e-commerce site trendyol.com operating in the fashion-oriented retailing sector. The contributions of the study can be summarized as follows:

- A personalized search engine has been developed to recognize and help online shoppers find what they are looking for and discover a broader and more relevant range of products in the trendyol.com catalog.
- The index, search, and data collection infrastructures and a brand-based user-segmented product listing algorithm have been designed and implemented to realize the search engine.
- A fashion-oriented and personalized site search has been enabled that successfully reveals products that have never been thought of before by directly associating the products the customers want.

The rest of the paper is organized as follows. Section 2 outlines the related works. Section 3 introduces the details of indexing, search, and data collection infrastructures. Section 4 describes the brand-based user-segmented product listing algorithm. Section 5 presents the results and discussion. Finally, Section 6 concludes the paper along with possible future works.

2. Related Works

This section first outlines the current textual and visual search solutions offered in the literature. Afterward, the differences between the current study and studies from related literature are summarized.

The first methods that proposed to address textual information retrieval were based on token counts, e.g. Bag-of-Words [4] or TF-IDF [5]. Later, [6] designed two model architectures for computing continuous vector representations of words from extensive data sets. The quality of these representations is measured in a word similarity task, and the results are compared to the previously best-performing techniques based on different types of neural networks. Significant improvements in accuracy at much lower computa-tional cost were reported. [7] proposed GloVe, a new global log-bilinear regression model for the unsupervised learning of word representations that outperforms other models on word analogy, word similarity, and named entity recognition tasks. GloVe com-bines the advantages of the two prominent model families in the literature: global matrix factorization and local context window methods. [8] proposed an intelligent retrieval method based on the semantic characteristics of intelligent retrieval. This methodolo-gy performs research from both the document retrieval model and user perspective. [9] proposed a multimodal search engine that combines visual and textual cues to retrieve items from a multimedia database aesthetically similar to the query. The goal of the engine is to enable the intuitive retrieval of fashion merchandise such as clothes or furniture. [10] proposed search engine using ML tech-nique that will give more relevant web pages at the top for user queries. [11] proposed a personalized ranking mechanism based on a user's search and click history. [12] proposed a deep learning-based search ranking framework that can expeditiously update the ranking model by capturing real-time user clickstream data. [13] proposed a framework that combines contextual information with advanced information representation techniques to help existing web tools understand domain-specific concepts and provide more accurate and personalized results. This framework, which integrates information representation and long-term memorization, has been found to enhance the search engine experience, offering the potential for more personalized and contextually accurate results. [14] aimed to develop a collaborative search engine that helps reach specific decisions by improving search quality through the inte-gration of user experiences with hierarchical user profiles. They uploaded the collected data to recommendation servers of search engines like Google/Yahoo. [15] presented a new personalized search engine based on user keyword profiles and long-tail keyword optimization techniques, aiming to provide better results in terms of relevance, recall rate, and accuracy compared to existing search engines. The model was developed using the Hypertext Preprocessor platform for simulation. [16] proposed a Cognitive Personal-ized Search (CoPS) model that integrates Large Language Models (LLMs) with a cognitive memory mechanism inspired by human cognition. CoPS, which uses LLMs to enhance user modeling and search experience, used a three-step approach supported by sen-sory memory for quick responses, working memory for sophisticated cognitive re-sponses, and long-term memory for storing histor-ical interactions. According to the experimental results, CoPS was indicated to outperform baseline models in zero-shot scenarios.

Nevertheless, these previous studies focus on finding items aesthetically similar to the textual or visual query without considering the query personalization aspects. Unlike the studies in the literature, a personalized search engine is proposed, which is fed with the product data of the e-commerce site trendyol.com operating in the fashion-oriented retailing sector. In comparison to the studies from the related literature, the study has many innovative aspects;

- Search engine can index and merge different formats such as Comma-Separated Values, eXtensible Markup Language, and JavaScript Object Notation from various sources.
- Search engine can dramatically edit the search phrase when the search engine cannot find a match in the subword, e.g. by changing letters.
- Search engine supports multiple languages.
- Option to show items from the same store/brand/campaign side by side in search results.
- All network traffic is recorded and analyzed in MSSQL database for volume and customer behavior. Different statistics such as response time and memory usage are monitored.

3. The Purposed Fashion Oriented Personalized Search Engine Figures

Three teams worked together for the development of the Trendyol product sorting mechanism. The Indexing team developed the system where the stock, price, campaign, name, and scores of the products are kept. The Search team created a product pool based on the search term when a search occurs. Data Science creates the scores that will be used to rank the products.

The Data Science team, which calculates the product scores, transfers the data to the Indexing team with the Kafka manager tool. These scores are processed in the database where the information of the products is stored. The Search team, on the other hand, creates the product pool using the database created by the indexing team when a search request comes in and ranks the products according to the scores created by the Data Science team.

For segmented product ranking, the system is managed through different score IDs created on the products. There is a database where customization documents are stored. In this database, the products in the search result of the users who have the document are sorted by the score corresponding to the ID assigned to them. In this way, products are sorted differently for users. Figure 1 illustrates how the entire system works in an end-to-end manner, i.e., what the input is, how the data flows, what each component does, and finally, the output.

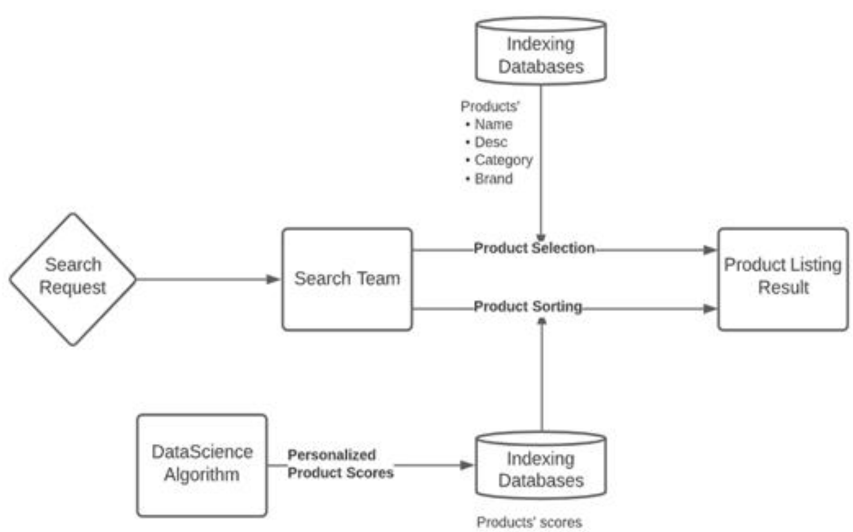

Figure 1. Overview of the Entire System Working in an End-To-End Manner

3.1. Indexing, Search and Data Collection Infastructures

The indexing infrastructure is one of the essential parts of the personalized search engine architecture. The primary goal of this infra-structure is to index millions of documents very quickly and without compromising data consistency. The sources from which the data is collected and the structure that will index the data must work quickly and consistently. To this end, a study has been carried out on which data are needed primarily. According to the results, it was necessary to collect and index the data from approximately ten different places. These places of data include (a) product master data, (b) campaigns to which the product is affiliated, (c) promo-tions that can be applied to the product, (d) suppliers of the product, (e) supplier-based prices of the product, (f) supplier-based stocks of the product, (g) the scores of the product to be used for ranking, (h) information on which supplier will stand out when showing the product, and (i) product brands and categories.

As we prefer the microservice architecture, nine different services are required to collect all these data. On the other hand, R&D stud-ies have been carried out to rapidly index millions of data from so many various sources. The actor model was preferred for indexing a large amount of data. According to the actor model approach, after collecting common data, thousands of actors at the same time will process thousands of products in parallel and allow them to be indexed. After deciding on the indexing model, it was time to choose which programming language to encode it with. Options included .NET Core, JAVA, and Scala. As the language in which the actor model works best and effectively, Scala came to the fore in all our research.

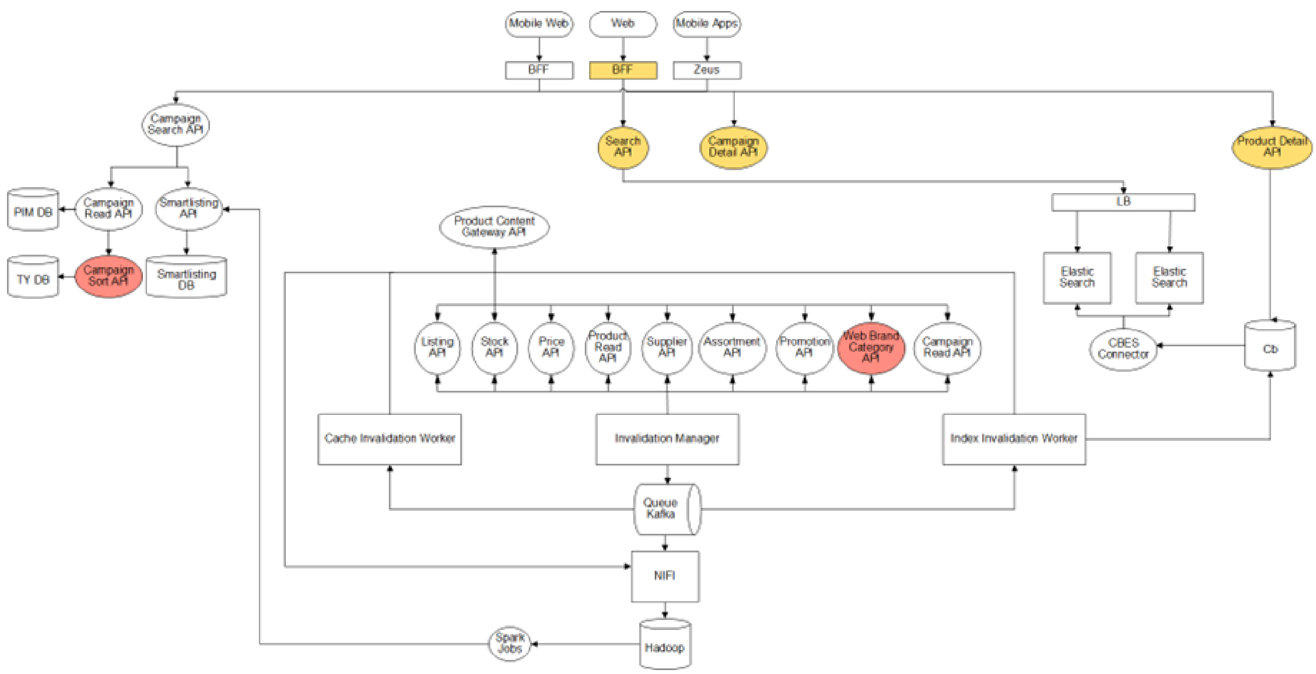

Figure 2. Indexing Infrastructure

Figure 2 shows the indexing infrastructure. Product Content Gateway API collects all the required data like stock, price, promotion etc. from different APIs to create content data. Index Invalidation Worker gets the content data from Product Content Gateway API and sends them to our ElasticSearch and Couchbase data sources. Product Detail Services use Couchbase data source and Search Services use ElasticSearch data sources. Content data is sent to Hadoop via Nifi jobs. Our Spark jobs use these data to calculate listing and campaign scores. Campaigns and contents are sorted according to these scores.

The design of the search infrastructure was the work we started in parallel with the design of the indexing infrastructure. When we reveals our needs in this process, features such as searching, filtering, sorting, error correction, and automatic suggestions ap-peared. The ElasticSearch structure, which we can use as an open source for both the suggestion system and search pages, has been pre-ferred. Figure 3 illustrates the designed search infrastructure.

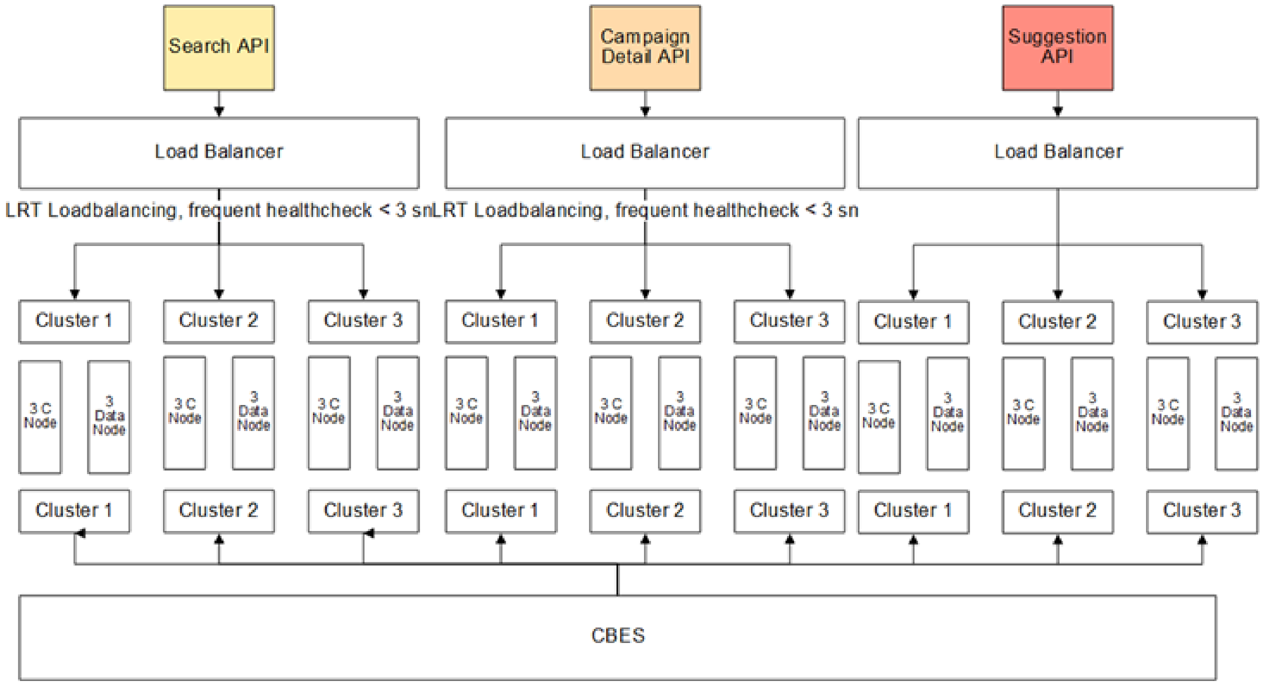

Figure 3. Search Infrastructure

The clusters shown in Figure 3 are ElasticSearch clusters that contain multiple nodes. We have both master nodes responsible for the cluster's health, and data nodes responsible for writing and reading operations. We have tried many configurations for the performance and found out that master nodes and data nodes are essential. The indexing system is responsible for write operations. Search and Campaign Detail APIs provide search services. They convert different types of requests to queries which will be run on ElasticSearch clusters. Suggestion API is an autocomplete service that suggests related keywords while the user starts typing the keyword for search. Since there are multiple ElasticSearch clusters behind each service, load balancer systems have been enabled to cause equal load on each cluster and provide high availability. The load balancer is checking the health of each cluster and forwards queries in the order of Least Response Time (LRT) pattern. So, the faster the clusters the more queries they execute.

