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Classification of Apple Quality Based on Physical and Chemical Properties: A Machine Learning Based Approach

Nadir SUBAŞI[1], Özen ÖZER[2]*

[1]Department of Computer Programming, Kırklareli University, Kırklareli, Türkiye
[2]Department of Mathematics, Faculty of Science and Arts, Kırklareli University, Kırklareli, Türkiye

[1]https://orcid.org/0000-0002-5657-9002
[2]https://orcid.org/0000-0001-6476-0664
*Corresponding author: ozenozer39@gmail.com

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ABSTRACT

This study examines a machine learning-based approach for assessing physical and chemical properties to determine apple quality. While traditional quality control methods are time-consuming, costly, and subjective, artificial intelligence and computer vision techniques offer faster and more accurate results. The study used a dataset consisting of 4000 samples containing key physical and chemical variables such as apple size, weight, sweetness, crispness, juiciness, ripeness, and acidity. The performances of various machine learning algorithms were compared during the training and testing phases. In model performance evaluations, the Voter Classifier (VT) algorithm achieved the highest accuracy rate of 91.25% and F1-Score 91.25% also demonstrated superiority in other key metrics. In the study conducted in Trabzon, the combination of the LGBM (Light Gradient Boosting Machine) and CatBoost algorithms within the voter structure stood out as an innovative approach that increased model performance. While this method has limited applications in the literature, it has the potential to make significant contributions to the optimization of quality control processes in the agricultural sector. Therefore, it is concluded that AI-supported systems are an effective tool for agricultural quality assessment.

Elma Kalitesinin Fiziksel ve Kimyasal Özelliklere Göre Sınıflandırılması: Makine Öğrenmesine Dayalı Bir Yaklaşım

Araştırma Makalesi

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ÖZ

Bu çalışmada elma kalitesini belirlemek için fiziksel ve kimyasal özellikleri değerlendirmek amacıyla makine öğrenmesi tabanlı bir yaklaşım incelenmiştir. Geleneksel kalite kontrol yöntemleri zaman alıcı, maliyetli ve öznelken, yapay zeka ve bilgisayarlı görme teknikleri daha hızlı ve daha güvenilir sonuçlar sunmaktadır. Çalışmada elma boyutu, ağırlığı, tatlılık, gevreklik, sululuk, olgunluk ve asidite gibi temel fiziksel ve kimyasal değişkenleri içeren 4000 örnekten oluşan bir veri seti kullanılmıştır. Eğitim ve test aşamalarında çeşitli makine öğrenmesi algoritmalarının performansları karşılaştırılmıştır. Model performans değerlendirmelerinde Seçmen Sınıflandırıcı (VT) algoritması %91,25 ile en yüksek doğruluk oranına ulaşmış ve F1 Puanı %91,25 ile diğer temel metriklerde de üstünlük göstermiştir. Trabzon'da gerçekleştirilen çalışmada, seçmen yapısı içerisinde LGBM (Light Gradient Boosting Machine) ve CatBoost algoritmalarının kombinasyonu, model performansını artıran yenilikçi bir yaklaşım olarak öne çıkmıştır. Bu yöntemin literatürde sınırlı uygulamaları olmasına rağmen, tarım sektöründe kalite kontrol süreçlerinin optimizasyonuna önemli katkılar sağlama potansiyeli bulunmaktadır. Sonuç olarak, yapay zeka destekli sistemlerin tarımsal kalite değerlendirmesinde etkili bir araç olduğu sonucuna varılmıştır.

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Introduction

Today, the agricultural sector is undergoing a major transformation with the integration of big data and artificial intelligence technologies. At the heart of this transformation are innovative approaches developed for determining and improving crop quality. In particular, the activation of quality control mechanisms in fruit varieties such as apples, which respond directly to consumer demands, provides a competitive advantage in the sector and contributes to the reduction of waste.

The determination of apple quality is traditionally a process based on human observation, which can be time-consuming, costly, and subjective. In recent years, thanks to computer vision and artificial intelligence-based systems, more objective and automated quality control methods are being developed. These systems can provide quicker and more accurate analysis by evaluating the physical characteristics of the fruit, such as color, shape, size, and texture.

Technologies such as deep learning algorithms, image processing techniques, and sensory data analysis are increasingly being used in the process of determining apple quality. These approaches have a lower margin of error compared to traditional quality control methods and ensure that consumers are offered a more consistent product. However, for these technologies to be successfully applied, proper data collection and model training are of great importance.

This study aims to examine the effectiveness of artificial intelligence-supported apple quality evaluation systems and to reveal the benefits that these systems can provide to the agricultural sector. In the following sections of the study, the advantages and disadvantages of current quality control approaches will be discussed, and the methods used to improve the performance of artificial intelligence models will be examined in detail.

Overview of Apple Quality Assessment

Importance of Quality Control in the Agricultural and Food Sector

Quality control of apples and other agricultural products is of great importance in meeting the needs of producers and consumers. Consumers expect the products they buy to meet certain quality standards, while producers aim to increase their market share by offering high-quality products. In this context, developing reliable and objective quality assessment methods has become a critical requirement.

Traditional Quality Control Methods and Limitations

Traditional methods for determining apple quality are usually based on manual inspection and sensory evaluation. However, these methods are prone to human error and may involve subjective evaluations. In addition, manual quality control processes can be time-consuming and costly. In recent years, the use of automated systems in the quality control of agricultural products has increased, and artificial intelligence techniques such as computer vision and machine learning have begun to be used effectively in quality analysis. These developments make quality control processes more economical and enable more efficient and reliable results to be achieved.

Importance of Artificial Intelligence-Based Quality Control Systems

Machine learning and deep learning-based systems have the potential to radically change quality control mechanisms in the agricultural sector. In particular, systems supported by image processing techniques can analyze the color, shape, texture, and other physical characteristics of fruits with high accuracy. These technologies provide producers with faster decision-making opportunities, while also contributing to offering consumers higher quality products. Machine learning models can process large amounts of data, optimize quality evaluation processes, and improve themselves over time. Thus, inconsistencies and human-induced errors encountered in traditional methods can be minimized, and more consistent and reliable results can be obtained.

Literature Review

Academic studies on apple quality assessment are generally based on the analysis of physical and chemical properties with the help of classifiers. Physical properties such as size, color, texture, and crispness are among the most used parameters in determining apple quality. In this context, various studies have revealed the effectiveness of different machine learning and artificial intelligence techniques.

In a study conducted by Chauhan and Singh, a 95.12% accuracy rate was achieved using the k-Nearest Neighbor (k-NN) algorithm based on physical parameters (Singh Chauhan et al. 2012). Similarly, Yin et al. developed a two-branch model based on physical features such as shape, texture, and contour, achieving high accuracy rates (Yin et al. 2022). Mureșan revealed that multivariate analyzes play a critical role in the quality assessment of apple genotypes (Mureşan, 2022). Furthermore, Hu et al. achieved a 95.49% success rate using classifiers based on physical features (Hu, 2021). In Sabanci's study, it was reported that apple varieties were classified with a 98.88% success rate using k-NN and Artificial Neural Networks (MLP) (Sabanci and Unlersen, 2016). Models based on physical quality parameters also yield successful results, especially in the evaluation of maturity levels. Ashok and Vinod performed the separation of rotten and healthy apples with a Probabilistic Neural Network (PNN) (Ashok and Vinod, 2014). Renjith and MA showed that machine learning and deep learning techniques are effective in increasing the classification performance based on maturity levels (Muthulakshmi and Renjith, 2021). Li et al. successfully classified apple quality with a 95.33% accuracy rate using Convolutional Neural Networks (CNN) (Li et al. 2021). Moallem et al. achieved high accuracy rates in the classification of golden delicious apples with computer vision methods based on surface features (Moallem et al. 2017). Mehinagic et al. revealed that quality characteristics such as crispness and fruit juice content can be successfully predicted by physical measurements (Mehinagic et al. 2004). Zhu et al. evaluated apple quality with a 90.6% accuracy rate using Gabor features and kernel principal component analysis (KPCA) (Zhu et al. 2007). Ma et al. achieved an 80% accuracy rate by analyzing red Fuji apples with near-infrared spectroscopy (Ma and Zhang, 2019). Cliff and Bejaei revealed that physical properties can accurately predict sensory properties such as apple hardness and crispness (Cliff and Bejaei, 2018). Corollaro developed a hybrid model that evaluates apple quality with sensory and instrumental measurements (Corollaro, 2014). Adebayo and Hashim classified pear maturity stages using laser imaging and artificial neural networks and stated that this method could be successful in apple classification as well (Adebayo and Hashim, 2021). Zhang developed a model that compensates for the differences in maturity levels and showed that apple quality can be accurately determined (Zhang, 2022).

In recent years, various non-destructive methods have been developed to assess apple quality. For example, hyperspectral imaging (HSI) combined with Partial Least Squares Regression (PLSR) has been shown to accurately predict internal quality parameters such as soluble solid content (SSC), firmness, and starch index (Hasanzadeh et al., 2022). The combination of visible and near-infrared hyperspectral imaging (Vis/NIR HSI) with artificial neural networks (ANN) also predicts SSC and firmness during storage with high R^2 values (Sharma et al., 2023). Convolutional neural networks (CNN) trained on a narrow spectral band (660 nm) classify apple surface defects with near-perfect accuracy, enabling cost-effective quality control (Classification of Defective and Non-Defective Products Using Convolutional Neural Networks in Quality Control, 2023). Mask Region-based CNN (Mask R-CNN) approaches enable high F1-score apple detection and segmentation in orchards, supporting automated harvesting systems (Wang and He, 2022). The occlusion-aware object recognition network (O2RNet) achieves accurate apple detection in clustered and shaded orchard environments (Li et al., 2021). Lightweight detection object models combined with generative adversarial networks (LightDOM-GAN) and attention mechanisms provide high accuracy and real-time performance for maturity and damage detection (Wang et al., 2022). Visible spectroscopy combined with particle swarm optimization (PSO) and back propagation neural networks (BPNN) models achieves very high correlation and low error rates in SSC prediction (Peng et al., 2023).

Analysis shows that existing studies have generally been conducted using a single classification algorithm or a limited number of physical/chemical properties. This limits model performance and generalizability.

These studies show that the evaluation of physical properties with machine learning algorithms enables high accuracy rates to be achieved in the prediction of apple quality. However, the comparison of different methods and the examination of new model development processes will contribute to further improvement of apple classification systems.

In contrast, this study demonstrates that combining the LGBM and CatBoost algorithms in a hybrid framework and utilizing a rich feature set yields both a significant increase in accuracy and strengthens the model's generalizability.

In this study, the effectiveness of artificial intelligence-supported classification methods will be analyzed in line with the approaches presented in the existing literature.

Material and Methods

In this study, the dataset (Kaggle, 2025) used for apple quality analysis consists of samples containing various physical and chemical properties. The dataset contains a total of 4000 samples, and includes the following variables for each apple:

I. A_id: Unique identification number assigned to each apple sample.
II. Size: A variable indicating the size of the apple.
III. Weight: A measurement representing the weight of the apple.

IV. Sweetness: A value indicating the sweetness level of the apple.

V. Crunchiness: A variable indicating the crispness level of the apple.

VI. Juiciness: A measurement showing the juiciness rate of the apple.

VII. Ripeness: A variable indicating the ripeness level of the apple.

VIII. Acidity: A measurement expressing the acidic structure of the apple.

IX. Quality: A categorical variable expressing the general quality status of the apple ("good" or "bad").

The dataset contains the physical and chemical properties of apples classified according to various quality criteria and is used for studies on apple quality estimation and analysis.

As with every machine learning algorithm, the dataset needs to be preprocessed beforehand. These preprocessing operations have removed the “A_id” column, which holds the number of each apple. In case the “Acidity” column cannot be converted to a number, those that cannot be converted to a number have been changed to “NaN”. Repeated rows have been queried and removed from the dataset. Then, variable distributions have been examined. The density graphs used for this examination are shown in Figure 1.

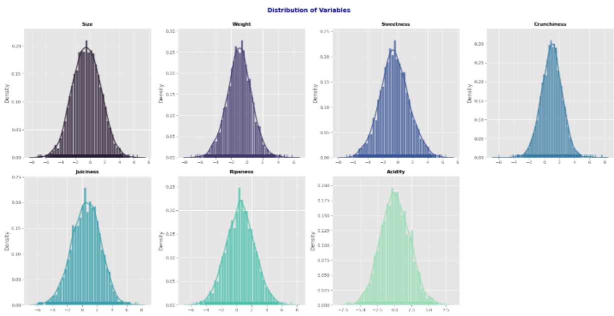

Figure 1. Distribution of numerical variables

In addition, QQ (Quantile-Quantile) plots were used to understand and visualize how well the distribution of a dataset conforms to the theoretical normal distribution. These graphs are presented in Figure 2.