Another critical decision is the design of the data collection infrastructure that we will use for personalization. It must serve the personalization infrastructure by collecting all the customers' activities, even under high traffic. Since the size of the data to be collected would be very large, the cloud seemed to be the best solution. We need to collect and process terabytes of data. From an architectural point of view, we thought of a structure as illustrated in Figure 4. Our clickstream application collects user events from our several clients (i.e., web, mobile web, and mobile apps). Once data has been sent to the application, it immediately stores it on several topics in our Apache Kafka cluster. An Apache Flume application continuously ingests topics and writes the user data to object storage to the cloud provider we are using. Our batch Apache Spark applications run in a scheduled way, process new raw data in object storage, and store it in object storage again. We have many tables in Apache Hive Metastore, pointing to the processed data paths in object storage, so processed data can be queried via Apache Hive or Presto query engine. Lastly, reporting applications like Tableau use Presto to create analytics reports.

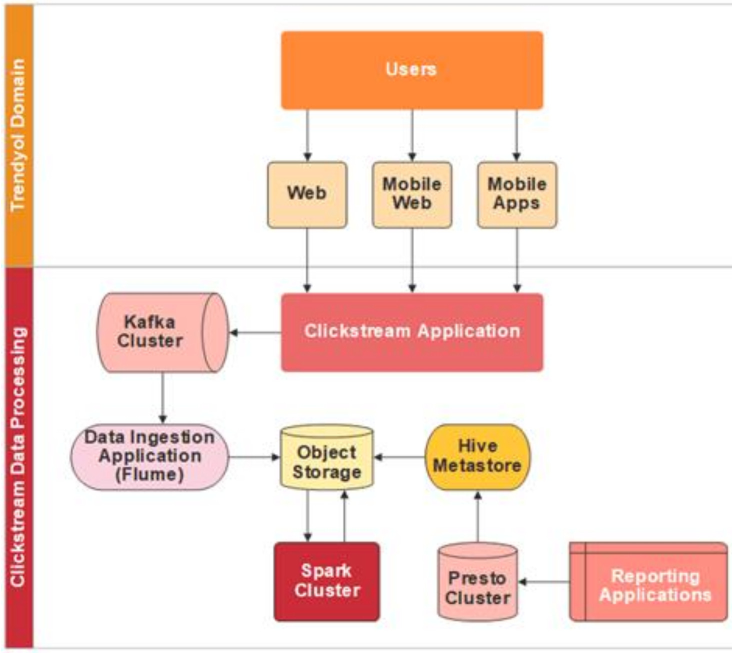

Figure 4. Data Collection Architecture

3.2. Brand-Based User-Segmented Product Listing Algorithms

The purpose of the brand-based user-segmented product listing algorithm is to prioritize the products the user may be interested in by making segment-based product sorting. To make segment-based product sorting, user segments must be created first. To create user segments, brands are first divided into segments. Then, users were assigned to these brand segments so that user segments were created. Then, product sales prediction models specific to user segments were designed and product scores were studied for segment-based product ranking.

Products belonging to approximately 550 different brands in the fashion category are used for brand segmentation. Three different methods were studied for segmentation. The first method segments the brands into different numbers of quantiles only according to their prices (such as cheap, medium, and expensive brands). The second approach intends to create features of brands (i.e., price, relative price to category, ratio, filter count, impression 14Day etc.) and make a segmentation on this feature space. Another method is to use BuytoBuy, SearchtoSearch and VisittoVisit similarity metrics. The rationale is to calculate BuytoBuy similarity between brands A and B, while calculating a similarity between sessions where brand A sells and sessions where brand B sells, using the intersection over union (IoU) method. This value should always be between 0 and 1 regardless of its volume (i.e., brands A and B never sold in the same session = 0; brands A and B always sold in the same session = 1; and being symmetrical (sim (A, B) = sim (B, A)). Subsequently, a brand similarity matrix of 550x550 is formed, and brand clusters are formed by clustering methods. DBSCAN, K-Means, and K-Medoids were used as clustering methods. With these methods, brands are clustered so that the number of clusters varies between 1 and 20.

Assigning users to brand clusters answers the following question: For every user, what is the most likely brand-cluster that he/she will place an order? To this end, shopping possibilities for all brand clusters are calculated for each user with logistic regression. The model calculates the probability of a user to shop on a brand in the next seven days based on the values of product visit count, favorite product count, product order count, product basket count, product order count target in the past 28 days. Users are assigned the brand segment with the highest probability to shop.

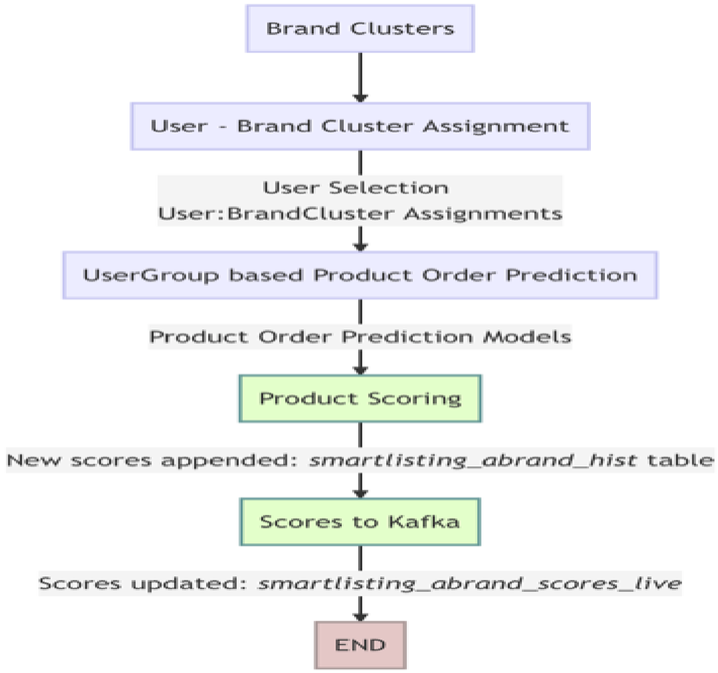

Figure 5. Flowchart of Brand-Based User-Segmented Product Listing Algorithm

Figure 5 illustrates the steps followed by the brand-based user-segmented product listing algorithm. First, the best brand sets are extracted according to the metrics we use (Brand Clusters). Then, the probability of purchasing products from these sets is calculated for each user, and these users are included in the brand sets (User - Brand Cluster Assignment). For each cluster created by the users defined in the brand sets, the purchasing forecast of all products on the site is modeled (UserGroup based Product Order Prediction). Hourly script runs to change product scores on the site, and order predictions are prepared by normalizing in accordance with the score scale on the site. Product and score information is added to the smartlisting_abrand_hist table at the end of each job (Product Scoring), where historical data is kept. Product scores are left to Queue Kafka shown in Figure 1, and current product scores are held in the smartlisting_abrand_scores_live table (Scores to Kafka).

For each user segment, a product-based sales forecast model was trained using only people's purchasing behavior in that user segment. Here, the sales volume of the products in the next 12 hours from the user segment data of the last one month is estimated.

4. Results and Discussion

As the result of this research, a personalized search engine, fed with the product data of the e-commerce site trendyol.com, has been developed to recognize and help online shoppers find what they are looking for and discover a broader and more relevant range of products in the trendyol.com catalog. In more detail, the following activities were carried out and successfully implemented within the scope of the project;

- Real-time synchronization and catalog indexing,
- Combining and synchronizing different data sources and formats,
- Creating a list of related results in addition to direct results,
- Showing query suggestions that will lead to similar results such as the original query,
- Making suggested spelling corrections,
- Automatically solving minor typos and generating results without any human intervention,
- Searching for other things than products (e.g., advertisements, blogs, articles, etc.),
- Determining popular queries and auto-complete suggestions and suggestions according to the frequency of popularity,
- Development of static synchronization filters determined by order such as out of stock, available in the store, not yet published.

- Development of filters created based on live dynamic user information,
- Creating a ranking according to popularity,
- Sorting products by any attribute (e.g., popularity, price, newest / oldest, etc.),
- Listing results and categories based on a user's unique personal taste using the browser cookie or user ID,
- Making reflections on all devices used by a person with cross-device personalization.

The proposed personalized search engine went live on January 2022, and its efficiency has been compared to our previous platform based on quarter 1 (Q1) of the years 2021 and 2022. Table 1 shows the comparison results.

Table 1. Comparing the personalized search engine and our previous platform

	Previous Search Platform	Proposed Search Platform
Listing rate of products that personally fits users	2021 Q1: 33%	2022 Q1: 72%
Loading time of search results	2021 Q1: 0.83 s	2022 Q1: 0.65 s
Users shopping rate	2021 Q1: 69%	2022 Q1: 81%
Query personalization	n/a	Personalized site search
Fashion-oriented search capabilities	n/a	Available

5. Conclusion and Future Work

In this study, a fashion-oriented and personalized site search was enabled that successfully reveals products that have never been thought of before by directly associating the products the customers wanted. The index, search, and data collection infrastructures and a brand-based user-segmented product listing algorithm have been designed to realize the search engine. The results show that personalizing the search queries increase the odds of success. With the development of the personalized search engine, it is expected that Trendyol's revenues will grow in a short time through users visiting the site.

With the experience and results we gained in this study, we need to include more users in the personalization structure with the growing product pool and user base. We aim to increase the number of clusters we had created from 5-6 levels to 100-500 clusters in the next steps. However, we are planning to obtain more accurate product sets for all product groups on the site by adding non-fashion products to the product sets we use in clustering. We aim to provide the user with a dynamic and personal experience in all search results on Trendyol by meeting the computational power needed in the new structure with more effective and scalable data flows.

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Original Paper

Comparative Analysis of Face Recognition Algorithms for Facial Recognition in Diverse Environments

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Abstract

Facial recognition technology has evolved significantly over the last five decades and plays a central role in various applications such as biometrics, information security, access control, law enforcement and surveillance. In this study, the performance of two face recognition algorithms, Dlib and FaceNet, is evaluated using datasets obtained from video recordings in different environments. The Dlib algorithm uses the Histogram of Oriented Gradients (HOG) method for face detection, while FaceNet uses the Multi-Task Cascaded Convolutional Neural Network (MTCNN). The experimental results show that both algorithms achieve high accuracy in controlled environments, with Dlib showing greater robustness in complex scenarios. This study makes an important contribution to this topic by presenting a comparative analysis of the face recognition performance of the OpenFace, ArcFace, Exadel, and Dlib methods under different environmental conditions and scenarios. The results show that while the tested methods achieve high accuracy in controlled environments, their performance differs in more complex environments. In the results, OpenFace and ArcFace showed lower success rates than the other two algorithms. In particular, Dlib proved superior in dynamic and challenging scenarios, achieving an overall accuracy of 96.1% compared to 94.6% for Exadel. Exadel, on the other hand, performed slightly better in certain controlled environments, highlighting its potential strength in certain applications. These results emphasize the importance of selecting the appropriate algorithm based on the specific environmental conditions and requirements of the application. This research not only improves our understanding of the performance characteristics of leading facial recognition technologies, but also provides practical insights into their use in real-world applications.

Keywords: Face recognition, FaceNet, Dlib, Exadel, CCTV, Alarm Systems

1. Introduction

In today's digital age, facial recognition technology has evolved into a powerful tool with wide-ranging applications in various fields. What began nearly five decades ago as a nascent field of research in pattern recognition and computer vision has now evolved into a sophisticated technology capable of identifying individuals with remarkable accuracy. This technological advancement has paved the way for widespread application in areas such as biometrics, information security, access control, law enforcement, smart cards, and surveillance systems.

Rapid advances in computer technology have catapulted facial recognition systems to new heights, surpassing human capabilities in many tasks. With the ability to analyze and match facial features with unprecedented precision, these systems have become indispensable when it comes to enhancing security, streamlining identification processes, and enabling efficient surveillance in various scenarios. The proliferation of facial recognition technology has sparked discussions about privacy, ethical considerations, and the need for responsible implementation. Finding the right balance between the benefits of this technology and dealing with potential risks remains a key challenge for societies worldwide [1].