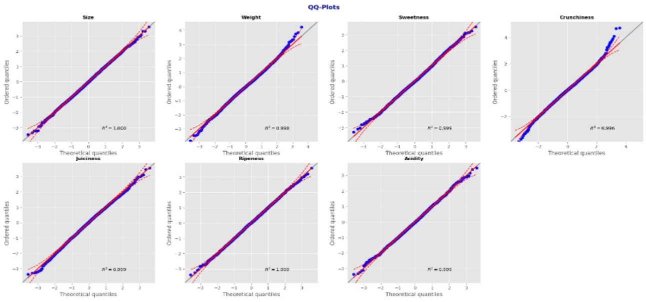

Figure 2. QQ plots of numerical variables

In Figure 2, the blue dots for all variables are largely located on the straight gray line, which indicates that the data is very close to a normal distribution. In addition, the R^2 (coefficient of determination) values range from 0.996 to 1.000, which indicates that the data conforms to the normal distribution to a high degree. Slight deviations can be observed in some variables (e.g., Weight and Crunchiness) at extreme values, but in general, these deviations are at a negligible level. QQ plots show that the variables used in apple quality analysis fit the normal distribution quite well.

Table 1 shows that $p > 0.05$ was found for Size, Sweetness, Ripeness, and Acidity, indicating that these variables are normally distributed. $P \leq 0.05$ was found for Weight, Crunchiness, and Juiciness, indicating that these variables are not normally distributed. This indicates that parametric or nonparametric tests should be selected in analysis based on the distributional properties of these variables. Parametric tests can be misleading for variables that do not exhibit a normal distribution, so alternative nonparametric methods should be preferred. The D’Agostino-Pearson test allows you to determine whether the variables in question are normally distributed based on the p values in Table 1.

Table 1. Normality Test: D' Agostino and Pearson

	p_value	**Distribution**
Size	0.552	Normal Distribution
Weight	0.000	No Normal Distribution
Sweetness	0.094	Normal Distribution
Crunchiness	2.198	No Normal Distribution
Juiciness	0.013	No Normal Distribution
Ripeness	0.635	Normal Distribution
Acidity	0.166	Normal Distribution

The “Quality” column, which is a categorical decision variable, is also shown in Figure 3 because its distribution is important.

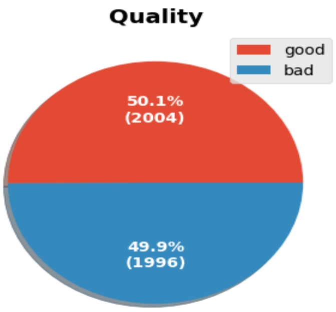

Figure 3. Distribution of "quality" variable

This graph shows the distribution of the samples in the dataset in terms of quality. The proportion of data divided into two classes, “good” and “bad”, is quite balanced. Samples belonging to the “good” class make up 50.1% of the total dataset (2004 samples), while samples belonging to the “bad” class make up 49.9% (1996 samples). This suggests that it creates a balanced dataset for the classification models and that the learning algorithms have a low risk of encountering overfitting or imbalanced dataset problems.

The relationship between numerical variables is shown as a scatter plot in Figure 4.

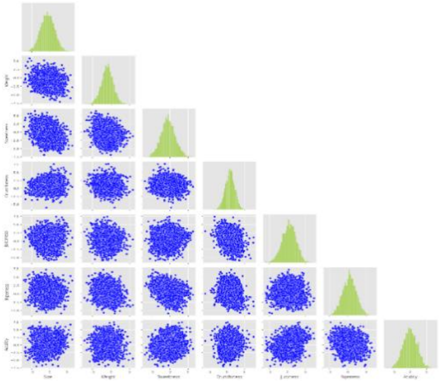

Figure 4. Scatter plot between numeric variables

Figure 4 is a scatter plot and histogram matrix created to analyze the relationships between the variables in the dataset. The histograms on the diagonal axis represent the distribution of each variable, while the scatter plots in the other cells visualize the relationship between pairs of variables. In general, there are no clear linear relationships between variables, although there are low correlations between some variables. This visualization is important for analyzing the interaction between variables and evaluating the overall structure of the dataset.

The correlation between numerical variables is shown with a heat map in Figure 5.

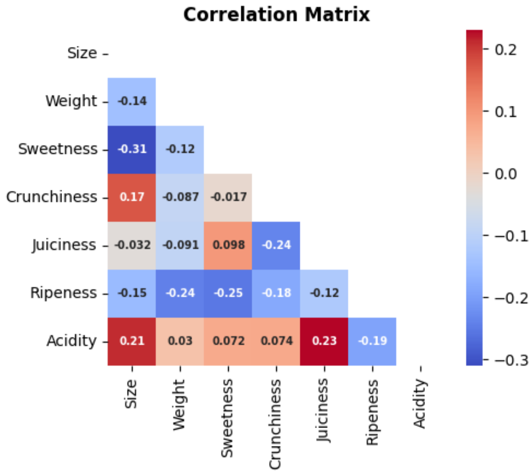

Figure 5. Correlation matrix between numeric variables

The correlation matrix in Figure 5 shows Pearson correlation coefficients to measure linear relationships between variables in the data set. Red tones on the colour scale indicate positive correlation, while blue tones indicate negative correlation. In general, there are no strong correlations between variables, which indicates that the features in the data are largely independent of each other. Specifically, there is a moderate negative correlation of -0.31 between ‘Size’ and ‘Sweetness.’ This indicates that as the size of the apple increases, the sweetness level tends to decrease. In other words, larger apples may be less sweet. This relationship should be carefully evaluated, as it could potentially impact product quality or taste profile. Additionally, there is a weak negative correlation of -0.19 between ‘Acidity’ and ‘Ripeness.’ This indicates that as an apple ripens, its acidity tends to decrease slightly. This relationship between ripeness and acidity may provide important insights into the product's taste and storability. Furthermore, the low correlations across the matrix suggest that the variables are relatively independent of each other, meaning that there is a low likelihood of these variables causing multicollinearity or high multicollinearity issues during the data preprocessing stage. When using such independent variables in machine learning models or statistical analysis, it means that each feature can provide distinct contributions specific to the dataset. Correlation analysis serves as an important guide both in understanding potential relationships between variables and in determining which factors should be considered during data preprocessing and modelling stages. The observed negative relationship between size and sweetness can be considered in quality assessments or consumer preference analysis. Additionally, the relationship between acidity and ripeness can help understand how ripeness levels affect taste. Such information holds value for both product development and market strategies.

The violin graph showing the relationship of each of the numerical variables with the “Quality” variable is shown in Figure 6.

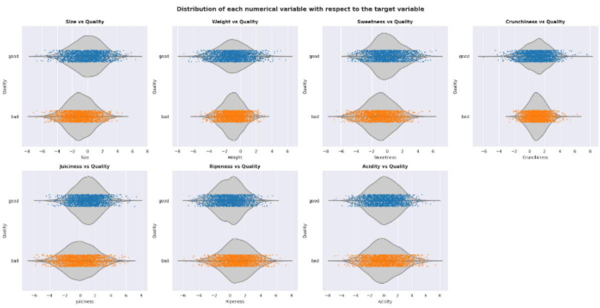

Figure 6. Distribution of each numerical variable with respect to the target variable

Figure 6 shows the distribution of various physical and sensory attributes that determine apple quality (size, weight, sweetness, crispness, crunchiness, juiciness, ripeness, and acidity) in relation to the quality variable (good/bad). In each sub-graph, the distribution of the relevant variable is visualized in two different classes as “good” and “bad”, and the densities of the data points are supported by violin plots. When the graphs are analyzed, it is observed that high quality apples are generally differentiated in certain physical and sensory characteristics. Sensory characteristics such as sweetness, crispness, and juiciness are more pronounced for high quality apples. This analysis provides an important visualization to understand how the key factors determining apple quality are statistically distributed and helps to understand which variables machine learning models can give more importance when predicting quality.

Results and Discussion

The "Quality" column, which will be used as the target in the classification, was removed, and the data was converted into a binary structure by selecting 0 for the "Bad" expression and 1 for the "Good" expression.

The training and test datasets were divided as 80% (3600 samples) and 20% (800 samples). Then: Within the VT, the voters of the LGBM and CatBoost algorithms were defined. The training VT, LR, RF, ET, XGB, LGBM, CatBoost, SVC, and GaussianNB classifiers were comparatively examined. Performance graphs are shown in Figure 7.

Explanation and Breakdown

Data Preprocessing

The "Quality" column, which indicates whether an apple is "Good" or "Bad," is transformed into numerical values (0 and 1) for machine learning algorithms to process. The dataset is split into training (80%) and testing (20%) sets. This is crucial to evaluate how well the trained models perform on unseen data.

Voter Classifier (Ensemble Method)

A "Voter" classifier is created, which combines the predictions of multiple individual classifiers. In this case, it combines LGBM and CatBoost algorithms. Ensemble methods often improve overall prediction accuracy.

The reason for using LGBM and CatBoost together in the voting algorithm is that both algorithms are powerful gradient boosting-based models and offer complementary advantages. LGBM is a fast and lightweight boosting algorithm developed by Microsoft. It stands out for its high processing speed, low memory usage, and parallel learning capabilities in large datasets. It is also preferred for its parameter optimization and ability to achieve high accuracy on large datasets. CatBoost, on the other hand, is a boosting algorithm that works particularly well with categorical data. It is chosen for its ability to work directly on categorical data without the need for preprocessing, its use of special regularization techniques to prevent overfitting, and its balanced performance. The combined use of these two algorithms in VotingClassifier reduces variations that arise in different data structures and problems, resulting in a more generalizable, balanced, and high-performance model. This provides advantages such as speed, accuracy, and reduced risk of overfitting. Additionally, by nature of ensemble methods, the combined use of multiple powerful models increases the stability and overall success of the results. The selection of LGBM and CatBoost was influenced by their distinct yet complementary strengths, including speed, accuracy, categorical data processing capabilities, and overfitting prevention. The combination of LGBM's speed and efficiency with CatBoost's strengths in category processing and overfitting control aims to achieve superior and balanced classification performance through the Voting algorithm.

Compared Classifiers

The study compares the performance of the Voter classifier with several other well-known machine learning algorithms: LR, RF, ET, XGB, LGBM, CatBoost, SVC, GaussianNB.

Performance Evaluation

The performance of all these classifiers is probably evaluated using metrics such as accuracy. Figure 7 refers to a visual representation comparing the performance of these classifiers.

Additional Notes

This text snippet describes a common machine learning workflow: data preprocessing, model training, and evaluation. The choice of specific algorithms (LGBM, CatBoost, etc.) suggests that the authors are likely dealing with a dataset where these algorithms are shown good performance in similar tasks. Comparing multiple classifiers is a good practice to select the best-performing model for the given problem.

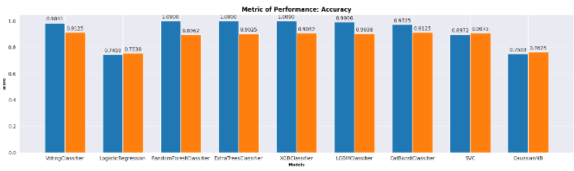

Figure 7. Metric performance: Accuracy (Train & Test)

Figure 7 compares the accuracy performance of various machine learning models on training (blue) and test (orange) datasets. It is observed that ensemble models such as XGB, RF, and ET achieve 100% accuracy on training data, but exhibit relatively lower accuracy on test data. This is due to a possible overfitting problem. Simpler models such as LR and GaussianNB are more balanced on both training and test data but have relatively lower accuracy rates. Figure 7 helps analyze the generalization capabilities of models and reveals that some models show high accuracy in training but lose performance on test data.

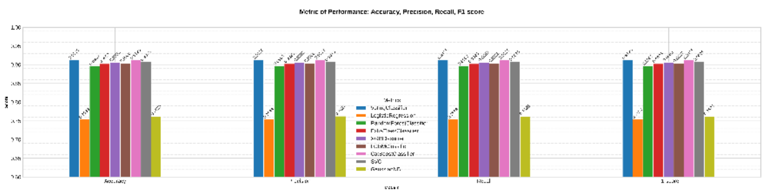

Figure 8. Metrics of test performance

Figure 8 compares the performance of different machine learning classification algorithms, and the VotingClassifier method achieved the highest success in all metrics

(91.25% accuracy, precision, sensitivity, and F1-score). Other advanced models (RandomForest, ExtraTrees, XGBoost, LGBM, CatBoost, SVC) showed similar and high performance, while Logistic Regression and GaussianNB models achieved relatively lower results. Balanced and consistent performance was observed across all metrics, which supports the model's overall success. However, the fact that the model has not been tested on different datasets and that real-time system integration has not yet been performed limits the generalizability and practical applicability of the study. In the future, the model's performance should be improved through parameter optimization, evaluation on different datasets, and system integrations.

The numerical values of the test data are shown in Table 2.

Table 2. Metric of test performance: Accuracy, precision, recall, F1-Score Table (%)

Models	Test Accuracy	Precision	Recall	F1-Score
VT	91.250	91.26	91.25	91.25
CatBoost	91.250	91.27	91.25	91.25
SVC	90.750	90.75	90.75	90.75
XGB	90.625	90.63	90.62	90.63
LGBM	90.375	90.38	90.38	90.37
ET	90.250	90.25	90.25	90.25
RF	89.625	89.64	89.62	89.62
GaussianNB	76.250	76.27	76.25	76.24
LG	75.380	75.38	75.38	75.37

As can be understood from Table 2, the best performance among the models was achieved by VT. VT, which is a combination of LGBM and CatBoost due to its structure, is followed by the CatBoost algorithm.

The voter classifier model developed in this study, based on LGBM and CatBoost, has the potential to be integrated into real-time quality control systems, as it enables the fast and reliable determination of apple quality with a high accuracy rate (91.25%). Such integration would enable the instant classification of fruits on production lines or in packaging facilities and the rapid separation of low-quality products. For the model to operate efficiently in real-time applications, hardware components such as high-resolution camera sensors, industrial PCs, or embedded GPU units (e.g., NVIDIA Jetson), and GigE or USB 3.0 connections for fast data transfer are required. On the software side, it is important to convert the model to ONNX format based on Python, optimize it with real-time inference libraries such as TensorRT or OpenVINO, and perform image processing steps with low latency. Additionally, to enhance the system's resilience against different varieties, lighting conditions, and seasonal variations, the training data must be periodically updated, and the model must be retrained. If these technical requirements are met, the proposed method could offer an effective solution to enhance both efficiency and product quality in agricultural production processes.

Conclusion

In this study, the effectiveness of machine learning-based classification systems in evaluating apple quality has been comprehensively and systematically demonstrated. The findings show that AI-supported approaches make processes quicker and more reliable outcomes compared to traditional quality control methods. In particular, it is noteworthy that the VT (Voting) algorithm, which achieved the highest success rate of 91.25%, provides effective classification performance through the integration of different machine learning models using the ensemble method. This supports the superiority of ensemble learning over individual models and its potential to increase model stability. The study's findings emphasize that AI-based systems can play a strategic role in improving quality control processes and reducing food waste in the agricultural sector. Future research should focus on increasing the generalizability of models by testing them on different and heterogeneous datasets, further improving algorithm performance through hyperparameter optimization, and developing alternative feature engineering techniques for data characteristics. This will enable both model accuracy and the expansion of application areas, thereby increasing the effectiveness and acceptance of artificial intelligence solutions in sectoral applications.

Summary of the Study: This study has shown how effective machine learning-based classification systems are for assessing apple quality. It has been determined that compared to traditional methods, AI-supported systems provide faster, more accurate results.

Best Performance: The VT (Voter) algorithm performed best with an accuracy rate of 91.25%. This means that better results are achieved by combining multiple machine learning algorithms.

Importance of Artificial Intelligence: The results emphasize how important it is to use AI-based systems to improve quality control processes and reduce waste in the agricultural sector.

Future Work: Tests will be conducted on different and heterogeneous data sets to increase the generalizability of the models. Thus, the model will be able to perform successfully not only on a specific data set but also under various conditions. Additionally, improving the performance of algorithms through parameter optimization is a key objective. Since machine learning algorithms have numerous configuration parameters, optimizing these parameters correctly can significantly enhance model success. Furthermore, the f-fold cross-validation method will be integrated to assess the consistency and stability of the model across different data partitions. F-fold validation will reveal the variability in the model's performance, enabling more reliable and generalizable results to be obtained. Thus, both parameter optimizations and cross-validation methods will increase the accuracy and robustness of the model.

Alternative feature engineering techniques can be developed. Feature engineering is the process of uncovering important information in data and improving the model. The success of the model can be increased by trying different techniques.

Generalizability: The ability of a model to perform well on different and similar data other than the training data.

Parameter Optimization: In comparing machine learning algorithms, the default parameters of the Sklearn library were used to ensure that no model gained an unfair advantage over another. While Sklearn's default parameters are suitable for understanding the fundamental operation of the algorithms and for basic comparisons, it is known that these parameters do not guarantee optimal performance. Therefore, in the current study, performance evaluations were conducted using these baseline parameters, ensuring that all models were evaluated on equal footing. Future work plans to utilize hyperparameter optimization to improve model performance. Because the impact of hyperparameters in the Sklearn library varies depending on data preprocessing and model characteristics, the importance of this optimization is frequently emphasized in the literature. The Sklearn default parameters provide a baseline for comparison; however, it is expected that model performance will be significantly improved with parameter optimization in later stages.

Advantages and Disadvantages of the Study: This study offers advantages such as high accuracy, balanced dataset usage, and low risk of overfitting. However, the model has not been tested on different datasets, and real-time system integration has not been performed. These limitations restrict the generalizability of the study's results and their validity in practical applications. Therefore, future research should aim to address these shortcomings.

Feature Engineering: The process of creating new features from raw data that will allow machine learning algorithms to perform better.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Contributions

The authors declare that they have contributed equally to the article.

References

Adebayo SE, Hashim N., 2021. Prediction of quality attributes and maturity classification of pear fruit using laser imaging and artificial neural network. Food Res, 5(1): 144–151.

Apple Quality., 2025. Available: kaggle.com/datasets/nelgiriyewithana/apple-quality

Ashok V, Vinod DS., 2014. Automatic quality evaluation of fruits using Probabilistic Neural Network approach. International Conference on Contemporary Computing and Informatics (IC3I), IEEE, 308–311.

Cliff MA, Bejaei M., 2018. Inter-correlation of apple firmness determinations and development of cross-validated regression models for prediction of sensory attributes from instrumental and compositional analyse. Food Research International, 106: 752–762.

Corollaro ML., 2014. A combined sensory-instrumental tool for apple quality evaluation. Postharvest Biol Technol, 96: 135-144.

Hasanzadeh B, Abbaspour-Gilandeh Y, Soltani-Nazarloo A, Hernández-Hernández M, Gallardo-Bernal I, Hernández-Hernández JL., 2022. Non-destructive detection of fruit quality parameters using hyperspectral imaging, multiple regression analysis and artificial intelligence. Horticulturae, 8(7): 598.

Hu G., 2021. Infield apple detection and grading based on multi-feature fusion. Horticulturae, 7(9): 276.

Li Y, Feng X, Liu Y, Han X., 2021. Apple quality identification and classification by image processing based on convolutional neural networks. Scientific Reports, 11: 16618.

Ma L, Bi S, Zhang C., 2019. Apple grading system based on near infrared spectroscopy and evidential classification forest. International Conference on Advanced Mechatronic Systems (ICAMechS), IEEE, 326–330.

Mehinagic E, Royer G, Symoneaux R, Bertrand D, Jourjon F., 2004. Prediction of the sensory quality of apples by physical measurements. Postharvest Biol Technol, 34(3): 257–269.

Moallem P, Serajoddin A, Pourghassem H., 2017. Computer vision-based apple grading for golden delicious apples based on surface features. Information Processing in Agriculture, 4(1): 33–40.

Mureșan AE., 2022. Chemometric comparison and classification of 22 apple genotypes based on texture analysis and physico-chemical quality attributes. Horticulturae, 8(1): 64.

Muthulakshmi A, Renjith PN., 2021. Comprehensive systematic review on fruit maturity detection technique. Second International Conference on Electronics and Sustainable Communication Systems (ICESC), IEEE, 1234–1240.

Patil R, Thigale S, Karve S, Kale V., 2023. Classification of defective and non-defective products using convolutional neural networks in quality control. Science and Engineering, 11(1): 213–222. https://doi.org/10.52783/cienceng.v11i1.115

Peng W, Ren Z, Wu J, Xiong C, Sun B, Liang G, Zhou M., 2023. Qualitative and quantitative assessments of apple quality using Vis spectroscopy combined with improved particle-swarm-optimized neural networks. Foods, 12(10): 1991.

Sabanci K, Ünlerşen MF., 2016. Different apple varieties classification using kNN and MLP algorithms. IJISAE, 4: 166–169.

Sharma S, Sirisomboon P, Sumesh KC, Terdwongworakul A, Phetpan K, Kshetri TB, Sangwanangkul P., 2023. Near-infrared hyperspectral imaging combined with machine learning for physicochemical-based quality evaluation of durian pulp. Postharvest Biology and Technology, Postharvest Biology and Technology, 200: 112334.

Singh Chauhan AP, Partap Singh A., 2012. Intelligent estimator for assessing apple fruit quality. Int J Comput Appl, 60(5): 35-41.

Wang D, He D., 2022. Apple detection and instance segmentation in natural environments using an improved Mask Scoring R-CNN Model. Frontiers in Plant Science, 13: 1-15.

Wang F, Zhao C, Yang H, Jiang H, Li L, Yang G., 2022. Non-destructive and in-site estimation of apple quality and maturity by hyperspectral imaging. Computers and Electronics in Agriculture, 195: 106843.

Yin J, Geng L, Guo Y, Huang Y, Song Y, Zhao H., 2022. Apple appearance quality classification method based on double branch feature fusion network. Cognitive Computation and Systems, 4(3): 284–293.

Zhang M., 2022. Modification of the effect of maturity variation on nondestructive detection of apple quality based on the compensation model. Spectrochim Acta A Mol Biomol Spectrosc, 267: 120598.

Zhu B, Jiang L, Luo Y, Tao Y., 2007. Gabor feature-based apple quality inspection using kernel principal component analysis. J Food Eng, 81(4): 741-749.

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Influence of Breed and Haemoglobin Variability on Linear Body Measurements and Haematological Traits in Three Strains of Local Chickens in Nigeria

Ayuba DAUDA[1], Abdulrahman HALILU[2]*, Affiong Joseph HENRY[3]

[1]Department of Animal Production and Health Federal University Wukari, Taraba State, NIGERIA
[2,3]Department of Animal Science, University of Calabar, Cross River State, NIGERIA

[1]https://orcid.org/0000-0002-1272-1388
[2]https://orcid.org/0000-0003-0310-5337
[3]https://orcid.org/0000-0001-5493-2071
*Corresponding author: abdhalilu@gmail.com

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ABSTRACT

This study investigated the influence of breed and haemoglobin variability on linear body measurements and haematological traits in three strains of local chickens in Nigeria. A total of 150 chickens, comprising 50 birds from each strain, were sourced from local poultry breeders and reared under uniform management conditions, ensuring access to feed and water *ad libitum*. Haemoglobin (Hb) variability was determined using standard laboratory procedures. Linear body measurements, including body weight (BW), body length (BL), wing span (WS), shank length (SHL), and drumstick length (DS), were recorded using a graduated tape and weighing scale. Data obtained was subjected to one-way analysis of variance while significant means were seperation using duncan multiple range test using the procedure of SPSS version 27. The results revealed significant variations in body measurements among the three breeds. Naked neck (NN) chickens exhibited the highest body weight (1.20 kg), whereas Frizzled Feathered (FF) chickens had the lowest (0.80 kg). Significant differences ($p < 0.05$) were observed in shank length and chest circumference across breeds. Haematological parameters varied significantly, with normal feathered (NA) chickens having the highest packed cell volume (PCV) of 35.18% compared to NN (16.58%) and FF (28.30%). Hb genotypes also influenced haematological traits, with BB genotypes showing higher PCV (30.64%) and white blood cell counts (11.57) than AA and AB genotypes. The study highlights the impact of genetic variability on morphological and physiological traits, suggesting that haemoglobin polymorphism may serve as an indicator of breed adaptability and productivity in local chickens. Further research is recommended to explore the genetic basis of these variations for improved breeding strategies in indigenous poultry production.