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However, the proliferation of facial recognition technology has triggered discussions about privacy, ethical considerations and the need for responsible implementation. The collection and storage of biometric data raises significant concerns about data security and potential misuse. In addition, the use of facial recognition systems in public spaces has led to debates about individual privacy rights and the potential for mass surveillance. To gain public trust and achieve social acceptance, it is important to ensure that these technologies are used in an ethical and transparent manner.

Finding the right balance between the benefits of this technology and dealing with potential risks remains a key challenge for societies worldwide. Policymakers, technologists, and ethicists need to work together to develop robust frameworks for the use of facial recognition technology. These frameworks should address issues such as consent, privacy, algorithmic bias, and accountability. By promoting a multidisciplinary approach, it is possible to harness the potential of facial recognition technology while protecting individual rights and promoting ethical standards.

2. Literature Review

Ahmed A. Elngar and Mohammed Kayed propose a vehicle surveillance and alarm system that uses biometric authentication based on IoT technology to enhance vehicle security. The system, called VSS-IoT, uses a Raspberry Pi 3 Model B+ development board, a Pi camera, a PIR sensor, and a smartphone interface to grant full access only to authorized drivers. The proposed algorithm uses the Haar cascade method to detect faces and a customized PCA algorithm for identification. The VSS-IoT achieved an accuracy of 98.2% on the ORL dataset and 99.6% on their own dataset [2].

According to the study by Dhimas Tribuana et al. [3], a compact model was developed using MobileNet V2 and Transfer Learning for the Raspberry Pi platform, which contains five facial recognition classes and one class for unknown faces. The model showed an accuracy of 97.29%, a perfect recognition of 100% and a precision of 89.7%, making it an effective and feasible solution for secure access control in office environments [3].

In their study, Sergei Shavetov and Vladimir Sivtsov conducted a comparative analysis of face detection algorithms, including MTCNN, FD-CNN, and Viola Jones. In the test results with the FDDB dataset (5171 faces from 2845 images), MTCNN showed superior performance, achieving an Area Under the Curve (AUC) value of 0.944. In addition, FaceNet was used due to its superior performance in face recognition in the LFW dataset, using a deep learning-based approach to detect spoofing attempts. Moreover, to improve the performance of the proposed system, the system uses image processing techniques such as image resizing, face cropping, and sharpening [4].

In another work, a CNN framework developed for robust face recognition in uncontrolled environments is presented. This study emphasizes the effectiveness and flexibility of the model by using aggressive data augmentation and an adaptive fusion strategy. In particular, the high success rates of 99.2% on the LFW dataset and 96.63% on the YTF dataset emphasise the effectiveness of this approach. Their model approaches the accuracy rate of FaceNet by about 0.66%. Ultimately, FaceNet was trained on a large database of 200 million photos of eight million people [5].

In a survey by Li et al. [6], face recognition technology is explored from various perspectives, encompassing its development stages, underlying technologies, research on real-world applications, evaluation metrics, standard databases, and future directions. The authors perform a comparative analysis of various datasets, considering factors like the number of individuals included, image variations, and difficulty levels. Additionally, they compile successful methodologies employed within these datasets and offer a comprehensive survey of existing techniques present in the current literature [6].

In this study, the Dlib face recognition algorithm, available via the repository on GitHub, and the FaceNet algorithm, implemented via the open source project Exadel, were used. The OpenFace and ArcFace algorithms, available via the repository on GitHub DeepFace. The facial recognition performance of these four systems was tested on four self-generated datasets. The test samples, which originate from video recordings, were processed according to specific guidelines in order to obtain meaningful results. The results of these four approaches were compared and reported to evaluate their effectiveness in face recognition [7, 8, 9].

Table 1. Comparison of Studies in the Literature with Our Study

Algorithm/Technique	Accuracy (%)	Dataset	Authors
AlexNet	100	ORL	Atsu et al. [10]
LeNet	96.67	YALE	Atsu et al. [10]
SVM + PCA	88	Custom	Radhika et al. [11]
MLP + LDA	87	Custom	Radhika et al. [11]
CNN	98	Custom	Radhika et al. [11]
DCNN + DeepFace / ArcFace	87.5	Custom	Özlem Güven [12]
Dlib	96.1	Ours	-

Various literature studies were searched and the performance of the algorithms was compared, as shown in Table 1. In the study conducted by Atsu Alagah Komlavi and his team, the results of certain models were shared on two different datasets. The study concluded that deep learning-based models perform better with increasing data size. Among these studies, the best results were obtained by AlexNet on the ORL dataset and by LeNet on the YALE dataset. The ORL dataset contains 400 images from 40 different individuals, while the YALE dataset contains 165 images from 11 different individuals. AlexNet achieved an accuracy of 100% on the ORL dataset, while LeNet achieved an accuracy of 96.67% on the YALE dataset [10]. In the study conducted by Radhika C. Damale and his team, a custom dataset was used, but no information was provided on the size of the dataset. In this study, the highest accuracy rates were achieved by CNN, SVM+PCA and MLP+LDA with 98%, 88% and 87% accuracy, respectively [11]. Özlem Güven's study aimed to identify and authorize drivers. The data collected from her own drivers included 578 images of 50 different people. The tests conducted with DCNN + DeepFace / ArcFace achieved an accuracy of 87.5% [12]. The above comparisons clearly show the performance of the different studies on different datasets. Using this analysis, we compared and evaluated our own results with existing work in the literature.

The use of different video datasets created by the researchers allowed for an exemplary application study that significantly expanded the scope of the work by using a higher number of video samples compared to many existing studies in the literature. Careful consideration of the distribution of different individuals, genders, and age groups makes the study's contribution to the literature even greater. This approach enables a detailed evaluation of the performance of face recognition algorithms in different demographic groups. The comprehensive test conditions used in the study take into account possible biases that can occur in face recognition systems.

Compared to the existing literature, this study provides a unique contribution by specifically analyzing the performance of OpenFace, ArcFace, Dlib, and Exadel FaceNet in different real world environments. Previous studies often focus on controlled environments and provide limited insight into real world applicability. For example, previous research on Dlib has typically emphasized its effectiveness in static environments with uniform illumination and minimal occlusion without thoroughly investigating its robustness in dynamic scenarios. Similarly, studies on FaceNet have largely focused on its high accuracy in benchmark datasets, but without thoroughly investigating its performance under different environmental conditions.

Our study fills this gap by providing empirical evidence of how these algorithms perform in both controlled and complex, real-world environments. This comparative analysis underscores the need to evaluate face recognition algorithms beyond standard benchmarks, taking into account real world challenges.

3. Material and Method

This section describes the dataset used and the methods used for face detection, face embedding, and face identification. The dataset consists of video recordings from different locations showing people in different scenarios. Advanced algorithms are used to recognize faces in these videos. Subsequently, face embeddings are generated using architectures such as FaceNet and Dlib. The final step is face identification, where algorithms predict identities based on these embeddings. The experimental setup outlines the rules and procedures for processing the videos and evaluating the facial recognition systems.

3.1 Data Sets

The recordings include scenarios in which people move from about 5 meters away to 1-2 meters close to the camera. For the testing processes, 4 datasets were created with video records collected from different locations. The videos were recorded at the following locations: Biges Warehouse (16 videos), Hybrone Turnstile Area (61 videos), Biges Office Room(31 videos), and the Hybrone Test Room (22 videos). These different settings enable a comprehensive view of the test subjects from different perspectives.

These test videos record people from CCTV cameras positioned at a maximum distance of 5 meters. The people can enter the frame either at the beginning or at any point during the video. Although different cameras were used, all videos in this set were recorded at a high shutter speed of 25 fps and a resolution of 1920x1080.

3.2 Face Detection

Facial detection is the process of identifying and localizing human faces in images or videos. It is a crucial first step in many facial recognition and analysis systems. This process usually involves the use of machine learning models that are trained to recognize facial features and distinguish them from other objects in the image. Once a face has been recognized, the system can analyze and process the facial data for various applications such as authentication, tracking, and identification [13].

Dlib

Dlib uses the Histogram of Oriented Gradients (HOG) method for face detection, which captures the distribution of gradient orientations in an image to identify facial features. This method is known for its accuracy and efficiency in recognizing faces in images and videos [7, 14].

Exadel

Exadel uses the Multi-Task Cascaded Convolutional Neural Network (MTCNN) for face detection, a deep learning-based method known for its robustness in detecting faces under different conditions [11]. MTCNN uses a cascaded architecture to detect faces at different scales and accurately localize facial features [8, 15].

RetinaFace

RetinaFace is a cutting-edge facial detection algorithm using deep learning to achieve high accuracy and robustness. It employs a multi-task learning framework for face detection, landmark localization, and pose estimation. This algorithm has shown superior performance on benchmark datasets, making it widely adopted in research and practical applications [16].

3.3 Face Embedding

Face embedding is a technique used to represent facial images as numerical vectors in a high-dimensional space to capture the unique features of each face. Algorithms such as FaceNet and Dlib are commonly used to generate face embeddings and enable efficient comparison and recognition of faces [17].

FaceNet

FaceNet, a deep learning architecture developed by Google, achieves remarkable performance with an accuracy of 99.58% on the Labeled Faces in the Wild (LFW) dataset, proving its efficiency in facial recognition under different conditions and in different environments [18].

Dlib

The Dlib face embedding algorithm uses a metric learning approach based on deep metric learning techniques, enabling accurate verification of face pairs. This algorithm achieves high performance in determining whether two facial images belong to the same person or not, which makes it suitable for face recognition tasks [19].

OpenFace

OpenFace is a leading facial recognition algorithm that uses deep learning to provide high accuracy and flexibility. It is designed for facial landmark detection and face alignment, offering robust performance on various datasets. This algorithm is widely used in both research and practical applications due to its open-source availability and effectiveness [20].

ArcFace

ArcFace is an advanced facial recognition algorithm that leverages deep learning to deliver superior accuracy and robustness. It utilizes an additive angular margin loss to enhance discriminative feature learning, improving face verification and identification. ArcFace has consistently outperformed other methods on benchmark datasets, making it a preferred choice in academic and practical settings [21].

3.4 Face Verification

Face verification is the identity of a person that is determined on the basis of their facial image. The facial features extracted from an input image are compared with the features stored in a database of known faces so that the system can identify the person if a match is found. Both the Exadel and Dlib methods use the Euclidean distance metric to compare the feature vectors extracted from the facial images. Both the ArcFace and OpenFace methods use the Cosine distance metric to compare the feature vectors extracted from the facial images. This comparison allows the systems to measure the similarity between faces and determine whether they belong to the same person. This method is often used in security systems, access control, and personalized services [22, 23].

3.5 Experimental Setup

The experiments were conducted on a high-performance computer system to ensure accurate and efficient processing of the face recognition tasks. The hardware setup for conducting these experiments includes an NVIDIA 3090ti GPU, which provides significant computing power for processing complex algorithms and large data sets. The system is equipped with 24 CPU cores, 64 GB of RAM and a 2 TB SSD for ample storage capacity. This robust configuration enables the execution of intensive facial recognition processes.

A data set with 5 female and 2 male photos was integrated into the systems for OpenFace, ArcFace, Dlib, and Exadel methods. Subsequently, the images extracted from the videos using the Dlib-based method were subjected to prediction. After prediction, the individual with the highest number of predictions (at least 3 predictions with more than 0.6 confidence) was determined as the final prediction. In cases where there were less than 3 predictions, the result was classified as an unknown individual.
In the Exadel system, the face recognition results were compared with the confidence intervals (between 0.99 and 0.9) extracted from the video images. Rules were then established on the basis of these confidence intervals:

1. Predictions with a confidence interval above 0.98 and a single occurrence were considered correct.
2. For predictions with a confidence interval above 0.98 and 4 or more occurrences, the individual with the highest predictions was considered correct.
3. Predictions with a confidence interval above 0.95 and a single occurrence associated with 8 or more predictions were considered correct.
4. For predictions with a confidence interval greater than 0.95 and 20 or more occurrences, the individual with the highest predictions was considered correct.
5. For predictions with a confidence interval of over 0.90 and 25 or more occurrences, the individual with the most predictions was considered correct.

Both OpenFace and ArcFace methods use RetinaFace for face detection. For OpenFace, more than 5 guesses made by the same person in the video are considered as final prediction, while for ArcFace, this number is chosen as 10. This methodology was applied to all videos to evaluate the performance of both methods.

4. Results and Discussion

The results of our experiments, in which we evaluated the face recognition performance of the OpenFace, ArcFace, Exadel, and Dlib methods on different test sets, show remarkable differences in terms of accuracy, computational efficiency, and robustness to various challenging scenarios. All methods were tested on the same test datasets.