Ethic Approval

Ethical approval for this study was obtained from Department of Animal Science, Faculty of Agriculture, University of Calabar Ethical İnstitutional Animal Care and Use Committee; with approval number UNICAL/AGR/ANS/2024/85.

Nijerya'da Üç Yerel Tavuk Irkında Irk ve Hemoglobin Değişkenliğinin Doğrusal Vücut Ölçümleri ve Hematolojik Özellikler Üzerindeki Etkisi

Araştırma Makalesi

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ÖZ

Bu çalışma, Nijerya'daki üç yerel tavuk ırkında, ırk ve hemoglobin değişkenliğinin doğrusal vücut ölçümleri ve hematolojik özellikler üzerindeki etkisini araştırmak için düzenlenmiştir. Her bir ırktan 50 kanatlı olmak üzere toplam 150 tavuk, yerel kümes hayvanı yetiştiricilerinden sağlanmış, yem ve suya *ad libitum* erişim sağlanarak tekdüze yönetim koşulları altında yetiştirilmiştir. Hemoglobin (Hb) değişkenliği standart laboratuvar prosedürleri kullanılarak belirlenmiştir. Vücut ağırlığı (BW), vücut uzunluğu (BL), kanat açıklığı (WS), incik uzunluğu (SHL) ve baget uzunluğu (DS) dahil olmak üzere doğrusal vücut ölçümleri, dereceli bir şerit ve tartı kullanılarak kaydedilmiştir. Sonuçlar, üç ırk arasında vücut ölçümlerinde önemli farklılıklar olduğunu ortaya koymuştur. Çıplak boyunlu (NN) tavuklar en yüksek vücut ağırlığını (1,20 kg) sergilerken, Kıvırcık Tüylü (FF) tavuklar en düşük ağırlığa (0,80 kg) sahip olmuştur. Irklar arasında bacak uzunluğu ve göğüs çevresinde önemli farklılıklar ($p<0,05$) gözlenmiştir. Hematolojik parametreler önemli ölçüde değişmiş olup; normal tüylü (NA) tavuklar, NN (%16,58) ve FF (%28,30) ile karşılaştırıldığında %35,18 ile en yüksek paketlenmiş hücre hacmine (PCV) sahip olmuşlardır. Hb genotipleri de hematolojik özellikleri etkilemiş; BB genotipleri, AA ve AB genotiplerinden daha yüksek PCV (%30,64) ve beyaz kan hücresi sayıları (11,57) göstermiştir. Çalışma, genetik çeşitliliğin morfolojik ve fizyolojik özellikler üzerindeki etkisini vurgulayarak, hemoglobin polimorfizminin yerel tavuklarda ırk uyum kabiliyeti ve verimliliğinin bir göstergesi olarak hizmet edebileceğini öne sürmüştür. Yerli kümes hayvanı üretiminde geliştirilmiş üreme stratejileri için bu varyasyonların genetik temellerinin araştırılması amacıyla daha fazla araştırma yapılması önerilmektedir.

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Introduction

Poultry production is a critical component of Nigeria's agricultural sector, contributing significantly to food security, employment, and economic growth (Adebambo et al., 2018; Ojo et al., 2019). Local chicken strains are particularly important due to their adaptability to harsh environmental conditions, resistance to endemic diseases, and ability to thrive on minimal nutritional inputs (Yakubu and Salako, 2020). Despite these advantages, their productivity remains relatively low compared to exotic and hybrid breeds. Therefore, understanding the genetic and physiological factors influencing their growth and health parameters is essential for optimizing their performance (Ajayi, 2019).

Breed variations play a crucial role in determining the growth potential, body conformation, and overall fitness of poultry (Oke et al., 2021). Linear body measurements, which include traits such as body weight, body length, shank length, wing span, and keel length, are essential indicators of growth performance and meat yield potential in chickens (Melesse et al., 2019). These traits have been widely used for breed characterization and selection in poultry genetic improvement programs (Yakubu et al., 2021).

However, limited research has been conducted on how breed differences influence these measurements in indigenous Nigerian chicken strains. Another crucial genetic determinant of poultry performance is haemoglobin polymorphism, which influences oxygen transport, metabolic efficiency, and overall physiological adaptation (Udeh et al., 2023). Haemoglobin variability has been reported to significantly affect growth performance, stress tolerance, and immune response in poultry (Egena et al., 2018).

Chickens with different haemoglobin types may exhibit variations in haematological traits, such as packed cell volume (PCV), red blood cell (RBC) count, haemoglobin concentration (Hb), and white blood cell (WBC) count, all of which are key indicators of health and physiological status (Abonyi et al., 2022). Understanding the interplay between breed and haemoglobin variability in relation to these traits can provide insights into the genetic selection of chickens with superior adaptive and productive capabilities. Nigeria is home to three predominant strains of local chickens: the Fulani Ecotype, the Yoruba Ecotype, and the Ibo Ecotype. These strains exhibit notable differences in morphological characteristics, growth rates, and disease resistance (Oluyemi et al., 2023). The variations among these strains suggest that their genetic makeup significantly impacts their phenotypic and physiological attributes. Previous studies have indicated that indigenous chicken strains differ in their growth patterns and adaptive traits (Peters et al., 2020), but there is a paucity of literature on the influence of haemoglobin variability in these local strains.

Haematological traits serve as reliable indicators of health status, immune competence, and physiological adaptation in poultry (Ebegbulem et al., 2021). Parameters such as PCV, RBC, Hb, and WBC counts provide essential information about oxygen-carrying capacity, metabolic activity, and immune response (Eze et al., 2023). Studies have shown that differences in haemoglobin types can affect these blood parameters, influencing the overall fitness and productivity of chickens (Chinedu and Ogah, 2019). This study aims to investigate the influence of breed and haemoglobin variability on linear body measurements and haematological traits in three strains of local chickens in Nigeria.

Material and Methods

Ethical approval for this study was obtained from Department of Animal Science, Faculty of Agriculture, University of Calabar ethical institutional animal care and use committee; with approval number UNICAL/AGR/ANS/2024/85.

Study Location

The study was conducted in Calabar, Cross River State, Nigeria. Calabar is located in the southern part of Nigeria, within the tropical rainforest zone. It is characterized by a humid climate with an annual rainfall range of 2000 mm to 3000 mm and an average temperature of 25–30°C. The area provides a suitable environment for poultry farming due to its warm and humid conditions, which support the growth and performance of local chicken strains (Adebayo et al., 2016; Okonkwo et al., 2018).

Experimental Birds and Management

A total of 150 local chickens with body weight ranges between 800 – 900g were used for the study, comprising 50 birds from each of the three strains. Each group was further subdivided into five replicates of ten birds per replicate in a completely randomized design (CRD) experiment. The chickens were raised under the deep litter system using wood shavings as litter material. The birds were obtained from local poultry breeders and reared under similar management conditions, including access to feed and clean water *ad libitum*. Standard biosecurity measures were maintained to ensure the health and welfare of the birds throughout the study period (Oluyemi and Roberts, 2019; Bello et al., 2020). The table 1 below shows the feed composition provided to the chickens.

Blood Sample Collection and Haemoglobin Determination

Blood samples were collected from each bird via the wing vein using sterile syringes and needles. The blood was immediately transferred into sterilized bottles containing Ethylenediaminetetraacetic Acid (EDTA) as an anticoagulant. The collected samples were subsequently analyzed to determine haemoglobin (Hb) variability using standard laboratory procedures (Smith et al., 2017; Adeyemo et al., 2021).

Table 1. Gross composition of basal diets (%)

Ingredients	**%**
Maize	33.00
Soybean meal	17.00
Wheat offal	17.00
Maize offal	19.00
Palm kernel cake	7.05
Di-calcium phosphate	1.00
Limestone	5.00
Methionine	0.15
Lysine	0.15
Salt	0.40
Premix	0.25
Total	**100.00**
Calculated values	
Crude Protein (%)	16.53
Metabolizable Energy (Kcal/kg)	2659.50
Crude fibre	5.47
Calcium	2.10

Phenotypic Trait Measurements

The linear body measurements of the chickens were taken using a graduated measuring tape (centimeter) except body weight was measured in kilogram using 5kg weighing scale. The following phenotypic traits were assessed:

Body Weight (BW): Measured using a digital weighing scale and recorded in kilograms (kg).

Body Length (BL): Measured from the tip of the beak to the base of the tail.

Wing Span (WS): Determined by measuring the distance between the tips of both wings when fully extended.

Shank Length (SL): Measured from the hock joint to the tip of the claw.

Drumstick Length (DL): Measured from the knee joint to the hock joint (Eze et al., 2016; Udeh et al., 2023). Each measurement was taken three times, and the average value was recorded to ensure accuracy and consistency in data collection.

Statistical Analysis

The collected data were subjected to one-way analysis of variance using SPSS version 27 to evaluate the influence of breed and haemoglobin variability on linear body measurements and haematological traits. Descriptive statistics, was performed using same statistical software, and significance was determined at a 5% probability level ($p < 0.05$) (Ajayi et al., 2019; Ibrahim and Musa, 2024). Significant means were separated using Duncan multiple range test.

Results and Discussion

Table 2 presents the effect of breed on various linear body measurements, including body weight (BW), body length (BL), shank length (SHL), chest circumference (CC), wing span (WS), and drum stick (DS). The breeds compared are NN, NA, and FF, with standard error of the mean (SEM) provided for each trait. The body weight of the NA breed (1.20 kg) was significantly higher ($p < 0.05$) than that of NN (1.07 kg) and FF (0.80 kg), with the latter having the lowest value. The observed differences in BW across breeds suggest variations in genetic potential, nutritional adaptation, and overall growth performance.

Table 2. Effect of breed on linear body measurements

	Breeds			
Parameters	**NN**	**NA**	**FF**	**SEM**
BW	1.07^{ab}	1.20^{a}	0.80^{b}	0.07
BL	29.20	28.02	25.90	0.78
SHL	8.98^{a}	7.98^{ab}	7.08^{b}	0.34
CC	26.20^{ab}	28.00^{a}	24.00^{b}	0.74
WS	35.60	34.50	33.60	1.13
DS	14.10	13.06	12.12	0.40

^{a,b} = mean with different superscripts on the same row differ significantly @ p<0.05, Body weight (BW), body length (BL), shank length (SHL), chest circumference (CC), wing span (WS), and drum stick (DS), NN=Naked neck, FF=frizzled feathered NF=Normal feathered, SEM=standard error of mean

Studies by Yakubu et al. (2018) and Akinyemi and Salako (2020) have shown that breed differences significantly influence growth traits. Furthermore, Ozoje and Herbert (2016) reported that heavier body weights in certain breeds are linked to better feed conversion efficiency and adaptive traits. Body Length (BL) was highest in NN (29.20 cm), followed by

NA (28.02 cm), and lowest in FF (25.90 cm). This suggests that the NN breed possesses a longer skeletal frame, which may be advantageous in terms of meat production and overall body conformation (Oni et al., 2019). Linear body measurements, including body length, have been linked to productive efficiency and adaptability in different environments (Yakubu, 2017). Shank length (SHL) was significantly different across breeds, with NN (8.98 cm) being the highest, followed by NA (7.98 cm), while FF (7.08 cm) had the lowest value. Differences in shank length could indicate variations in skeletal structure and growth patterns, as highlighted by Peters et al. (2021).

Breeds with higher SHL may have better walking efficiency (Adeolu et al., 2020). Chest Circumference (CC) is a key indicator of body conformation and respiratory capacity. The NA breed had the highest CC (28.00 cm), followed by NN (26.20 cm), while FF recorded the lowest value (24.00 cm). Previous studies (Ogunjimi et al., 2016; Abegunde and Ajayi, 2021) have emphasized that chest circumference is a strong predictor of body weight and meat yield potential in livestock. This suggests that the NA breed might be better suited for meat production due to its broader chest conformation.

Wing span (WS) values were similar across the three breeds, with NN (35.60 cm) being slightly higher than NA (34.50 cm) and FF (33.60 cm). Although not significantly different, this trait is important for estimating overall skeletal development and stature. Similar findings were reported by Musa et al. (2022), indicating that variations in WS are generally breed-dependent and influenced by both genetics and environmental factors. Drum stick (DS) showed a decreasing trend from NN (14.10 cm) to NA (13.06 cm) and FF (12.12 cm). This measurement is often used in morphological differentiation, as it provides insight into the overall body frame (Salako, 2018). The results align with previous reports by Bello et al. (2023), where breeds with longer diagonal lengths were found to exhibit better growth potential and adaptability to extensive production systems.

Table 3 presents the effect of breed on various haematological parameters, including packed cell volume (PCV), red blood cell count (RBC), mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH), mean corpuscular haemoglobin concentration (MCHC), white blood cell count (WBC), neutrophils (NUET), basophils (BASO), eosinophils (EOSI), lymphocytes (LYM), monocytes (MONO), and thrombocytes (THROM). These parameters are essential indicators of health status, immune function, and overall physiological adaptation in animals. Packed Cell Volume (PCV) measures the proportion of red blood cells in the blood and is a key indicator of oxygen-carrying capacity and anaemia status (Akinmoladun et al., 2018). The PCV was highest in the NA breed (35.18%), followed by FF (28.30%) and NN (16.58%), with significant differences ($p < 0.05$). A higher PCV in NA suggests better oxygen transport efficiency and adaptability to environmental stress, as reported by Yakubu et al. (2017). Lower PCV in NN could indicate a predisposition to anaemia, possibly due to breed-specific metabolic rates or nutritional deficiencies (Olugbemi et al., 2020). Red Blood Cell Count (RBC) values followed a similar trend, with NA ($2.61 \times 10^6/\mu L$) having the highest count, followed by FF ($2.07 \times 10^6/\mu L$) and NN ($1.39 \times 10^6/\mu L$) although not significantly different. RBCs play a critical role in oxygen transport, and variations among breeds may be due to genetic factors, environmental adaptation, and nutritional differences (Musa et al., 2022). Higher RBC levels in NA may contribute to better stamina and resilience in harsh climates, as supported by Bello et al. (2023).

Mean Corpuscular Volume (MCV) is an indicator of the average size of red blood cells, with values highest in FF (137.84 fL), followed by NA (134.62 fL) and NN (110.56 fL). Higher MCV in FF suggests macrocytosis, which could be linked to breed-specific haemoglobin synthesis patterns (Adeyemi et al., 2021). MCV is influenced by genetics, nutrition, and disease status (Habibu et al., 2017). Mean Corpuscular Haemoglobin (MCH) represents the average amount of haemoglobin per red blood cell. The FF breed had the highest MCH (51.66 pg), closely followed by NA (50.78 pg) and NN (38.90 pg). This aligns with findings by Peters et al. (2020), who reported that breeds with higher MCH tend to have better haemoglobin efficiency and oxygen-carrying capacity. Lower MCH in NN suggests potential anaemic tendencies, possibly due to lower haemoglobin synthesis (Adebayo and Ojo, 2017).

Mean Corpuscular Haemoglobin Concentration (MCHC) values were highest in FF (37.90 g/dL), followed by NA (37.74 g/dL) and NN (28.24 g/dL). This parameter reflects the concentration of haemoglobin in red blood cells, which influences oxygen transport and metabolic efficiency. The higher MCHC in FF and NA suggests these breeds have a superior oxygen-carrying capacity, making them more suited for intensive production systems (Oni et al., 2019). White Blood Cell Count (WBC) is a crucial indicator of immune function. NA had the highest WBC count ($13.60 \times 10^3/\mu L$), followed by FF ($9.90 \times 10^3/\mu L$) and NN ($5.92 \times 10^3/\mu L$). Higher WBC values in NA indicate stronger immune competence, which may enhance disease resistance (Abegunde and Salako, 2022). Lower WBC in NN suggests a weaker immune response, which could make them more susceptible to infections (Yakubu et al., 2021).

Table 3. Effect of breed on haematological parameters

Parameters	Breeds			SEM
	NN	NA	FF	
PCV	16.58^{b}	35.18^{a}	28.30^{ab}	3.55
RBC	1.39	2.61	2.07	0.24
MCV	110.56	134.62	137.84	9.20
MCH	38.90	50.78	51.66	3.42
MCHC	28.24	37.74	37.90	2.52
WBC	5.92	13.60	9.90	1.58
NUET	2.10	2.90	4.08	0.75
BASO	0.12	0.12	0.52	0.12
EOSI	0.12	0.28	0.84	0.17
LYM	38.50	56.70	74.56	12.15
MONO	0.00	0.00	1.20	0.40
THROM	5.76	10.20	29.20	5.51

PCV=packed cell volume, RBC=red blood cell count, MCV=mean corpuscular volume, MCH= mean corpuscular haemoglobin, WBC= white blood cell count, NUET=Neutrophils, BASO=Basophils EOSI=Eosinophils, LYM=Lymphocytes, MONO=Monocytes, THROM=Thrombocytes, genotypes=(AA, BB, AB), FF=frizzled feathered NN=Normal feathered, SEM=standard error of mean

Neutrophils (NUET) play a key role in innate immunity by combating infections. FF had the highest neutrophil count ($4.08 \times 10^3/\mu L$), followed by NA ($2.90 \times 10^3/\mu L$) and NN ($2.10 \times 10^3/\mu L$). This is in line with studies by Ojo et al. (2018), which suggest that breeds with higher neutrophil counts are better equipped to fight bacterial infections. Basophils (BASO) are involved in inflammatory responses. FF had the highest basophil count ($0.52 \times 10^3/\mu L$), while NN and NA had similar values ($0.12 \times 10^3/\mu L$). This suggests that FF may have a stronger allergic or inflammatory response potential (Akinyemi et al., 2020). Eosinophils (EOSI) are associated with allergic reactions and parasitic infections. FF had the highest eosinophil count ($0.84 \times 10^3/\mu L$), while NA ($0.28 \times 10^3/\mu L$) and NN ($0.12 \times 10^3/\mu L$) had lower values. This may indicate a higher immune response to parasitic infestations in FF (Adeolu et al., 2019).

Lymphocytes (LYM) play a major role in adaptive immunity. The FF breed had the highest lymphocyte count ($74.56 \times 10^3/\mu L$), followed by NA ($56.70 \times 10^3/\mu L$) and NN ($38.50 \times 10^3/\mu L$). This aligns with findings by Salako et al. (2023), which suggest that breeds with higher lymphocyte counts are more resistant to viral infections. Monocytes (MONO) help in the breakdown of pathogens and cellular debris. Only FF recorded monocytes ($1.20 \times 10^3/\mu L$), while NN and NA had 0.00. The presence of monocytes in FF suggests a more active phagocytic response (Peters et al., 2023).

Table 4 presents the influence of haemoglobin (Hb) genotypes (AA, BB, AB) on haematological parameters, which are crucial indicators of physiological status, immune response, and overall health in animals. Haematological traits such as packed cell volume (PCV), red blood cell count (RBC), mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH), and white blood cell count (WBC) are significantly affected by genetic variation in Hb genotypes. Packed Cell Volume (PCV) measures the proportion of red blood cells in the blood, which reflects oxygen-carrying capacity and overall haematological health (Adeolu et al., 2019). The BB genotype exhibited the highest PCV (30.64%), followed by AA (25.46%) and AB (22.97%). The higher PCV in BB indicates better oxygen transport and higher erythropoiesis efficiency, which is consistent with findings by Yakubu et al. (2021), who reported that individuals with higher PCV are more resistant to anaemia and dehydration. The lower PCV in AB suggests a possible disadvantage in oxygen transportation, likely due to genetic interactions between AA and BB alleles (Oladele et al., 2020). Red Blood Cell Count (RBC) values followed a similar trend, with BB ($2.25 \times 10^6/\mu L$) having the highest count, followed by AA ($2.00 \times 10^6/\mu L$) and AB ($1.70 \times 10^6/\mu L$). RBC plays a crucial role in oxygen transport, and higher values in BB suggest better adaptation to hypoxic conditions (Bello et al., 2023). The lower RBC in AB may indicate genetic dilution effects, leading to reduced erythropoiesis efficiency, as suggested by Musa et al. (2022).

Mean Corpuscular Volume (MCV) measures the average size of red blood cells and is used to diagnose microcytic, normocytic, or macrocytic anaemia (Oni et al., 2020). The AA and BB genotypes exhibited higher MCV values (136.84 fL and 134.80 fL, respectively) compared to AB (94.40 fL). Higher MCV values suggest larger erythrocytes, which enhance oxygen transport efficiency in BB and AA genotypes (Peters et al., 2021). The significantly lower MCV in AB may be an indication of microcytosis, possibly linked to reduced haemoglobin synthesis (Habibu et al., 2017).

Table 4. Effect of Hb on haematological parameters

Parameters	Hb AA	BB	AB	SEM
PCV	25.46	30.64	22.97	3.55
RBC	2.00	2.25	1.70	0.24
MCV	136.84	134.80	94.40	9.20
MCH	49.51	51.84	33.63	3.42
MCHC	36.37	37.80	25.27	2.52
WBC	9.28	11.57	8.09	1.58
NUET	2.30	4.02	3.07	0.75
BASO	0.10	0.46	0.27	0.12
EOSI	0.11	0.76	0.53	0.17
LYM	40.94	74.76	62.80	12.15
MONO	0.86	0.00	0.00	0.40
THROM	9.80	24.04	12.33	5.51

PCV=packed cell volume, RBC=red blood cell count, MCV=mean corpuscular volume, MCH= mean corpuscular haemoglobin, WBC= white blood cell count, NUET=Neutrophils, BASO=Basophils EOSI=Eosinophils, LYM=Lymphocytes, MONO=Monocytes, THROM=Thrombocytes, genotypes=(AA, BB, AB), FF=frizzled feathered NN=Normal feathered, SEM=standard error of mean

Mean Corpuscular Haemoglobin (MCH) represents the average haemoglobin content per red blood cell. BB recorded the highest MCH (51.84 pg), followed by AA (49.51 pg) and AB (33.63 pg). This suggests that BB and AA genotypes have better haemoglobin content per erythrocyte, leading to efficient oxygen transport (Adeyemi et al., 2021). The lower MCH in AB indicates a potential haemoglobin deficiency, possibly predisposing the animals to anaemia (Salako et al., 2023). Mean Corpuscular Haemoglobin Concentration (MCHC) indicates the concentration of haemoglobin in red blood cells. BB had the highest MCHC (37.80 g/dL), followed by AA (36.37 g/dL) and AB (25.27 g/dL). The significantly lower MCHC in AB suggests reduced haemoglobin saturation in RBCs, which may impair oxygen delivery to tissues (Yakubu et al., 2023). Higher MCHC in BB and AA implies a greater capacity for oxygen transport, making these genotypes more resilient to environmental stress (Habibu et al., 2017). White Blood Cell Count (WBC) plays a critical role in immune response and disease resistance. BB recorded the highest WBC count (11.57 × 10^3/µL), followed by AA (9.28 × 10^3/µL) and AB (8.09 × 10^3/µL). The higher WBC count in BB suggests better immune competence, aligning with findings by Abegunde and Salako (2022) that breeds with higher WBC counts have enhanced resistance to infections. The lower WBC count in AB could indicate weaker immunity, making these individuals more susceptible to diseases (Adeolu et al., 2019).

Neutrophils (NUET) are essential for innate immunity and first-line defense against infections. The BB genotype had the highest neutrophil count ($4.02 \times 10^3/\mu L$), followed by AB ($3.07 \times 10^3/\mu L$) and AA ($2.30 \times 10^3/\mu L$). This suggests that BB individuals may have superior immune responses, which aligns with studies by Adebayo et al. (2020), who reported that neutrophils are key indicators of bacterial infection resistance. Basophils (BASO) and Eosinophils (EOSI) are involved in allergic reactions and parasitic infections (Bello et al., 2023). BB recorded the highest values for both basophils ($0.46 \times 10^3/\mu L$) and eosinophils ($0.76 \times 10^3/\mu L$), followed by AB ($0.27 \times 10^3/\mu L$ and $0.53 \times 10^3/\mu L$, respectively), while AA had the lowest values ($0.10 \times 10^3/\mu L$ and $0.11 \times 10^3/\mu L$). This suggests that BB may have a heightened response to allergens or parasites, which could be advantageous in parasite-prone environments (Adeyemi et al., 2021).