Table 2. Comparative Analysis of ArcFace, OpenFace, Dlib and FaceNet for Accuracy in Different Environments

Environment	Number of Videos	ArcFace	OpenFace	Exadel	Dlib
Biges Warehouse	16	100%	100%	100%	100%
Hybrone Turnstile Area	61	95.10%	62.20%	93.40%	98.30%
Hybrone Test Room	22	100%	22.70%	100%	100%
Biges Office Room	31	74.20%	25.80%	90.30%	87.10%
Overall	130	91.54%	51.48%	94.59%	96.12%

Table 3. Comparative Analysis of ArcFace, OpenFace, Dlib and FaceNet for Precision in Different Environments

Environment	ArcFace	OpenFace	Exadel	Dlib
Biges Warehouse	100%	100%	100%	100%
Hybrone Turnstile Area	95%	39%	94%	97%
Hybrone Test Room	100%	34%	100%	100%
Biges Office Room	88%	9%	93%	88%
Overall	94.79%	38.50%	95.46%	95.54%

Table 4. Comparative Analysis of ArcFace, OpenFace, Dlib and FaceNet for Recall in Different Environments

Environment	ArcFace	OpenFace	Exadel	Dlib
Biges Warehouse	100%	100%	100%	100%
Hybrone Turnstile Area	95%	62%	94%	98%
Hybrone Test Room	100%	23%	100%	100%
Biges Office Room	74%	26%	90%	87%
Overall	91.45%	51.49%	94.63%	96.12%

Table 5. Comparative Analysis of ArcFace, OpenFace, Dlib and FaceNet for F1 measure in Different Environments

Environment	ArcFace	OpenFace	Exadel	Dlib
Biges Warehouse	100%	100%	100%	100%
Hybrone Turnstile Area	95%	48%	94%	98%
Hybrone Test Room	100%	27%	100%	100%
Biges Office Room	77%	13%	89%	86%
Overall	92.16%	42.5%	94.39%	95.48%

The results of the test series show that the face recognition performance of the methods varies depending on environmental conditions and scenario types, as shown in Table 2. Exadel, Dlib, and ArcFace methods achieved 100% accuracy in controlled environments and less demanding scenarios, such as the Biges Warehouse and the Hybrone Test Chamber. However, OpenFace was only able to achieve full success on the Biges Warehouse dataset. Dlib (98.3%) showed higher accuracy than Exadel (93.4%) in the Hybrone Turnstile Area. ArcFace accuracy has decreased with more complex enviroments. This suggests that Dlib may be more resilient to more complex environmental factors and moving regions. Although Exadel (90.3%) achieved slightly higher accuracy than Dlib (87.1%) in the Biges Office Room, the performance of both methods decreased in this more challenging environment. Overall, Dlib achieved an accuracy of 96.1%, outperforming Exadel's overall accuracy of 94.6%. Although the ArcFace method achieved better results than the OpenFace method, it fell behind the other two methods.These results indicate that although Dlib generally performs better, it demonstrates greater resilience in certain complex scenarios. But OpenFace result Data Management Center (DMC) Alert was not triggered in any scenario, but different environments present different challenges.

Table 6. DMC Alarm State in Different Environments

Environment	ArcFace	OpenFace	Exadel	Dlib
Biges Warehouse	0	0	0	0
Hybrone Turnstile Area	1	0	0	0
Hybrone Test Room	0	0	0	0
Biges Office Room	7	4	0	0
Overall	8	4	0	0

As part of our system, we have a product called Data Monitoring Center (DMC), which is used by our alarm monitoring center. The inclusion of the DMC alarm status in Table 6 is critical due to its role in our security protocol. A DMC alarm is triggered when an unidentified person disarm security panel. This results in an automatic alarm being sent and our staff contacting the customer to inform them that an unidentified person has disarm the panel and the police are sent to the address. This means that the face recognition system misidentifies a known person as unknown, which can lead to significant security responses. Therefore, the inclusion of the DMC alarm in the table emphasizes the practical implications of misidentification by our facial recognition system and highlights the need for high accuracy to avoid false alarms and ensure reliable security measures. These results show that the Exadel and Dlib methods can be successful under ideal test conditions, but the OpenFace and ArcFace methods are not suitable.

5. Conclusion

The comparative analysis of the algorithms of Dlib and Exadel shows that both methods are very effective in face recognition tasks, especially in controlled environments. Dlib proved to be consistently more robust in more complex and dynamic environments, such as the Hybrone Turnstile Area. In contrast, Exadel FaceNet showed slightly higher accuracy in the Biges Office Room. Overall, the comparative evaluation shows that Exadel achieved a higher accuracy of 96.1%, while Dlib demonstrated a slightly lower overall accuracy of 94.6%, though Dlib proved to be more robust in complex environmental scenarios.

These results suggest that while both algorithms are suitable for high-accuracy face recognition, the choice of algorithm may depend on the specific challenges of the environment and the requirements of the application. The study highlights the importance of considering both algorithm performance and environmental factors when deploying facial recognition systems in real-world scenarios. Further research could investigate hybrid approaches that leverage the strengths of both methods to optimize performance under different conditions.

The practical applications of the results obtained from this study are significant and far-reaching. The comparative analysis of face recognition methods under different environmental conditions provides important insights for the use of these technologies in practice. The higher overall accuracy and robustness of Dlib in dynamic and complex scenarios suggest that it is suitable for environments such as public transportation hubs, surveillance in crowded areas, and dynamic office environments where variability and movement are prevalent. Conversely, Exadel's slightly better performance in controlled environments highlights its potential for secure access control in stable environments such as warehouses and test chambers.

Furthermore, the integration of these results into security systems such as our Data Monitoring Center (DMC) highlights the importance of reliable facial recognition to avoid false alarms and ensure a timely and accurate response to security breaches. By demonstrating that Dlib is generally more resilient in complex scenarios, organizations can make informed decisions about deploying this technology in highly sensitive environments, improving security measures and operational efficiency. This study highlights the need to select the appropriate facial recognition algorithm based on specific application needs and environmental challenges, ultimately contributing to the advancement and optimization of security systems worldwide.

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Original Paper

Development of an Autonomous UAV-Based Irrigation Decision Support System Utilizing Image Processing and Machine Learning Techniques

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Abstract

Efficient management of water resources is essential for sustaining the global food supply amidst growing populations and climate change. Traditional irrigation methods are often plagued by inefficiencies, leading to significant water wastage. This paper presents the development and validation of an autonomous UAV-based irrigation system that leverages advanced image processing and machine learning techniques to optimize water usage in agriculture. The system employs standard low-cost cameras to capture high-resolution aerial images, which are processed to accurately predict the water needs of the plants and inform irrigation deci-sions in real-time also it can do autonomous watering by controlling the electrical water valve in the specified irrigation areas. Comprehensive field tests conducted on pepper crops demonstrate the system's ability to enhance water use efficiency and improve crop yields. By integrating state-of-the-art technologies such as TensorFlow techniques, scikit-learn and Convolutional Neural Networks (CNNs) for machine learnig with an overall accuracy of 91% and Precision of 85%, image analysis and autonomous navigation capabilities, the proposed solution represents a significant advancement in precision agriculture. As a conclusion, the developed system waters the crops where and when it needed. So as a result, it reduced water consumption up to 31.5% while maintaining or enhancing crop productivity, thereby promoting sustainable agricultural practices.

Keywords: Precision agriculture, autonomous UAVs, image processing, machine learning, irrigation management.

1. Introduction

1.1 Background

Global Water Resources and Agriculture

Water resources are vital for the global population, with agriculture being a significant consumer (Figure 1.). However, increasing demand, deteriorating water quality, and declining groundwater levels threaten these resources. In Turkey, high investment costs and challenging terrain hinder the full utilization of water resources, leading to significant water wastage due to a lack of precise irrigation knowledge [1].

Challenges in Traditional Irrigation Methods

Traditional irrigation methods often rely on fixed schedules or manual observations, leading to inefficient water use. It often result in overwatering or underwatering, leading to water waste and suboptimal plant health [3]. It also Require significant manual labor for monitoring and adjusting irrigation schedules. So as a result it may involve higher operational costs due to inefficient water use and increased labor requirements [4,5]. While the developed system ensures water is applied only where and when needed. It also can control water valves to manage irrigation autonomously. This approach not only conserves water but also reduces operational costs.

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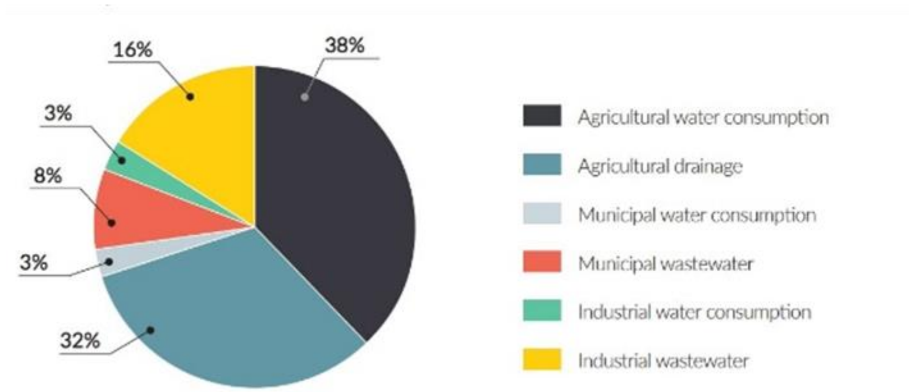


Figure 1. Water usage percentages [2]

Emergence of Precision Agriculture

Precision agriculture (PA) uses technology to optimize field-level management, improving the efficiency of inputs like water, fertilizers, and pesticides by considering soil and crop variability [6]. Key technologies include remote sensing, GIS, and variable rate technology (VRT). One way of PA is to use soil mositure sensors across the large fields but it has some limitation. Require a large number of sensors to cover extensive fields, leading to high initial setup costs, also it need regular maintenance and calibration to ensure accuracy, which can be labor-intensive and costly [3]. Another method is to use satellites but it has some limitations. It provide large-scale data but with lower resolution compared to UAVs, making it less precise for field-level water predictions, also its subject to longer revisit times, mean-ing data may not be as up-to-date [7]. While the developed system uses live image processing and machine learning to estimate the water need so it doesn't use soil moistre sensors. Also compared to the satellite images it takes live images and can work for small scale fields so it doesn't have the limitations of the satellites.

Role of UAVs in Precision Agriculture

UAVs are valuable in precision agriculture for capturing high-resolution aerial imagery and real-time data [8]. Equipped with multispectral and thermal cameras, UAVs monitor crop health, soil moisture, and pest infestations, enabling informed decision-making and optimized resource use. But it has the following limitaions like equipment cost; high-end thermal imaging UAVs are expensive, with costs ranging from several thousand to tens of thousands of dollars [9]. Data Processing Costs, it require advanced processing capabilities and software to interpret thermal data, adding to the overall cost. Finally, thermal imaging UAVs Provide detailed thermal maps, but interpreting these maps requires expertise and may not directly translate to water needs [10]. While the developed system of this paper aimed to reduce the cost of the drone by developing a low-cost autonomous drone using open source flight controller and softwares. It eliminated the need of high cost thermal and multispectral camera by using a low cost standart camera supported with machine learing. Fially the data processing is user friendly since it shows te reslts in term of graphes and watering commands even it can do watering autonomously.

1.2 Objectives

To address the problems and limiations of the topics that mentioned above, A unique system was developed that integrates low-cost, high-resolution imaging with advanced machine learning algorithms to provide real-time, precise irrigation management. This system aims to overcome the inefficiencies and high costs associated with traditional and current advanced methodologies, offering a practical and affordable solution for farmers.

2. Material and Method

2.2 System General Description

In response to the critical need for efficient water management in agriculture, this research proposes the development of an advanced Image Processing and Machine Learning-based Irrigation Decision Support System (IDSS) utilizing autonomous UAV technology. This innovative system aims to address the inefficiencies of traditional irrigation methods by providing precise, real-time assessments of the water needs of the plants and to do autonomous irrigation. Also it aims to create a base to make already trined libraries for different crop types and in different locations to make it available for large number of farmers. The system comprises a robust, lightweight au-tonomous UAV equipped with a low-cost standart camera, GPS, and IMU for data collection and an open source flight controller for autonomous navigation. In the field we have ARUCO markers used for planning and defining the irrigarion areas so under each mark-er we have an electrical water valve to receive the watering commands from the UAV. Each makers has a unique ID and is placed in postion where the UAV can easily detects using the camera that's in the UAV. So simply the UAV autonomously takes off, flies to the already spified markers location while it tries to find the markers starting with the maker that has the first ID. If it detects the marker, it tries to center it to the UAV center even if it doesn't reach the specified location of the marker. After the UAV centers the marker it lowers its altidude to 5 m and makes a circle around that area while it records a video and runs a real time water prediction algoriths. Then it continues to the next marker. The result of the water prediction algorithm is that it gives the quantities of plant that needs water and the ones that does not need water, then it gives the result based on the average of that area to give water order or not to the watering valve.

2.2. Hardware Setup

UAV Frame and Propulsion Systems

The UAV frame is designed to be lightweight yet robust so carbon fiber tubes and plates was used, ensuring stability and durability. also we used PLA 3D printed material to make the cover , landing gears and some sensitive parts (Figure 2.) . It is designed as hexa copter so it is equipped with 6 high-efficiency DC type motors and propellers, electronic speed controllers (ESCs), and an open-source controller (pixhawks), a raspberry pi (used as a mini computer)and a camera. The propulsion system is calibrated to provide stable flight and precise maneuvering capabilities, essential for accurate data collection. To calculate the total time that the UAV can fly, the following formula can be used; $T_{flight}=(Q/\ I_{flight\ load})*60/1000$ .T_{flight} the flight time in minutes. Q, is the LiPo battery capacity in mAh. $I_{flight\ load}$, the total ampers drawn by the motors and other electirical equipments in our case the camera and microproceesor in A. A lithum battary was used with a capacity of 6S 16000mah. And the full load is calculated as 50 A so the total flight time is calculated to be 19.2 min. Due to wind resistance in real life the total flight time was measured to be 16 min 48 s. The time needed for mapping the field of 3600 m^2 (length 60 m x width 60 m) can be calculated using the following formula Time = Distance / UAV speed. Also since it will do a circle around the defined points the time needed to make the circle can be calculated by the finding the circumference of the circle 2 π*radius. The radius of the circle is 15 m and the drone speed is 2.5 m/s. So the time is calculated to be 246.8 s = 4.11 min. Due to wind resistance and the UAV lowers its altitude before staring the circle also it fly higher again so the total measured time needed for the mapping is 6.35 min. The UAV is equipped with a variety of sensors, A high-resolution camera captures detailed aerial images of the agricultural fields also it used to detects marker for mapping of the irrigation area. Also it has a GPS module provides accurate geolocation data, and an inertial measurement unit (IMU) ensures flight stability and navigation accuracy.

Autonomous Operation and Control

The UAV was programmed using python programming language and it implements some open source liabraries such as DroneKit. DroneKit is an open-source library for Python that allows developers to create custom applications for UAVs running the ArduPilot firmware. It provides a high-level API to control and manage the UAV's behavior, making it easier to implement autonomous flight operations [11]. The UAV operates autonomously, following predefined flight paths and executing tasks based on the system's analysis.

- *Flight Planning:* Predefined flight paths are set to ensure comprehensive coverage of the agricultural field. The UAV follows these paths to capture images and collect data.
- *ArUco Markers:* ArUco markers are placed strategically on the ground to aid in the creation of a precise land map and to identify specific areas needing irrigation. These markers, which are two-dimensional barcodes each with a special ID number, are easily detectable by the UAV's camera system (Figure 3.). When the UAV captures images of the field, the ArUco markers provide reference points that facilitate accurate mapping of the terrain. This method enhances the UAV's ability to navigate and precisely locate areas requiring irrigation. So after detecting theses markers the UAV centers the markers and lowers its altidude to 5 m. Then it makes a circle around that loaction while it performs the water need prediction algorithm. After it finishes it continues to the next marker.
- *MissionPlanner* is a ground control station software for the ArduPilot platform. It allows users to plan, simulate, and monitor UAV missions. MissionPlanner provides a graphical interface for setting waypoints, configuring flight parameters, and simu-lating missions in a virtual environment [12]. A lot of improvement, test and edits on the autonomous code was done using

the mission planner simulation software which shows all the detailed simulations by running the code that's the same as the one used in real UAV.

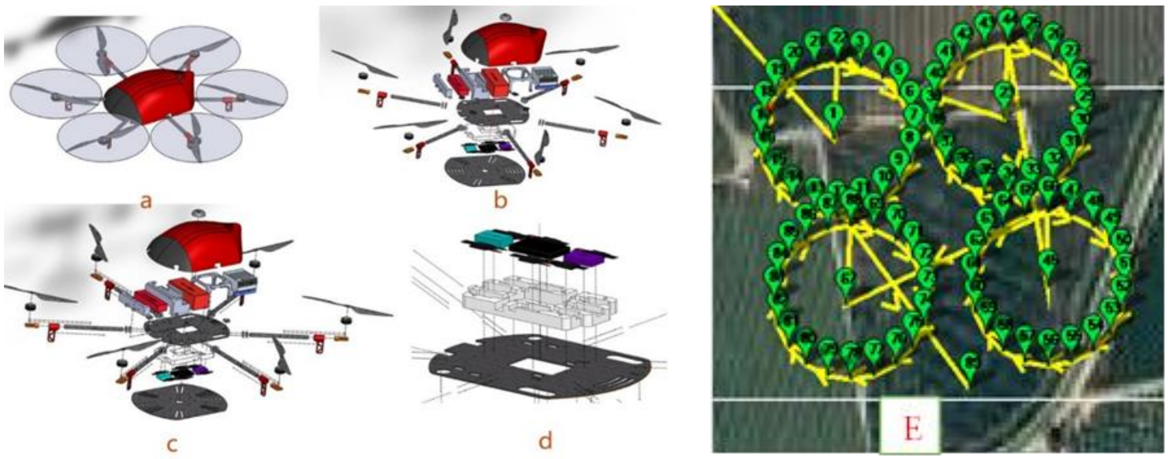


Figure 2. a) 3D Design of the UAV with the component's placements. b, c) The parts of the UAV. d) The placement of electronic components between two parts of the carbon fiber. e) waypoints movement of the UAV in the field. Points 1, 23, 45 and 62 are the center of the circles where the ARUCO markers are located

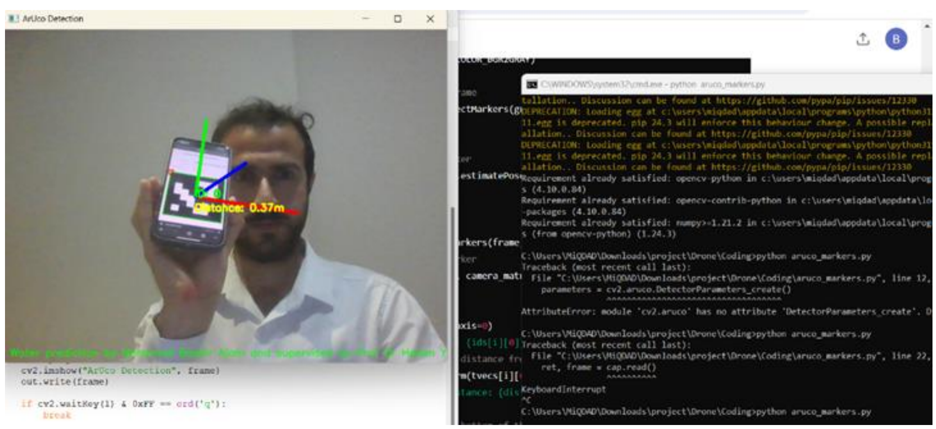


Figure 3. ARUCO marker detection algorithm tests and result

2.3. Software Setup

The development of the system requires a suite of software tools for image processing, machine learning, and data analysis. It analysis the image to detect if it has plant then it trains the system based on a lot of picures of test pepper crope kept at the lab and grouped in there dataset stressed pepper plant, less watered and good watered. After training the system it saves the training file and loads it into the prediction script to perform real time water need prediction.

Image Processing and Machine Learning

The system employs advanced image processing techniques to preprocess each frame of the captured videos. These include noise reduction, geometric correction, and radiometric calibration to enhance image quality. The primary tools and libraries used are Python, OpenCV, TensorFlow, Keras, Scikit-learn, and Mission Planner. Each of these tools plays a critical role in ensuring the efficient operation and accuracy of the system. The processed images are then analyzed using machine learning models, such as convolutional neural networks (CNNs), to predict the water needs of plants. Python serves as the backbone, enabling the use of OpenCV for image processing, TensorFlow and Keras for machine learning, Scikit-learn for data analysis, and Mission Planner for mission planning and execution. This cohesive setup allows for efficient development, testing, and deployment of the system, ensuring accurate and reliable operation in real-world agricultural settings.

Image processing techniques: By employing noise reduction, geometric correction, and radiometric calibration, the images are prepared for accurate feature extraction. Color analysis, texture analysis, and vegetation indices provide quantitative measures that are used to assess crop health and water needs. This cohesive approach allows for reliable and efficient irrigation management in agri-cultural settings. Each technique plays a vital role in ensuring the accuracy and reliability of the system.

- *Noise Reduction*; is used to improve the clarity and quality of the images by removing unwanted random variations (noise) by applying Gaussian Filtering and Median Filtering [13].
- *Geometric Correction*; is used to correct distortions caused by the camera's perspective, lens distortions, and UAV movement, ensuring accurate spatial representation of the image using Homography Transformation [14].
- *Radiometric Calibration*; is used to normalize pixel values, correcting for sensor irregularities and environmental conditions, ensuring consistent and accurate representation of the image's brightness and color [15].
- *Feature Extraction:*
  - *Color Analysis*; is used to detect signs of plant health and water stress by examining the color characteristics of the image. Healthy plants typically exhibit specific color ranges that can be quantitatively assessed by mean of Color Histograms [13].
  - *Texture Analysis*; to assess the texture of the crops, which can indicate water availability and health. Texture features such as roughness, smoothness, and regularity can indicate the presence of water stress or other issues. We use Gray Level Co-occurrence Matrix (GLCM) which measures the frequency of pairs of pixel values occurring at a specified spatial relationship. GLCM is used to extract texture features such as contrast, correlation, energy, and homogeneity.
- *Vegetation Indices*; assess plant health and vigor using indices derived from RGB imagery. These indices provide a measure of plant greenness, which correlates with chlorophyll content and overall plant health. Using Visible Atmospherically Resistant Index (VARI) which is an index derived from RGB imagery that provides a measure of plant greenness [16].

Machine learning models:

- *Deep Learning-Based Feature Extraction*: particularly Convolutional Neural Networks (CNNs), have revolutionized feature extraction by automatically learning hierarchical features from raw image data. CNNs consist of multiple layers, each ex-tracting increasingly abstract features. **Convolutional layers**; apply convolution operations to the input image, using learna-ble filters to capture spatial hierarchies. These layers detect edges, textures, patterns, and complex structures. **Pooling layers**; reduce the spatial dimensions of the feature maps, retaining the most salient features while reducing computational complexity. Common pooling methods include max pooling and average pooling [17,18].
- *TensorFlow* is an open-source machine learning framework developed by the Google Brain team. is used for training and deploying machine learning models. These models analyze processed images to predict the water needs of crops based on extracted features. Key Features: Supports deep learning and traditional machine learning algorithms.Flexible architecture allows deployment across a variety of platforms (CPUs, GPUs, TPUs).Extensive libraries and tools for building machine learning models.Strong community support and comprehensive documentation [19,20]. Key TensorFlow algorithms and techniques used in our system include:
  - **Transfer learning;** leverages pre-trained models (e.g., VGG16, ResNet) trained on large datasets like ImageNet. By fine-tuning these models on our specific dataset, we achieved high performance with limited data and computational resources [21].
  - **Fine-tuning;** is a process where the pre-trained model is further trained on the new dataset with a very low learning rate. This adjusts the weights of the pre-trained model slightly to better fit the new dataset while retaining the learned features from the large dataset [22].
  - **Data augmentation;** is a critical technique in machine learning, particularly in image processing, to increase the diversity of the training data without actually collecting new data. It involves creating new training examples by applying various transformations to the original images. This helps to improve the robustness and generalization capability of the model. Some techniques used; Rotating the image by a certain degree, Shifting the image along the horizontal (width) or vertical (height) axis, Applying a shearing transformation to the image, which tilts the image in a certain direction, Zooming in or out on the image and Flipping the image horizontally [23].

- *Keras;* is an open-source software library that provides a Python interface for artificial neural networks. It is used on top of TensorFlow to simplify the creation and training of complex machine learning models. Its user-friendly API allows for quick prototyping and experimentation with different neural network architectures. Integration with TensorFlow, making it a powerful and flexible tool for deep learning [24].
- *Scikit-learn;* provides simple and efficient tools for data mining and data analysis. It is used for tasks such as feature extraction, data preprocessing, and the training of machine learning models. Built on NumPy, SciPy, and matplotlib. Open-source and commercially usable under the BSD license [25].

Model Training and Validation

The water prediction model was trained on a dataset of annotated plant images, with labels indicating the water needs, three sets of pepper plants was used (Figure 4.) . Each set is labeled with relative training set names: "no-water," "less-water," and "good-water." Each plant is carefully watered to ensure accurate labeling. Images are collected using digital cameras or smartphones. More than 400 pictures were captured from different angles, distances and lightening then grouped for training the system. As a result of the training we got the training dataset file that we upload into the prediction code. The dataset was split into training and validation sets, and the model's accuracy was evaluated on the validation set.

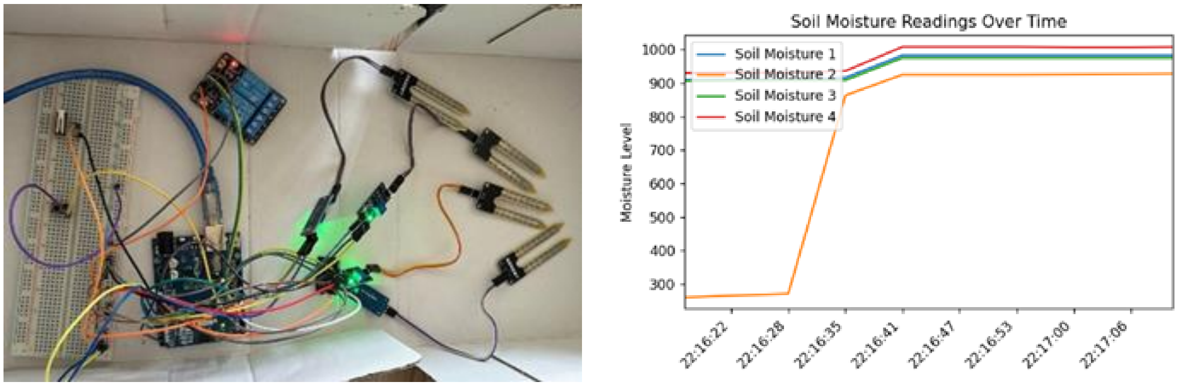
a) b)

Figure 4. a) Pepper crops set up in our lab, b) Pepper crops field in Adana city in Turkey

To ensure the accuracy and reliability of the system, the output results from the image analysis are validated by comparing them with in-ground Arduino-based soil moisture sensors data (Figure 5.). Where moisture content and other relevant data have been recorded and analyzed. This robust benchmarking process provides a reliable measure of the system's performance.

This setup provided accurate and real-time data on the soil moisture levels, which served as the ground truth for the validation process. Also this set automatically water the plant to insure stable pilot plant at the set moisture values all the time.