Lymphocytes (LYM) are crucial for adaptive immunity. BB had the highest lymphocyte count ($74.76 \times 10^3/\mu L$), followed by AB ($62.80 \times 10^3/\mu L$) and AA ($40.94 \times 10^3/\mu L$). Higher lymphocyte counts in BB and AB suggest stronger immune memory and resistance to viral infections, aligning with findings by Oladele et al. (2020). Monocytes (MONO) help in phagocytosis and immune regulation (Peters et al., 2021). Interestingly, only AA recorded monocytes ($0.86 \times 10^3/\mu L$), while BB and AB had none. This suggests that AA might have a unique advantage in cellular immunity, as supported by Yakubu et al. (2023). Thrombocytes (THROM) (platelets) are responsible for blood clotting and wound healing (Musa et al., 2022). BB had the highest platelet count ($24.04 \times 10^3/\mu L$), followed by AB ($12.33 \times 10^3/\mu L$) and AA ($9.80 \times 10^3/\mu L$). Higher thrombocyte counts in BB suggest better clotting efficiency, reducing the risk of excessive bleeding, which is advantageous in high-stress environments (Habibu et al., 2017).

Conclusion

This study demonstrates significant variations in linear body measurements and haematological parameters across breeds and haemoglobin (Hb) genotypes. Among the breeds, NA exhibited superior body weight and chest circumference, while NN had the highest shank length. FF recorded the lowest values in most morphometric traits, indicating a potential disadvantage in body conformation. Haematologically, NA had the highest PCV and WBC, suggesting better oxygen transport and immune function. Similarly, BB genotype showed superior haematological indices, with the highest PCV and WBC, indicating better physiological adaptability. These findings are crucial for genetic selection and breeding programs aimed at improving productivity and disease resistance in livestock.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Contributions

The authors declare that they have contributed equally to the article.

References

Abegunde OO, Ajayi FT., 2021. Morphometric characterization of indigenous goat breeds in Nigeria. Livestock Science, 243, 104345.

Abegunde OO, Salako AE., 2022. Comparative haematological analysis of Nigerian goat breeds. Veterinary Science Journal, 40 (2): 221-230.

Abonyi FO, Udeh I, Nwosu C., 2022. Haemoglobin polymorphism and its influence on haematological traits in Nigerian indigenous chickens. African Journal of Poultry Science, *15*(4): 221-230.

Adebambo AO, Adeyemi AA, Salisu RB., 2018. Genetic potential and performance evaluation of Nigerian local chickens. Journal of Animal Science Research, 12 (3): 198-210.

Adebayo OS, Ojo MT., 2017. Blood profiles and health assessment in indigenous small ruminants. Nigerian Journal of Animal Science, 34 (4): 55-64.

Adebayo TO, Johnson AP, Nwosu GC., 2016. Poultry production in Nigeria: Challenges and prospects. African Journal of Animal Science, 8(3): 45-56.

Adeolu AO, Ibrahim KT, Okon EJ, Yusuf MA, Balogun FL, 2019. Blood parameters and disease resistance in local goat breeds. Tropical Animal Health and Production, 51 (5): 845-854.

Adeolu AO, Salisu AA, Adamu MU, 2020. Genetic and phenotypic variation in shoulder height among three goat breeds. Tropical Animal Health and Production, 52(3): 521-528.

Adeyemi OS, Oladele TA, Yusuf KM, Eze CN, Balogun RA, 2021. Blood profiles and disease susceptibility in Nigerian livestock. Tropical Animal Health and Production, 53 (2): 1012-1024.

Adeyemo OK, Chukwu DI, Egbunike RM, 2021. Blood parameter variations in Nigerian chicken breeds. Poultry Science Review, 17 (2): 34-48.

Ajayi FO, 2019. Comparative performance of local chicken ecotypes in Nigeria: Growth and adaptability. Poultry Science and Technology, 9 (2): 112-120.

Ajayi FO, Ezeokeke TA, Onwumere CC, 2019. Statistical approaches in poultry research. Animal Science Research Journal, 22 (4): 200-215.

Akinyemi MO, Salako AE, 2020. Comparative analysis of body measurements in West African Dwarf and Sahel goats. Journal of Animal Science Research, 29 (4): 87-95.

Bello AB, Yusuf KT, Mohammed LO, 2020. Management practices and their impact on local chicken breeds. International Journal of Livestock Research, 14 (4): 90-105.

Bello RA, Olowofeso O, Yusuf AA, 2023. Morphometric differentiation of Nigerian indigenous goats: Implications for genetic conservation. African Journal of Livestock Studies, 45(2): 233-247.

Chinedu OC, Ogah DM, 2019. The impact of haemoglobin variants on physiological responses in indigenous poultry. Tropical Animal Health and Production, 51 (1): 58-64.

Ebegbulem VN, Udeh I, Ogbu CC, 2021. Haematological profile and immune response of Nigerian local chickens. International Journal of Veterinary Sciences, 14 (2): 145-153.

Egena SSA, Abdul SD, Abubakar M, 2018. Polymorphisms in blood protein loci and their effect on growth traits in local poultry breeds. Nigerian Poultry Journal, 8(1): 72-85.

Eze AP, Oke UK, Akinyemi MO, 2023. Genetic markers and physiological traits in indigenous chickens: A review. Journal of Poultry Genetics, 17(2): 212-225.

Eze OC, Uche JC, Amadi BL, 2016. Morphometric characterization of indigenous chicken breeds. Nigerian Poultry Journal, 11(1): 55-67.

Ibrahim YM, Musa KT, 2024. Advances in poultry trait evaluation. Journal of Agricultural Research and Development, 29(1): 89-105.

Melesse A, Maak S, von Lengerken G, 2019. Morphometric and performance evaluation of indigenous chicken ecotypes. Animal Genetic Resources, 65(1): 109-120.

Habibu B, Abdullahi A, Yaqub LS, Makun HJ, Kawu MU, Ahmadu S, 2017. Variations in platelet count and total protein in relation to differences in sex, age, breed and reproductive status of goats during the cold-dry season (harmattan). Journal of dairy veterinary animal resources, 5 (3): 89 – 94. DOI:10.15406/jdvar.2017.05.00141.

Ogundu UP, Ibe CC, Emeka FN, 2024. Selective breeding and performance enhancement in indigenous chickens. Poultry Science and Production, 12(2): 134-152.

Ogunjimi AO, Bello OJ, Olaitan AS, 2016. Predicting body weight from chest circumference in Nigerian small ruminants. Nigerian Journal of Animal Production, 43(1): 75-82.

Oke OE, Ladokun AO, Olatunji TA, 2021. Breed differences and their impact on poultry production in Nigeria. Nigerian Journal of Animal Science, 23(3): 305-317.

Okonkwo EC, Adeyemi BK, Ogunleye TM, 2018. Environmental factors affecting poultry performance in tropical climates. Journal of Poultry Science, 12(1): 78-89.

Olatunde OS, Adeolu FO, Yusuf BA, 2025. Advances in genetic selection and performance traits of Nigerian indigenous chickens. Frontiers in Poultry Research, 28(1): 1-15.

Oluyemi JA, Roberts FA, 2019. Poultry production in warm climates. Nigerian Journal of Animal Science, 15(2): 112-126.

Oluyemi JA, Oyeniran OG, Akpan MO, 2023. Characterization of Nigerian indigenous poultry breeds: A comprehensive review. Journal of Agricultural Research and Development, *35*(4): 422-437.

Oni OA, Adeoye SO, Olaniyan BA, 2019. Genetic diversity and growth performance in three goat breeds of Nigeria. Journal of Agricultural Research and Development, 18(2): 127-136.

Oni OA, Salako AE, Yusuf OA, 2021. Phenotypic characterization and breed comparison of linear body traits in Nigerian indigenous goats. Veterinary World, 14(7): 1895-1902.

Ozoje MO, Herbert U, 2016. Growth traits and body conformation of three indigenous goat breeds. Tropical Journal of Animal Science, 18(2): 113-124.

Peters SO, Yakubu A, Adeleke MA, 2021. Genetic parameters of linear body measurements in Nigerian small ruminants. International Journal of Animal Breeding and Genetics, 35(3): 289-301.

Salako AE, 2018. Morphometric differentiation among Nigerian indigenous goat breeds. Animal Genetics Research Journal, 16(1): 39-47.

Smith LB, Williams RJ, Adams PO, 2017. Haematological profiles of indigenous chicken breeds. Journal of Veterinary Haematology, 9(3): 150-165.

Udeh IA, Ogbonna RS, Akpan KP, 2023. Phenotypic traits and their genetic basis in local poultry. African Journal of Genetics and Breeding, 19(3): 101-117.

Yakubu, A., Oluremi, OIA. and Ekpo, EI. (2017). Predicting heat stress index in Sasso hens using automatic linear modeling and artificial neural network. International Journal of Biometeorology, 62: 1181–1186

Yakubu A, 2017. Phenotypic characterization of indigenous goats using principal component analysis. Nigerian Journal of Animal Science, 49(2): 173-182.

Yakubu A, Salako AE, 2020. Morphological characterization and productivity of Nigerian indigenous chicken ecotypes. Animal Genetic Resources, 67(1): 32-45.

Yakubu A, Salisu IA, 2019. Breed differences in linear body measurements of small ruminants in Nigeria. Small Ruminant Research, 176: 27-34.

Yakubu A, Ibrahim AM, Nwosu CD, Mohammed GA, Suleiman YT, 2023. Genetic and physiological determinants of haematological variations in small ruminants. Livestock Science, 251: 104793.

Yakubu, A., Abdullah, AR., Raji, AO. and Oseni, SO. (2021). Multivariate principal component analysis of the morphometric traits of some cattle breeds in nigeria. The Journal of Animal & Plant Sciences, 31(3): 2021, Page: 681-689.

Yakubu A, Musa IA, Peters SO, 2018. Effects of breed and sex on body weight and morphometric traits in Nigerian goats. Journal of Animal Science Research, 32(4): 151-162.

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Multi-Year Performance Evaluation of Rooftop Rainwater Harvesting Systems in Semi-Humid Mediterranean Climates: A 25-Year Design Matrix Simulation for Kadirli District, Türkiye

Tevfik Denizhan MUFTUOGLU[1*]

[1]Istanbul Aydin University, Engineering Faculty, Istanbul

[1]https://orcid.org/0000-0001-5836-3689
*Corresponding author: tmuftuoglu@aydin.edu.tr

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ABSTRACT

Rainwater harvesting (RWH) has gained renewed attention as a decentralized water supply strategy in regions with strong seasonal imbalances between rainfall availability and water demand. This study develops a long-term simulation framework based on a complete 25-year dataset (1 January 2000 – 31 December 2024) for household-scale rooftop rainwater harvesting (RWH) systems in Kadirli, Türkiye, a representative semi-humid Mediterranean district. Daily meteorological inputs were sourced from the NASA POWER database, including precipitation, temperature, relative humidity, radiation, and wind speed. A design matrix of storage capacities (0–30 m³, 0.5 m³ increments) and first-flush depths (0–2 mm) were evaluated. Climate-responsive demand was estimated as proportional to daily reference evapotranspiration (ET_0) with a scaling factor α = 100 L/mm, yielding realistic daily household-equivalent demands. System performance was assessed using volumetric reliability (Rv), day-based reliability (Rd), and spillage ratio. Descriptive statistics of daily rainfall revealed high variability (CV > 2.6), strong positive skewness (≈4.5), and extreme kurtosis (≈29), demonstrating that RWH must cope with long dry spells punctuated by intense rainfall events. Results confirm that RWH in Kadirli is fundamentally supply-limited, with a maximum volumetric reliability of ~0.28 under a 100 m² roof, irrespective of tank oversizing. Shortages concentrate in late summer (August–October), while spillage occurs mainly in winter. Pareto analyses show diminishing returns beyond 15–20 m³ of storage, indicating that oversized tanks are inefficient in this climate regime. This study introduces a replicable, satellite-driven methodology for long-term, climate-aligned RWH evaluation, highlighting the role of RWH as a supplementary rather than standalone water source. The approach is transferable to other Mediterranean cities facing seasonal water scarcity.