The predicted water need results are compared with measurements from in-ground sensors to validate the accuracy of the image analysis and machine learning models (Figure 6.). The matrix of the results was created which can show true positive, true negative, false positive and false negative. From that values the system performance interms of, the accuracy, precision, recall, F1 Score is determined.



a) b)

Figure 5. a) Arduino and soil moisture sensors as ground truth set up, b) Soil moisture readings

```
# DATA VALIDATION 2
y_true = [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]  # Ground truth labels
y_pred = [1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, 1, 1]  # Model predictions
```

Figure 6. Validation matrix that compares the prediction results with the ground truth

3. Results and Discussion

As a result two main outputs is optained of this research. The first one is a fully functioning autonomous UAV integrated with water prediction algorithms. The Second output, a base for a user friendly website for water prediction algorithms integrated with AI was developed where a user can upload a video or a picture and it gives the water need predictions with the advices generated with open-AI based on the location and on the crop type.

Evaluation metrics are essential to assess the performance of a water prediction model. They provide a quantitative basis to compare the model's predictions against the actual ground truth data. Here we outline the key evaluation metrics: Accuracy; The proportion of correct predictions (both positive and negative) out of the total predictions made., Precision; The proportion of true positive predic-tions out of all positive predictions made, Recall; The proportion of true positive predictions out of all actual positives in the dataset, and F1 Score; The harmonic mean of precision and recall, providing a balanced measure of accuracy. For the evulation we used 44 test datas, we got the truth ground data gives 22 plants don't need water and 22 plants are stressed and needs water. With an im-proved training the prediction system gave 26 plants don't need water and 18 plants are stressed. With an individual accuracy up to 96.8 % in the ones that doesn't need water and up to 95.99%. in the ones that needs water.

a) b)

Figure 7. a) Prediction of plant that doesn't need water with an accuracy of 96.8% and b) Plant needs water with accuracy of 95.99%

Overall for the validation:

Table 1. Performance measurement

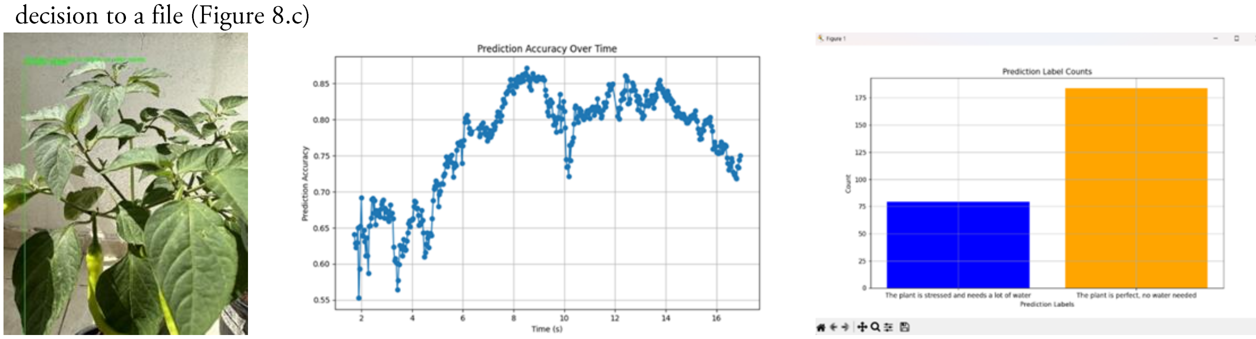
Accuracy	91
Precision	85
Recall	100
F1 score	92

Table 2. The test data

Total tests	44
True positive	22
True negative	18
False positive	4
False negative	0

After training the system with the data sets, a new picture was uploaded and in this case the system uses the live video that's being recorded in the UAV to do the water prediction of the relative irrigation area. The logic of the prediction script is as follows:

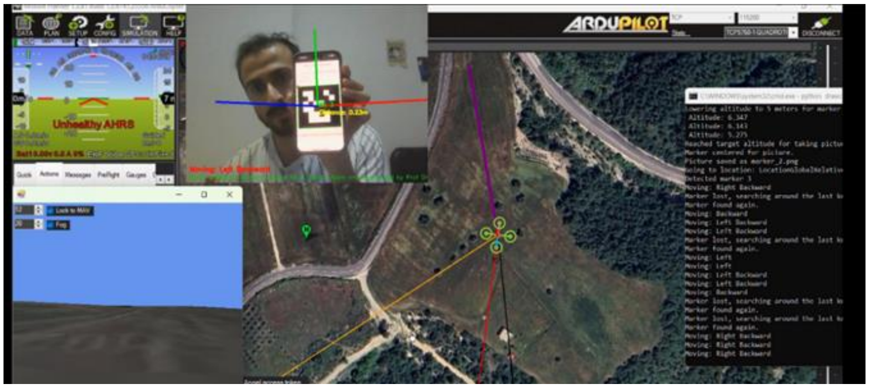
- Video Processing: The script reads the video frame by frame.
- Leaf Detection: Each frame is checked to see if it contains significant green areas (leaves).
- Preprocessing: Frames containing leaves are preprocessed and normalized.
- Prediction: The preprocessed frames are fed into the model to predict whether the plants in the frame need water.
- Annotation: Predicted areas are annotated on the video frames with rectangles and text (Figure 8.a).
- Saving: The annotated frames are saved into a new video with a watermark.
- Plotting: The script plots prediction accuracy over time and the count of prediction labels (Figure 8.b).
- Final Decision: The script determines whether the area needs water based on the most frequent prediction label and saves this decision to a file (Figure 8.c)



a) b) c)

Figure 8. a) The resultant plant with a rectangle showing the plant and the prediction result, b) The accuracy graph over time results, c) The predic-tion result showing the plants that needs water and the ones that doesn't need water

Fully functioning autonomous UAV code successfully integrated with the water prediction algorithm is obtained. As a result it gives the average predicted water need of the irrigations areas which is classified according to the ARUCO marker ID number. So each marker is set as one indepent irrigation area that takes irrigation commands seperatly (Figure 9.b). The autonomous flight code runs successfully in the simulation and in real life. In the simulation it shows the UAV GPS movements,commands sent to the UAV by the code, camera output and the in flight control (Figure 9.a). In the real life we can see the same as the simulation environment when we connect through mission planner software (Figure 10).



a)

```
File    Edit    View

Marker ID 0: The plant is perfect, no water needed
Marker ID 1: The plant is perfect, no water needed
Marker ID 2: The plant is perfect, no water needed
Marker ID 3: The plant is perfect, no water needed
```

b)

Figure 9. a) The full simulation of the autonomous code, b) The prediction code output

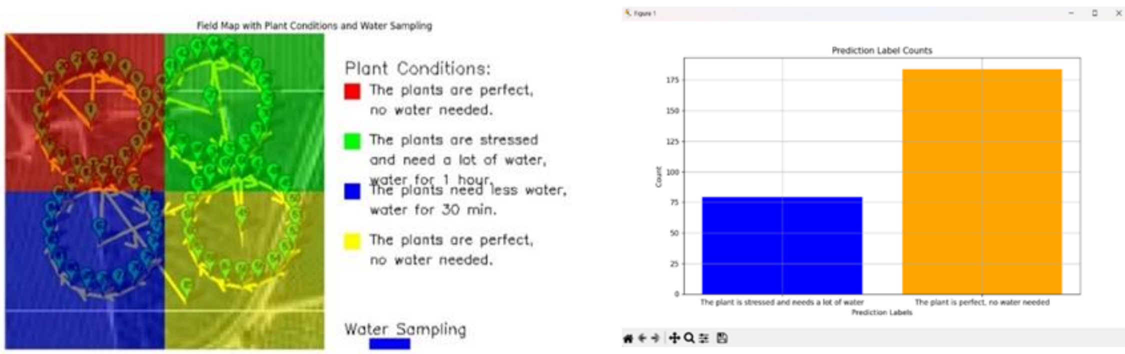
a) b)

Figure 10. a) The flight test of the real UAV, b) The real UAV after combining all the parts

4. Conclusion

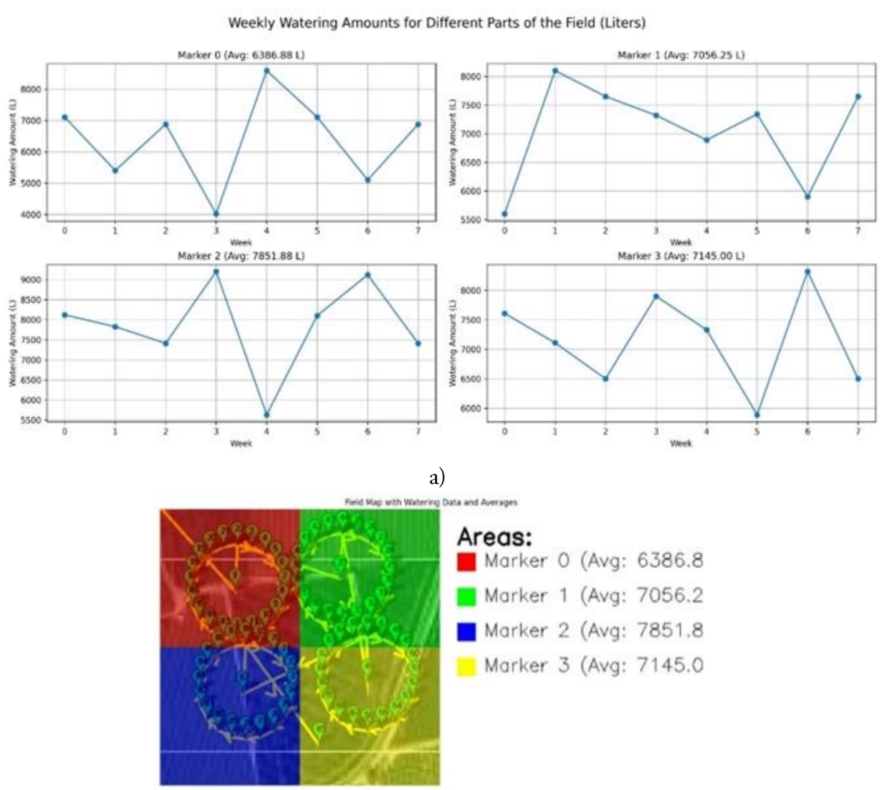
This study successfully developed and validated an autonomous UAV-based irrigation decision support system (IDSS) leveraging advanced image processing and machine learning techniques. Addressing the inefficiencies of traditional irrigation methods, the system utilizes low-cost, high-resolution imaging to provide precise, real-time assessments of plant water needs. The integration of Python, OpenCV, TensorFlow, Keras, and Scikit-learn enabled the creation of a robust solution that optimizes water usage and reduces labor costs.

Field tests on pepper crops demonstrated the system's effectiveness, enhancing water use efficiency and improving crop yields. The system was tested on a 3600 m^2 field of pepper crops. Traditional irrigation methods involved uniform watering schedules, the water consumption was measured the average to be approximately 11.5 liters per square meter per week. In total the average of this field consumed 41520 liters per week continuesly since it was uniform waterig schuales so it led to over watering of some parts of the field and under watering some as a result is consumes a lot of water and effects the crop yields. While the developed system ensures water is applied only where and when needed (Figure 11.). So for this field was devided it into 4 parts each one defined with an ARUCO marker and having an automatic watering valve which is opend and closed to a specific time and that received waterig commands from the UAV. The water consumption was measured it showed that the average consumption of the total field was 7.9 liters per week per square with a total of 28440 liters per week even in some weeks it was lower (Figure 12). The average amout of water saved is 41520 – 28440 = 13080 liters/week. So from these values the average water saving percentage can be calculated; ((13080 liters/week)/(41520 liters/week))*100 = 31.5% water saved.As a result of precious watering the crop yield was improved due to avoiding of over watering and under watering. The UAV captures high-resolution images, processes them to identify irrigation needs, and autono-mously controls water valves to manage irrigation. This approach not only conserves water but also reduces operational costs.



a) b)

Figure 11. a) Irrigation application map obtained after each field mission, b) Graph generated after scaning each area showing the number of frames detected that need water and the numbers that doesn't need water, then it gives the average of that area



b)

Figure 12. a) Weekly watering amount of different parts of the field, b) Field map with watering data and divided sections

The results indicate that the autonomous UAV-based system can significantly reduce water consumption while maintaining or enhancing crop productivity. In the test field set up, the field was divided into four equal irrigation areas and as a result of implementing the system the water consumption was reduced up to 31.5% which can be further improved by dividing the field into more than 4, for example 8 areas. By integrating technologies like TensorFlow for machine learning and autonomous navigation, the system repre-sents a significant advancement in precision agriculture. Future work will expand the system's capabilities to include more environ-mental factors and a broader range of crops and agricultural settings. Also to train the system on different crope types and locations and to allow the user train the system in their own crop type and farm then to create liabraires of it for fast reach and combine it with AI for more user friendly approaches. Additionally, further improvements in machine learning models and image processing techniques will enhance the system's accuracy and reliability. The potential for integrating additional sensors and IoT devices to monitor various envi-ronmental parameters will also be explored, further advancing the precision and effectiveness of the irrigation decision support system.

Overall, this development marks a significant step forward in precision agriculture. By leveraging cutting-edge technologies to optimize water usage and improve crop yields, the system not only contributes to sustainable agricultural practices but also offers a scalable solution to address the growing global demand for food and water resources.

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Original Paper

Biodegradable Films: Sustainable Solutions for Food Packaging Applications

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Abstract

The increasing environmental implications of conventional plastic packaging has led to a raising interest in biodegradable packaging materials as sustainable alternatives. Biodegradable materials, derived from sustainable resources such as plant-based biopolymers and natural fibers, offer significant environmental benefits, including reduced reliance on fossil fuels and decreased pollution. Various techniques can be employed for forming biodegradable packaging films, including extrusion, solvent casting, compression molding and electrospinning. To address the limitations of biodegradable materials compared to traditional plastics, modification techniques such as esterification, etherification, and grafting can be employed. Innovative advancements like active and intelligent packaging technologies can enhance the functionality and consumer engagement. This review explores the key properties, advancements, applications and challenges associated with biodegradable packaging materials, focusing on their effectiveness and sustainability in the food packaging industry.

Keywords: Biodegradable packaging, Sustainable materials, Food packaging, Active packaging, Film-forming techniques.

1. Introduction

The packaging serves a multitude of crucial purposes in the modern food industry and in our daily lives [1]. It acts as a barrier of protection safeguarding food products from physical damage, contamination and spoilage thereby preserving their quality, freshness and safety. Packaging also contributes substantially to extending the perishable commodities shelf life, reducing food waste and enabling efficient distribution and storage throughout the supply chain [2]. Additionally, packaging provides essential information to consumers, such as nutritional content, ingredients, allergen warnings, and expiration dates, empowering them to make informed purchasing decisions and ensure food safety. It facilitates convenience and portability, making it easier for consumers to transport, handle, and consume food products, whether at home, on-the-go, or in various settings [3].

Plastic-based food packaging has been widely used for its versatility, durability, and cost-effectiveness [4]. These plastic packaging materials also have significant drawbacks and environmental consequences [5]. One of the main disadvantages of plastic-based packaging of food is its persistence in the environment. Plastics accumulate in landfills, oceans, and ecosystems because they take hundreds to thousands of years to break down [6]. Because of ingestion and entanglement, this accumulation seriously endangers species and disrupts ecosystems and biodiversity. Moreover, millions of tons of plastic waste get generated annually as a consequence of plastic packaging, contributing to the global plastic pollution catastrophe [7]. Improper disposal and inadequate recycling infrastructure exacerbate this problem, leading to littering, pollution, and microplastic contamination in the environment, waterways, and food chain. The problem is so serious that even plastics of micro scale have been detected in human blood [8], human testis and semen [9]. Furthermore, a large portion of the manufacturing of plastic packaging utilizes fossil fuels, which increases greenhouse gas emissions and adds to the impact of climate change. The extraction, manufacturing, and disposal of plastics consume significant energy and resources, further exacerbating environmental degradation and resource depletion [4].

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These food packaging materials made of plastic frequently include dangerous chemicals like phthalates and bisphenol A (BPA), which may penetrate into food and drink and pose health hazards, particularly when exposed to them for an extended period of time [10]. The growing public awareness and demand for forced the development of biodegradable packaging materials.

A viable substitute for conventional plastic packaging is provided by biodegradable food packaging materials, which solve the environmental issues related to plastic waste and pollution [11]. As these materials are made to naturally decompose over time into non-toxic components, packaging waste has a lesser effect on the environment [12, 13]. One of the key advantages of biodegradable food packaging materials is their ability to mitigate plastic pollution. Unlike traditional plastics, which persist in the environment for hundreds of years, biodegradable materials undergo microbial degradation, returning valuable nutrients to the soil and water [14]. This helps prevent littering, reduces landfill accumulation, and minimizes harm to wildlife and ecosystems. Moreover, biodegradable food packaging materials are often derived from renewable resources, such as plant-based biopolymers, agricultural residues, or natural fibers [15, 16]. By utilizing renewable feedstocks, these materials reduce reliance on finite fossil fuels and contribute to a more sustainable and circular economy. In addition to their environmental benefits, biodegradable food packaging materials have some draw backs as their functionality and performance is inferior to traditional plastics. These materials need optimum modifications to make them suitable for their application [17]. Advancements in research and development have led to the emergence of innovative biodegradable packaging solutions, such as active and intelligent packaging technologies, which can enhance food quality, extend shelf life, and improve traceability and safety [18]. Biodegradable food packaging materials hold great promise as a sustainable alternative to plastic packaging, offering a pathway towards reducing plastic pollution, conserving resources, and promoting a more environmentally friendly and resilient food system. This review provides an overview of advancements in biodegradable food packaging.

2. Types of Biodegradable Materials

Several different types of materials have been utilized to develop biodegradable packaging materials some of these have been discussed below.

Biopolymers derived from renewable resources, such as plants or microorganisms. They include polylactic acid (PLA) [19], polyhydroxyalkanoates (PHA) [20], Polyhydroxybutyrate (PHB) [15], Carrageenan [21] and starch-based polymers [22]. These materials offer good barrier attributes and mechanical strength, making them suitable for a variety of food packaging applications. Natural fibers, such as cellulose [16], hemicellulose [23], and lignin [24] derived from plant sources and offer biodegradability and renewability. These materials can be used to reinforce biopolymer matrices or as standalone packaging materials. Different biodegradable materials can be combined to form composite materials to achieve specific properties and functionalities. Biodegradable polymers can be reinforced with natural fibers [16] or fillers [25] to enhance mechanical strength and barrier properties. Composite materials offer versatility and customization options, allowing for tailored solutions to meet specific packaging requirements. Proteins derived from plant or animal sources can be used to create biodegradable packaging materials with unique properties and functionalities. Proteins such as whey protein [26], gluten [27], or casein [28] can be processed into films, coatings, or edible packaging solutions. Protein-based biodegradable packaging materials offer advantages such as good barrier attributes, biocompatibility, and potential for edible applications. These biodegradable materials offer alternatives to traditional plastic packaging, providing sustainable options to reduce environmental impact and promote circularity in the food packaging industry.

3. Techniques to Develop Biodegradable Packaging

Various techniques have been employed to form biodegradable packaging materials. Some of them have been discussed below. Figure 1 shows various techniques to develop biodegradable films.

Solution Casting: On the lab scale solution casting approach has been employed predominantly [29]. In this method biopolymers to be used for film formation is dissolved in a solution along with the incorporation of other additives like plasticizers, crosslinkers, nanoparticles/fibrils and other bioactive compounds. After appropriate mixing these solutions are cast in petri dishes and vacuum dried to remove water. After drying the films are peeled and stored in desiccator till further processing [30]. The solution casting approach has its downside it cannot be used for large scale production of biopolymers. Solution casting method was utilized by Sutay et al. [31] to form plasticized hemicellulose films derived olive mill waste. Similarly Jaderi et al. [32] employed casting approach to form Malva sylvestris flower gum films.

Extrusion: For large scale production of biodegradable materials extrusion have been employed. In extrusion biopolymers and additives are mixed by application of high temperature, pressure and shear forces [33]. After blending the material is passed through a narrow die to get the desired shape. Extrusion has proved to be suitable option for large scale production of biodegradable material due to its continuous nature [34]. The extrusion technique was utilized by Faust et al. [35] to form pea protein isolate films using a twin screw extruder. Bahcegul et al. [36] utilized twin screw extruder to develop biodegradable polymeric material from xylan derived from corncobs.

Electrospinning: Electrospinning is an approach that can be employed at lab as well as at an industrial scale [37]. At first a solution of biopolymers and additives is created after that the solution is filled in a syringe. A high voltage is applied between tip and the collection plate of the syringe. A thin stream of the mixture emerges from the tip which is dried by the air. The dried material form fibers which are deposited on the collection plate. An elevated temperature can be utilized to further dry the fibers [38]. This method has a drawback that it cannot be utilized for formation of thin films [39]. Antimicrobial biodegradable films based on poly (butylene adipate-co-terephthalate) has been developed using electrospinning [40].

Compression molding: Compression molding method can be utilized at any scale to form biodegradable films [41]. It involves blending and molding biopolymers and additives. Either cold or hot compression can be applied to cure the films that is crosslinking of biopolymers [42]. de Matos Costa et al. [43] utilized compression molding to form films based on Polybutylene succinate and Polybutylene adipate-co-terephthalate.

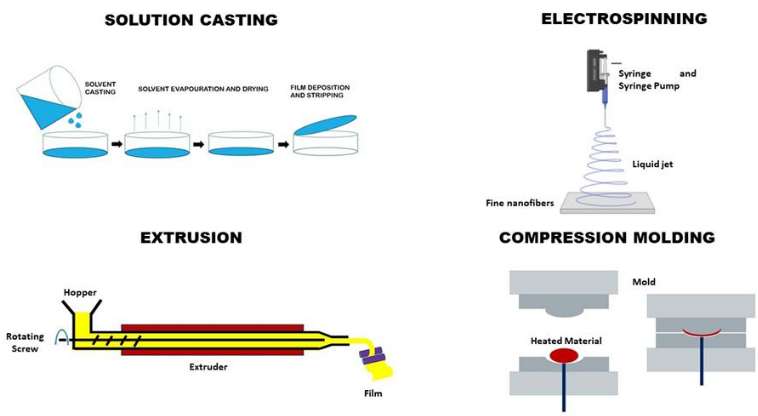


Figure 1. Various Techniques to Develop Biodegradable Films

The selection of a development method for packaging materials depends on the ingredients, desired attributes of the final product, and production scale. The casting method is versatile but suitable only for small-scale production. Other methods have their specific limitations like electrospinning requires electrically charged biopolymers, extrusion is unsuitable for biopolymers that degrade under compression methods, high temperatures, high pressures, or high shear rates are only appropriate for biopolymers that set when compressed or heated. Figure 2 provides a comparison of the film forming methods.

Solution Casting	Extrusion	Electrospinning	Compression Molding
Dissolving polymers in a solvent and pouring onto a flat surface; solvent evaporates, leaving a thin film	Forcing melted polymers through a die to form sheets or films; cooled and solidified by rollers	Using an electric field to draw a polymer solution into nanofibers, creating a porous, mesh-like structure	Placing material into a mold and applying heat and pressure to shape it into a solid form
Suitable for materials like Polysaccharides, proteins, cellulose derivatives	Suitable for materials like Starch, PLA, PHA, protein blends	Suitable for materials like Gelatin, PLA, PVA, chitosan	Suitable for materials like Starch-based, PLA, PHA
Simple setup, good for lab-scale experiments, allows for uniform film thickness	Scalable, high production rates, suitable for commercial use	Produces nanofiber structures, high surface area, lightweight, potential for active packaging	High-density, uniform thickness, suitable for thicker films and rigid packaging
Limited to small scale, slower drying times, solvent recovery challenges	Requires high temperatures, limited for thermally sensitive materials	Expensive setup, slower production rates, suitable for specific applications	Limited to materials that can withstand pressure and heat, requires specialized equipment

Figure 2. Comparison of the film forming methods

4. Properties and Characteristics

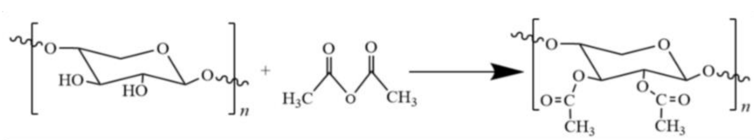
Biodegradable packaging materials exhibit several key properties essential for their effectiveness and sustainability in the food packaging industry. Firstly, their biodegradability enables them to naturally break down into harmless components when exposed to environmental conditions, reducing their environmental footprint and promoting circularity in the packaging lifecycle [44]. Additionally, these materials can be engineered to provide adequate barrier properties [45, 46] mechanical strength, thickness and opacity [32] ensuring the safety, quality, and freshness of packaged foods throughout their shelf life. The properties of biodegradable packaging materials play a pivotal role in balancing environmental considerations with functional requirements and regulatory compliance in the development of sustainable packaging solutions for the food industry however they are inferior to the attributes of plastic based packaging materials so there is a need to modify them.

5. Modifications of the Properties

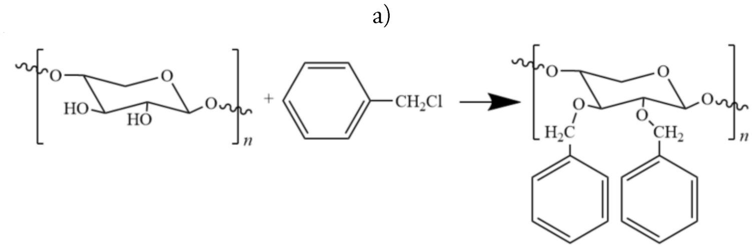
Modification of the attributes of biodegradable packaging materials involves tailoring their characteristics to meet specific application requirements and enhance their performance in various packaging contexts. Several strategies can be employed to modify the properties of biodegradable packaging materials, including:

Additives and reinforcements: Incorporating additives such as plasticizers [47], fillers [25], or reinforcements [48] into biodegradable materials can improve their barrier attributes, mechanical strength, and thermal stability. For example, fillers such as nanocellulose [49] or montmorillonite nanoparticles [50] can be added to biopolymer matrices to enhance their tensile strength and gas barrier properties, making them suitable for flexible packaging applications. Plasticizers such as glycerol and sorbitol can be incorporated to improve the properties of biodegradable films [32]. In a similar manner reforcements such as egg shell can be employed to achieve desirable characteristics [51].