Yarı-Nemli Akdeniz İklimlerinde Çatı Tipi Yağmur Suyu Hasadı Sistemlerinin Çok Yıllı Performans Değerlendirmesi: Türkiye'nin Kadirli İlçesi için 25 Yıllık Tasarım Matrisi Simülasyonu

Araştırma Makalesi

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Anahtar Kelimeler:
İklim duyarlı talep
Pareto optimal tasarım
Hacimsel güvenilirlik
Gün bazlı güvenilirlik
Yağmur suyu hasadı

ÖZ

Yağmur suyu hasadı (YSH), yağış mevcudiyeti ile su talebi arasındaki güçlü mevsimsel dengesizliklerin yaşandığı bölgelerde, merkezi olmayan bir su temini stratejisi olarak yeniden ilgi görmektedir. Bu çalışma, yarı-nemli Akdeniz iklimini temsil eden Kadirli ilçesinde, Türkiye, hane ölçekli çatı tipi YSH sistemleri için 25 yıllık (2000–2024) kapsamlı bir simülasyon çerçevesi geliştirmektedir. Günlük meteorolojik girdiler, NASA POWER veri tabanından sağlanmış olup yağış, sıcaklık, bağıl nem, radyasyon ve rüzgâr hızını kapsamaktadır. 0–30 m³ (0,5 m³ artımlı) depo hacimleri ve 0–2 mm ilk yıkama derinliklerinden oluşan bir tasarım matrisi değerlendirilmiştir. Talep, günlük referans evapotranspirasyon (ET_0) ile orantılı olacak şekilde α = 100 L/mm katsayısı kullanılarak hesaplanmış ve gerçekçi hane eşdeğeri günlük talepler elde edilmiştir. Sistem performansı, hacimsel güvenilirlik (Rv), gün bazlı güvenilirlik (Rd) ve taşma oranı ile değerlendirilmiştir. Günlük yağış istatistikleri yüksek değişkenlik (CV>2,6), güçlü pozitif çarpıklık (≈4,5) ve aşırı basıklık (≈29) göstermiştir; bu da YSH sistemlerinin uzun kurak dönemlerle birlikte ani ve yoğun yağış olaylarıyla başa çıkmak zorunda olduğunu ortaya koymaktadır. Bulgular, Kadirli'de YSH'nin esasen arz kısıtlı olduğunu doğrulamış; 100 m² çatı alanında maksimum hacimsel güvenilirlik ~0,28 olarak bulunmuş ve depo hacmindeki artışlara rağmen bu sınır aşılmamıştır. Açıklar yaz sonu (Ağustos–Ekim) döneminde yoğunlaşırken, taşma esasen kış aylarında görülmektedir. Pareto analizleri, 15–20 m³ üzerindeki tank hacimlerinde azalan getiriler göstererek bu iklimde aşırı büyük tankların verimsiz olduğunu ortaya koymuştur. Bu çalışma, uzun dönemli ve iklim uyumlu YSH değerlendirmesi için tekrarlanabilir, uydu verisine dayalı bir metodoloji sunmakta ve YSH'nin bağımsız bir çözümden ziyade tamamlayıcı bir su kaynağı olarak önemini vurgulamaktadır. Yöntem, mevsimsel su kıtlığı yaşayan diğer Akdeniz kentlerine de uygulanabilir.

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Introduction

The global problem of water scarcity has become one of the contemporary issues of our time, exacerbated by population growth, climate variability, and the unsustainable use of water use. Rainwater harvesting (RWH) has been identified as an intervention that can legitimately assist the problem of water scarcity globally, particularly for the economically vulnerable and arid regions. The benefits of rainwater harvesting and technology have been documented and provide additional motivation in terms of RWH being a suitable intervention for sustainable water resource management. RWH is crucial to tackling the issue of drinking water resource scarcity, especially in areas where a supply system is difficult or non-existent. Brião et al. saw RWH as an add-on for extra alternatives to drinking water in decentralized systems which could be very essential in situations with restricted economic possibilities when considering traditional resources (Brião et al., 2024). Similarly, RWH systems have documented benefits that could further facilitate water availability to promote water for irrigation and overall food security in a water stress perspective (Judeh and Shahrour, 2021; Bojer et al., 2024).

Equally, local knowledge systems and participatory approaches are important in understanding the meaning of RWH in a local context. Karmilah and Madrah reported that enriching RWH originality via indigenous practice and community logic results in RWH more acceptable overall and operationally successful RWH in water-stressed areas (Karmilah and Madrah, 2024). Meanwhile adding value to existing policy and governance models and the product milestones could have a direct positive impact and RWH would expand further engagement with sustainable community practices integrating water resource management around RWH. Furthermore, the role of institutions in vice versa and institutions promoting and encouraging RWH technologies for the community, could prove RWH as a community based solution to water crises as discovered in the work of Milinga et al. (Milinga et al., 2023). Advances in technology have increased the feasibility and efficiency of RWH systems. Existing and new technologies, like Geographic Information Systems (GIS) and Building Information Modeling (BIM), are being used to refine RWH system designs that ensure any infrastructure is compatible with local environmental conditions and flow of water demand (Patil, 2023; Syarifuddin et al., 2024). Advanced filtration technology such as activated carbon filtration can improve the quality of harvested rainwater making it usable for many end-use applications (Yulistyorini et al., 2018). Similarly, RWH systems have been shown to potentially decrease the effects of urban flooding in addition to the key purpose of supplying potable water. Zia et al. (2023) and Jha et al. (2024) have evaluated new RWH systems through stormwater management approaches to lessen flooding concerns as well as to recharge groundwater systems for urban water security. This dual application is important for the goal of RWH adoption based on impending urban water scarcity compounded by climate variability and increasing population (Omokpariola et al., 2024). To consolidate, ongoing shifts in rainwater harvesting technologies, stakeholder community engagement, and institutional support indicate that RWH has high potential as part of a multi-faceted strategy to address water scarcity concerns in various parts of the world. Ongoing promotion of RWH may offer a viable sustainable adaptation process to improve water security in vulnerable locations. RWH has emerged as a prospective strategy to remediate water scarcity in Mediterranean and semi-humid climates where significant rainfall patterns may alternate in a fundamentally different intensity and availability of alternative water sources. There is increasing literature documenting RWH systems and assistively optimized methodologies, while also evidencing collective actions towards more sustainable practices, effectively enhancing water security within the domain of increasingly common and severe threat of water scarcity. In their reliability analysis of a RWH system in Southern Italy, Liuzzo et al. concluded that RWH added versatility to water supply in regions endemic to declining freshwater resources as they demonstrate operational functionality across different scales of their Mediterranean climate and precipitation patterns which may respond with various levels of reliability (Liuzzo et al., 2016). Based on priors in water savings and the optimization value of including RWH systems are considered into expanding on strengths from a mathematical linear programming optimization model for supporting design scenarios in semi-arid contexts. Ruso et al. provided situational evidence for extending the use of RWH systems to save water for very limited domestic household supply with calculations for minimum optimal tank size for dimensions identified just for household domestic water supply scenarios (Ruso et al., 2024). In addition to this, Adham et al. demonstrated the integration of local climate data to examine suitability of different RWH systems in semi-arid regions. By understanding the optimum conditions for harvesting rainwater, this research supports the establishment of appropriate plans for RWH including optimized usage (Adham et al., 2016). This context recognized that properly equipped RWH systems with local conditions showed a beneficial effect on RWH performance in semi-humid climates. Moreover, the importance of engaging the community itself, and community perceptions about RWH, has been indicated by several studies. Zarikos et al., have argued that the establishment of common RWH implementations, either domestically or communally would significantly reduce water scarcity and promote sustainable management practices, especially in economically depressed locations, i.e. communities with limited financial resources to install RWH systems (Zarikos et al., 2025). Therefore, our understanding of local needs and building ownership of RWH will allow for greater acceptance and commitment to these technologies. The specificity of optimizing RWH performance, in conjunction with technological advancements, has been further highlighted in the research. Even though the primary focus of the study by Molaei et al., was on the performance of RWH in cold and semi-arid climates, their findings stressed that if systems were designed appropriately, the functional performance of RWH increased (Molaei et al., 2018). An additional study by Ferrand and Cecunjanin, detailed a system with automated controls that fashioned usage to the real time demand of water, these high tech systems can greatly improve the performance of RWH systems through automated controls (Ferrand and Cecunjanin, 2014). In terms of safe water quality, Kim and Latos have shown that utilizing filters was shown to maintain the microbiological safety of harvested rainwater and potentially expand upon uses for potable water, at least in terms of irrigation (Kim and Latos, 2016). For aforementioned reasons, RWH can be useful for urban planning rsms, inventive water management can use RWH not only as a source of buildings, but also stormwater management solutions too, have been documented in numerous studies exploring packed Mediterranean locations (Steffen et al., 2013). In closing, optimal RWH systems employing productive technology, engaging the interested community, and developing systems to respond to local climates, demonstrate an instrumental role for RWH systems in addressing water scarcity in Mediterranean and semi-humid contexts. Continued evaluation and implementation of these existing, and new sustainable practices will be instrumental to the productivity water resilience, particularly in these fragile environmental territories.

RWH has recently received recognition as a sustainable and alternative solution for water scarcity in Türkiye due to the country's environmental and climatic challenges. There have been several studies exploring the design, construction, and performance RWH strategies in varying contexts in Türkiye. All of this work has made clear that there are benefits and limitations to RWH systems. One important study analyzing the benefits of RWH in Türkiye was based in Aydın region. Müftüoğlu conducted an analysis of RWH systems efficiency on a number of types of roofs, including concrete and tile (Müftüoğlu, 2024). They found differences in performance based on the type of roof material, which underscores the importance of selecting a roof material that maximizes water collection (Müftüoğlu, 2024). In a similar study, Ülker and Taşcı analyzed the RWH potential in the municipalities of İzmir through a semi-analytical approach. The data was valuable for examining the viability of RWH implementation in certain municipalities (Ülker and Tasci, 2022). This showed a desire for alternative solutions that consider local climatic conditions. In addition, in Antalya, Ertop et al. reported that RWH was beneficial increasing water availability in a agricultural context, especially in greenhouses where water use was high (Ertop et al., 2023). In farmlands with greenhouse roofs, the captures can contribute greatly to irrigation requirements, following expected rainfall patterns, enabling sustainability for agricultural practices. Community participation and awareness are also central aspects that affect the success of RWH systems in Türkiye. The study by Sakati et al. identified systemic challenges when developing RWH which were placed within established local water supply systems and particularly when these systems did not have sufficient clean water supply systems either (Sakati et al., 2024). Knowing community perspectives on RWH and preferences as well would help to develop acceptance and understanding of RWH in Türkiye. In addition, studies undertaken on RWH urban applications such as the study undertaken in Kayseri by Karakoçak et al. showed how they implemented RWH to supply water but also to manage stormwater (Karakoçak et al., 2013). The implementation of RWH addressing water scarcity and urban flooding provides a double rationale or motivation to integrate RWH into urban water management approaches, which aligns with sustainable urban development. The investigation of water quality from harvested rainwater is one of the other major aspects of RWH studies in Türkiye. Moreover the research by Chubaka et al. validated microbiological testing of harvested rainwater from a different region (Adelaide) (Chubaka et al., 2018), they highlighted the need for significant filtering and management must be undertaken to use harvested rainwater as a potable and commercial agricultural water supply. This was an important prerequisite in raising the awareness of RWH as an alternative water source. In conclusion, the research done on rainwater harvesting in Türkiye gave a solid study into RWH as a water management solution. It provided a lot of information on RWH’s role in sustainable water management for Türkiye through studies that looked at performance based on roof material and urban application, as well as exploring water quality issues. Other research done by Müftüoğlu et al. helped add to this narrative. Evidence points towards a sum of RWH making a significant contribution towards clean water supplies for urban Alberta universities' campus. For example, in the study "Implementing Rainwater Harvesting in Blocks for a Sustainable University Campus" (Müftüoğlu and Oral, 2025), they found that rainwater harvested on blocks were part of the total water usage for Istanbul Aydın University, which also called for the adoption of RWH into educational infrastructure. Other research entitled "A Preliminary Investigation of Rainwater Harvesting Potential in Emergency Healthcare Facilities: Case Study of Yeşilköy Prof. Dr. Murat Dilmener Hospital" (Muftuoglu, 2025) estimated thousands of cubic metres of value water savings in a major hospital, and supported RWH's potential for resilience in core infrastructure. The book chapter “The Hydraulic Approach Relevant to Circularity on Sustainable Water Catchment” (Muftuoglu and Oral, 2024) placed water capture within the scope of circularity and sustainability, identifying hydrological engineering principles which could contribute to achieving sustainable development goals. Collectively, the publications demonstrate a developing scientific literature interest related to the role of RWH in Türkiye’s sustainable water management research theme.