Blending and composite formation: Blending biodegradable polymers with other materials or creating composite structures allows for the combination of different properties to achieve desired functionalities [52-54]. For instance, El Miri et al. [55] developed bionanocomposite films based of cellulose nanocrystals filled with alginate. In a similar manner polyvinyl alcohol and citric acid composite films were produced by Wang et al. [56].



a)



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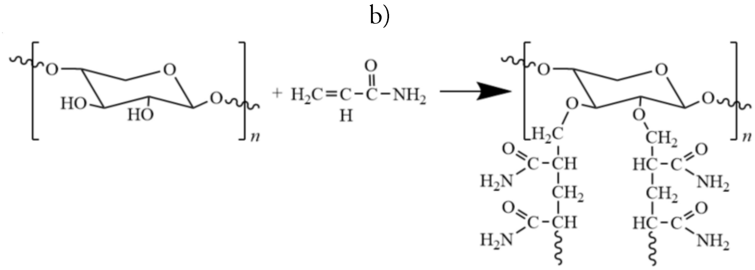

c)

Figure 3. Esterification (a), Etherification (b) and Grafting (c) of Hemicellulose

Chemical modifications: Esterification, etherification, and grafting are chemical modification approaches commonly utilized to enhance the attributes and functionality of polymers, including biodegradable packaging materials. Esterification can improve the compatibility, hydrophobicity, and thermal stability of polymers, thereby enhancing their barrier properties and mechanical strength [57]. Etherification of these materials can enhance the flexibility, solubility, and compatibility of polymers, making them more suitable for specific packaging applications [58]. Grafting process enhances the compatibility between biopolymers and additives or to introduce functional groups for targeted applications leading to improved mechanical strength, adhesion, or compatibility with other materials [59]. Figure 3 shows esterification, etherification and grafting of hemicellulose [17].

Crosslinking and polymerization: Crosslinking [60] or polymerization [61] reactions can be employed to modify the molecular structure of biodegradable polymers, leading to changes in their mechanical, thermal, and degradation properties. Figure 4 shows the crosslinking of hemicellulose films [17].

By tailoring the properties of biodegradable packaging materials to specific application requirements, it is possible to develop sustainable packaging solutions that meet the evolving needs of the food industry while promoting environmental stewardship and resource conservation

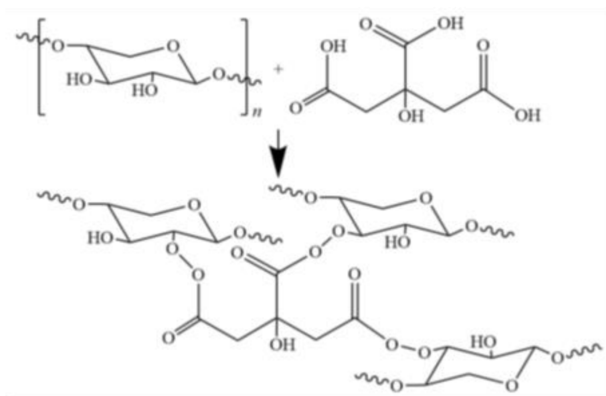

Figure 4. Crosslinking of Hemicellulose Films

6. Advencements

Advancements in biodegradable food packaging have led to the development of innovative solutions such as active and intelligent packaging, which offer enhanced functionality beyond traditional passive packaging materials [62]. Figure 5 Shows Active and Intelligent packaging systems for packaging.

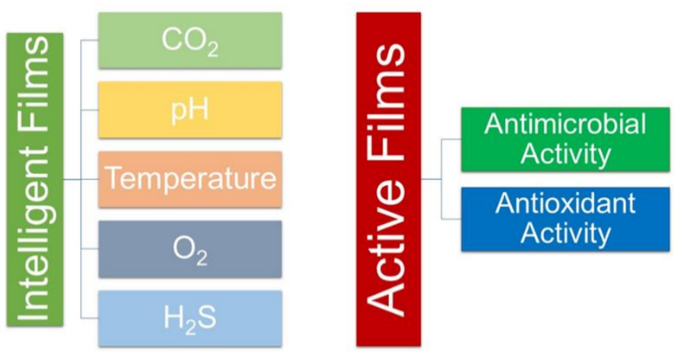

Figure 5. Intelligent and Active Food Packaging Systems

Active packaging systems are designed to interact with the packaged food or its environment to extend shelf life, maintain quality, and improve safety [63]. Active packaging systems typically incorporate active components, such as oxygen scavengers [64], antimicrobial agents [65], or ethylene scavengers [66], into the packaging material or the package itself. These components actively interact with the packaged food or its surroundings to inhibit microbial growth, control ripening, or reduce oxidative reactions, thereby extending the shelf life and preserving the quality of perishable foods. Biodegradable chitosan and gelatin films were formed by Xu et al. [67] these films were incorporated with hop extract which not only enhanced the antioxidant activity of these films but also proved effective against bacteria. Lian et al. [68] formed chitosan and pullulan active films by including thyme essential oil. A substantial decline in E. coli activity was noted by the incorporation of thyme essential oil. Citric acid was incorporated in PVA and starch based by Wu et al. [69] The activity of E. coli was sufficiently inhibited by the inclusion of citric acid. Table 1 provides a summary of effects of active materials on biopolymer based packaging

Table 1. A summary of effects of Active Materials on Biopolymer based Packaging

Biopolymer	Active Material	Effects	References
Chitosan	Pine needle extract	High antioxidant effect was noted.	[70]
Methylcellulose	Silver nanoparticles	Bacterial growth was inhibited	[71]
Poly(lactic acid)/ Poly(caprolactone)	thymol, carvacrol	Enhanced antioxidant activity was observed.	[72]
Gelatin	Rosmarinic acid	Bacterial growth was inhibited	[73]
Polylactic acid	thymol, kesum, curry	Bacterial growth was inhibited	[74]
Polyvinyl alcohol	Pomegranate peel extract	Bacterial growth was inhibited	[75]
Sodium lactate/whey protein isolate	E-Poly lysine	Bacterial growth was inhibited	[76]
Fish gelatin	Haskap Berry Extracat	radical scavenging activity was enhanced	[77]
Chitosan/Carboxymethyl Cellulose	ZnO nanoparticles	Bacterial and Fungal activity was sufficiently controlled.	[78]
Chitosan	Black plum peel extract	DPPH inhibition was enhanced and bacterial growth was controlled	[79]
Sodium alginate	ZnO nanoparticles	A decline in bacterial count was observed.	[80]
Hydroxypropyl methyl cellulose	*Thymus daenensis* EO	Bacterial growth was inhibited	[81]
Whey protein isolate	Lactoferrin, Lysozyme, and the Lactoperoxidase	Bacterial growth was inhibited	[82]

Sensors and indicators are incorporated into intelligent packaging to give real-time information about the state of the packaged goods [83]. These technologies represent significant advancements in the field of food packaging, offering benefits in terms of food preservation, quality assurance, and consumer convenience. Intelligent packaging incorporates sensors [84] and indicators [85] that give precise information regarding the state of the product in its packaging, including its Freshness, temperature, gas composition, moisture content. These technologies allow for monitoring and control of critical parameters throughout the supply chain, enabling timely interventions to maintain food safety and quality. Jamróz et al. [86] formed furcellaran and gelatin-based films with the incorporation of extract from pu-erh and green tea. Jung et al. [87] utilized 2-amino-2-methyl-1-propanol and chitosan as a carbon dioxide indicator to monitor quality of fermented foods. Pucci et al. [88] developed biodegradable PLA and PBS films with temperature indicator by incorporating 4,4′ -bis(2-benzoxazolyl) stilbene. Vu et al. [89] incorporated redox dyes in biopolymers to act as oxygen indicators. Table 2 provides a summary of effects of intelligent materials on biopolymer based packaging.

Table 2. A summary of effects of Intelligent Materials on Biopolymer based Packaging

Biopolymer	Intelligent Material	Effect	References
Chitosan/Polyvinyl Alcohol	Anthocyanin	Change of color provided spoilage indication.	[90]
Hydroxy propyl methylcellulose/ K-carrageenan	Anthocyanin	Change of color provided spoilage indication.	[91]
Cellulose acetate nanofibers	Alizarin	Change of color provided spoilage indication.	[92]
Glucomannan/Polyvinyl alcohol	Betacyanin	pH change was indicated by change of color.	[93]
Polylactide/Poly hydroxybutyrate	β-carotene, Chlorophyll, Curcumin, Lutein	Change in temperature changed the color.	[94]
Agar	*Arnebia euchroma* root	Change of color provided spoilage indication.	[95]
Bacterial cellulose nanofibers	Anthocyanin	Gas production changed the color.	[96]
Cellulose-Polyvinyl alcohol	Acidochromic dye	pH change was indicated by change of color.	[97]
Furcellaran, gelatin	Green tea extract	pH change was indicated by change of color.	[86]
Succinylated chitosan and hydroxy-propyl chitosan	Bromocresol blue and methyl red	Color change indicated change of carbon dioxide concentration.	[98]
Artemisia sphaerocephala Krasch. Gum	Anthocyanins	NH_3 presence changed the color.	[99]
Chitosan and agarose	Anthocyanins	Change of color provided spoilage indication.	[100]
Low-acyl gellan gum	Silver Nanoparticles	Color changed with the presence of H_2S.	[101]
Alginate	Molybdenum trioxide nanoparticles	Color changed with the presence of H_2S.	[102]

7. Applications of biodegradable Packaging

Innovations in food packaging have reached new heights with the advent of various cutting-edge films and coating materials, each with specific applications to enhance food preservation and consumer satisfaction. Anti-sprouting films, utilizing polymeric carriers infused with natural anti-sprouting agents like essential oils, are used to extend the shelf life of potatoes and other sprout-prone produce, providing a sustainable alternative to conventional fogging techniques [103]. High-performance UV-blocking films protect packaged foods such as dairy and beverages from photooxidation, ensuring prolonged shelf life and quality retention [104]. Nano-engineered films, incorporating nanomaterials, are applied to improve the mechanical strength and barrier properties of packaging for fragile items like snacks and baked goods [105]. Two-dimensional materials like nano-cellulose and metal nanoparticles are used to enhance the thermal and mechanical properties of packaging for perishable items like fruits and vegetables [106]. Multi-shaded films find application in the confectionery industry, making products like candies more visually appealing [107]. Taste and odor-masking films are particularly useful for packaging nutritious yet strong-smelling foods such as garlic, onions, and durian, improving consumer acceptance [108]. Oxygen [109] and water [110] resistant films are essential for packaging fresh produce, meats, and fermented foods, maintaining optimal freshness and quality [111]. Transparent films are ideal for packaging products like meat and seafood, allowing consumers to inspect the product visually [112]. The emergence of 2D and 3D printed films enables precise customization for high-end products and specialty foods [113]. Super-hydrophobic/hydrophilic films are used in applications requiring anti-fouling and self-cleaning properties, such as ready-to-eat meals [114]. Smart pH-sensitive films provide real-time monitoring of food spoilage, crucial for perishable goods like seafood and dairy products [115]. Multilayer films, integrating barrier, active, and control layers, are versatile for packaging a wide range of food items, from dry goods to liquids [116]. Active films enriched with antimicrobials and antioxidants are applied to packaging for fresh produce and meats to enhance food safety [117]. Plasticized [118] and cross-linked [119] are used in applications requiring flexibility and durability, such as packaging for processed foods and snacks. These advancements collectively herald a new era of innovation in food packaging technology, promising enhanced sustainability, functionality, and consumer satisfaction across the globe.

8. Future Directions and Challenges

The implementation of biodegradable packaging involves addressing key challenges and advancing the development, adoption and scalability of sustainable packaging solutions. While biodegradable packaging holds great promise for reducing environmental impact and promoting circularity in the packaging industry several challenges need to be overcome to realize its full potential. These challenges include technological limitations, regulatory barriers, market demand and end-of-life management considerations.

There is a need to heavily fund research and development in order to overcome the drawbacks of biodegradable packaging materials. Mechanical strength and barrier qualities can be enhanced by ongoing developments in biopolymer technology, such as the production of novel polymers like polylactic acid (PLA) and polyhydroxyalkanoates (PHA). Furthermore, the overall performance of biodegradable films can be enhanced by the development of nanocomposites using nanotechnology. Research collaborations between academic institutions, business partners, and government organizations could accelerate the development of economical and efficient sustainable packaging solutions. It is essential to have strong legal frameworks and uniform guidelines for biodegradable packaging materials. International organizations and governments need to collaborate to establish regulations that guarantee environmental sustainability, quality, and safety. A circular economy for plastics, for instance, is the goal of programs like the European Union's Plastics Strategy, which can be extended to include biodegradable materials. Involving stakeholders in the regulatory process can help create certification programs that increase customer confidence and make choosing biodegradable packaging solutions easier. Targeted consumer education initiatives are necessary to raise awareness of the environmental advantages of biodegradable packaging alternatives and drive market demand for them. Acceptance can be enhanced by interacting with customers on social media and showcasing successful biodegradable packaging case studies in marketing campaigns. To guarantee that consumers have access to reasonably priced and highly effective biodegradable products, manufacturers, merchants, and waste management firms must work together. End-of-life management considerations are essential for ensuring the effective disposal, recycling, and composting of biodegradable packaging materials. While biodegradation offers a promising solution to reduce packaging waste, infrastructure and logistical challenges exist in implementing widespread composting or recycling facilities. Investment in infrastructure development, improving collection and sorting processes, and promoting circular economy models to close the loop on biodegradable packaging materials is necessary to and maximize resource recovery.

9. Conclusion

Biodegradable packaging materials represent a promising solution to the environmental challenges posed by traditional plastic packaging. With advancements in biopolymers, natural fibers, and protein-based materials, these sustainable alternatives offer potential benefits such as reduced pollution, renewable sourcing, and improved food safety and quality. However, the successful implementation of biodegradable packaging requires overcoming several challenges, including technological limitations, regulatory barriers, market acceptance, and effective end-of-life management. Future efforts must focus on continued innovation, harmonized regulations, consumer education, and infrastructure development to fully realize the potential of biodegradable packaging. By addressing these challenges, the packaging industry can move towards a more sustainable and circular economy, minimizing environmental impact while meeting the functional needs of food packaging.

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