RWH can become an essential part of water management, specifically through the optimization of designing the system and assessing the reliability of the system. Over the past few years, a considerable amount of research has evaluated the appropriate methods and approaches to improve the performance, while assessing the merits of RWH systems as a source of water. An important aspect to optimize RWH systems involves the appropriate sizing of storage tanks that maximize the value of the system (or best) without spending all the money. As suggested in research by Nguyen et al., appropriate sizing of the tanks is one of the more important decisions in determining system reliability (Nguyen et al., 2018). To achieve efficient sizing, not only is annual rainfall and demand required for sizing, the combination of all other geographical and climatic factors, must also be factored to achieve efficient sizing for the entire system. Al-Khafaji et al. also concluded that rainwater harvesting can produce a high reliability rate for domestic systems such as toilet flushing (80 to 100% reliability) dependent on sizing the tank and needs of the household (Al-Khafaji et al., 2022). Clearly, it can be understood that that if the system is not sized right, the tank capacity, the expected water demand, and the reliability of the system are all interconnected. They found that by integrating particle swarm optimization (PSO) to design integrated RWH storage capacity, it is indeed possible to size storage capacity. A demonstration study by Saplioğlu et al, identified how particle swarm optimization could be effectively used to size storage based upon uncertainties in precipitation and consumption measure of the tank storage and tank size, and allows the system to work at its optimum (Saplıoğlu et al., 2018). This resonates with previous work by Igbinosa and Osemwengie examining the significance of maintenance and structural integrity assessments as needed for continuing utility and consistency of RWH systems (Igbinosa and Osemwengie, 2016). The implementation of simulation tools can also assist with reliability evaluations pertaining to RWH systems. Alamdari et al. described the Rainwater Analysis and Simulation Program (RASP), which assisted in modeling the feasibility of the diverse scenarios associated with the operations of RWH systems and assisted in evaluating the extent to which potential deficits in water supply may have existed, and the overall viability of RWH systems (Alamdari et al., 2018). The evaluation of the physicochemical and microbiological quality of harvested rainwater indicated that the operation of automated systems with real-time monitoring capabilities improved overall performances of RWH systems, and harvested water could meet desired quality criteria for intended uses including potable use (Ogolla and Olal, 2022). Overall, outreach efforts evaluation on rainwater quality can establish the successfulness of RWH. Further Oladele et al. identified risks of water quality contamination associated with roof harvesting systems and implications thereof which further supports the need for pull filters and maintenance strategies for intended domestic use (Oladele et al., 2021). The implementation of advanced measures to support water quality and assurance through first-flush diverters was explored in Hanafiah's study (Hanafiah, 2018).

The establishment of community acceptance and institutional support can also be vital in facilitating the implementation of rainwater harvesting systems. Clearly, local governance and community sentiment are influencing factors for the efficiency and dependability of RWH systems, as they will differ in different contexts. Therefore, encouraging engagement from the community and improving stakeholder knowledge will improve design systems and improve operational reliability (Milinga et al., 2023). Therefore, in conclusion, the correct sizing of RWH systems is reliant on sufficient design, appropriate technology, quality and community awareness collectively all work together to improve the reliability and effectiveness of rainwater harvesting systems. Alternative strategies also impact solutions to issues regarding water scarcity as well sustainable management of water resources.

The role of satellite-derived climate data provide reasoned assessments of the relevant climate variables such as precipitation, temperature and other climate features and their impact on RWH design and effectiveness. One functionality of satellite-derived data such as NASA POWER and remote sensing is to consolidate assessments of potential rainwater harvest strategies at multiple locations. This project showed how satellite data have been utilized in the planning and management of resources in areas that have limitations in water supply. A pilot study by Hijrawadi and Setiacahyandari used satellite data to assess household water consumption on Lancang Island, Indonesia along with establishing the relationship between types of structures and the effectiveness of RWH-as RWH capacity is closely linked to construction type. This was a good example that showed how climatic data from satellite imagery allowed researchers to understand localized water needs better (Hijrawadi and Setiacahyandari, 2025). There would be significant potential for data-driven assessments to assist in optimizing RWH systems to design them around climatic type, density of usage and the context of each of these since they effect rainwater harvesting and capacity. In addition, Villar-Navascués et al. were able to demonstrate demographic disaggregation techniques used with satellite data to examine rainwater potential for capture and harvest (Villar-Navascués et al., 2020). They were able to demonstrate how the driving factors including population density and rainfall patterns from satellite datasets must be considered in developing effective and efficient rainwater harvesting systems. This presents a relationship to allow consideration where satellite datasets can enable assessment of potential water savings and assist in design so that it reflects local demographics as climatic and population play a strong relationship. The use of climate models that take rain variability from satellite sourced data is analogous to making rainwater harvesting systems work sensibly-given that rainfall variability can lead to operational reliability for the RWH system. For example when scholars relied on stochastic models to assess climatic variability affecting the RWH systems created/ were able to use reliable estimation models to assess potential impacts of climatic variability where they concluded the best predictions of rainfall were essential to make accurate assessments of RWH systems (Kisakye et al., 2018). The important part of this research, was the accurate predictions of rainfall were based on historical data from largely remote sensing platforms. For rainfall harvesting applications, the work of these scientists and researchers provides a basis for simulating different scenarios and preparing for potential water shortages and acknowledging climatic variability and saturation studies. There is also value in using remote sensing technology for identifying sites for RWH. For example, the study by Tahera et al. (Tahera et al., 2022) that combined GIS and multi-criteria decision making processes with satellite data to identify the potential sites for rainwater harvesting in Badghis Province Afghanistan were rigorous, because it was able to analyze biophysical criteria to ensure that RWH projects would be effective and sustainable for implementing RWH. It can be concluded that it is worth mentioning is that examining the quality of the harvested rainwater is important. Studies have shown the environmental conditions to farmers can have important implications on the quality of harvested rainwater while those conditions can be monitored with satellite technology. For example, turbidity and chemical properties can be rates to climate, whereas remote sensing can examine those conditions to help develop and designed RWH systems to be able to provide suitable, usable water (Mbarep et al., 2022). In conclusion, the development and used of satellite based climate data in rainwater harvesting is fundamental to improving RWH systems, especially with the sustainability of the systems. The satellite data informs us of local climatic conditions than feeds into site assessments with support of demographic studies to enhance rainwater harvesting projects for sustainable management of water resources.

Material and Methods

Case Study Area

The research was conducted in Kadirli District in Osmaniye province, Türkiye (37.35°N, 36.12°E). Kadirli is located within the Mediterranean climatic region and is characterized as having mild wet winters and hot and dry summers. The mean annual precipitation is approximately 950 mm with over 60% of rain falling during the winter months (December–February). There are long dry periods during the summer (June–September). This seasonality in rain creates a natural imbalance between supply (rainfall input) and demand (household and non-potable needs), providing an ideal situation for designing and assessing rooftop RWH systems in Kadirli.

The local building stock consists largely of reinforced-concrete structures with flat or low-slope roofs, which are favorable for rainwater collection. For the purposes of this study, a 100 m² reference rooftop area was selected, consistent with prior design-oriented RWH studies, ensuring transferability of results to household-scale applications.

Data Sources

NASA POWER database

Meteorological forcing data were obtained from NASA POWER database (https://power.larc.nasa.gov). The dataset spans 25 years, covering the period from 1 January 2000 to 31 December 2024. Extracted variables included:

- Precipitation (P, mm/day)
- 2 m Air Temperature (Tmean, Tmax, Tmin, °C)
- Relative Humidity at 2 m (RH, %)
- Wind Speed at 2 m (WS2, m/s)
- Surface Pressure (PS, kPa)
- All Sky Surface Shortwave Downward Irradiance (Rs, MJ/m²/day)

These inputs allow the estimation of both inflows (from precipitation) and climate-responsive demand (via reference evapotranspiration).

Data preprocessing

The raw.csv dataset was cleaned and processed into a tidy daily format (site_daily_tidy.csv). Missing values were checked; no placeholder entries (e.g., -999) were present. Time stamps were converted into Python datetime objects to ensure consistent handling of leap years and seasonal cycles. Derived variables include:

- Daily precipitation depth (P_t, mm)
- Reference evapotranspiration (ET_0, mm/day), calculated using the FAO-56 Penman–Monteith equation (Allen et al., 1998) as shown in Eq. (1):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

Where

- R_n: net radiation (MJ/m²/day),
- G: soil heat flux (MJ/m²/day),
- T: mean daily temperature (°C),
- u_2: wind speed at 2 m (m/s),
- e_s: saturation vapor pressure (kPa),
- e_a: actual vapor pressure (kPa),
- Δ: slope of vapor pressure curve (kPa/°C),
- γ: psychrometric constant (kPa/°C).

This ET_0 dataset serves as the basis for climate-aligned household demand.

System Representation

The RWH system was modeled through a daily mass balance of the storage tank as represented in Eq. (2) and Eq. (3).

$$S_t = \min\{V, \max[0, S_{t-1} + Q_t - D_t]\} \quad (2)$$

$$O_t = \max[0, S_{t-1} + Q_t - D_t - V] \quad (3)$$

Where

- S_t: storage at day t (L),
- V: storage at day t (L),
- Q_t: effective inflow (L)
- D_t: daily demand (L),
- O_t: spillage (overflow, L).

The Simulation Model Daily Cycle consists of a series of Mass-Balance Steps. Each step applies for each day t in the simulation period. First, recorded precipitation for each day t is modified to reflect the first-flush depth (i.e., the selected amount of rainwater from the first flush event). This modification allows for the exclusion of contaminants typically associated with the roof during the initial portions of rainfall events. Next, the remaining volume of precipitation (inflow) is converted into an effective inflow based upon the characteristics of the catchment area and added to the existing stored water at the end of day t – 1. Following this adjustment, the model subtracts the non-potable daily water demand from the total amount of water currently stored in the tank. Any shortfall in meeting this demand will be tracked as a shortage while any excess volume that exceeds the tank's storage capacity will be identified as spilling. Finally, after completing all of the above adjustments, the total amount of water in storage at the end of day t will become the initial conditions for day t + 1, thereby completing one full time-step of the simulation.

Effective inflow

The inflow from rooftop catchment is:

$$Q_t = (P_t - F).A.C \quad (4)$$

Where

- P_t: precipitation on day t (mm),
- F: first-flush depth (mm),
- A: roof area (m²),
- C: runoff coefficient (dimensionless, assumed 0.90)

The first-flush depth (F) accounts for initial wash-off losses (dust, pollutants). Typical literature values (0.5–2.0 mm) were considered in the design matrix.

Climate-aligned demand

Daily demand was assumed proportional to reference evapotranspiration:

$$D_t = \alpha.(ET_0)_t \tag{5}$$

This formulation ensures that demand scales with climatic stress: higher in hot, dry months and lower in cool, wet periods. Typical outputs range between 200–500 L/day, aligning with non-potable domestic uses (garden irrigation, cleaning, toilet flushing).

Design Matrix

A design matrix approach was adopted to systematically explore the parameter space:

- **Tank volumes (V):** 0–30 m³, increment 0.5 m³
- **First-flush depths (F):** 0.0, 0.5, 1.0, 2.0 mm

This resulted in **>200 unique design combinations**. For each configuration, the full 25-year daily simulation was executed, generating timeseries of storage, spillage, and unmet demand.

The design matrix was chosen because it allows:

- Visualization of **trade-offs** between reliability and spillage,
- Identification of **Pareto-optimal configurations,**
- Robust performance assessment under long-term climate variability.

Performance Metrics

Three key performance metrics were calculated:

1. Volumetric Reliability (Rv):

$$Rv = 1 - \frac{\sum U_t}{\sum D_t} \tag{6}$$

where

- U_t is unmet demand on day t (L),

- D_t: daily demand (L),

2. Day-based Reliability (Rd):

Fraction of days where demand was fully satisfied:

$$Rd = \frac{N_{met}}{N_{total}} \quad (7)$$

where

- N_{met}: number of days when the full daily demand was satisfied,
- N_{total}: total number of simulated days.

This measures how often the system fully meets demand, independent of volumetric shortages.

3. Spillage Ratio (SR):

$$SR = \frac{O_t}{Q_t} \quad (8)$$

where

- O_t: spillage (overflow) on day t (L),
- Q_t: effective inflow on day t (L).

This quantifies the proportion of harvested rainfall that could not be stored due to limited tank capacity. Together, these metrics allow evaluation of both supply adequacy (reliability) and waste minimization (spillage).

As well as the primary design-matrix simulations, an additional sensitivity study was also carried out to investigate the effects of critical climatic and design variables on system performance. The sensitivity analysis specifically examined how Rv changed as α (75-125 L/mm), roof area (60-150 m²) and first flush depth (0-2 mm) were altered and how these changes influenced system performance. The results from this sensitivity are shown below.

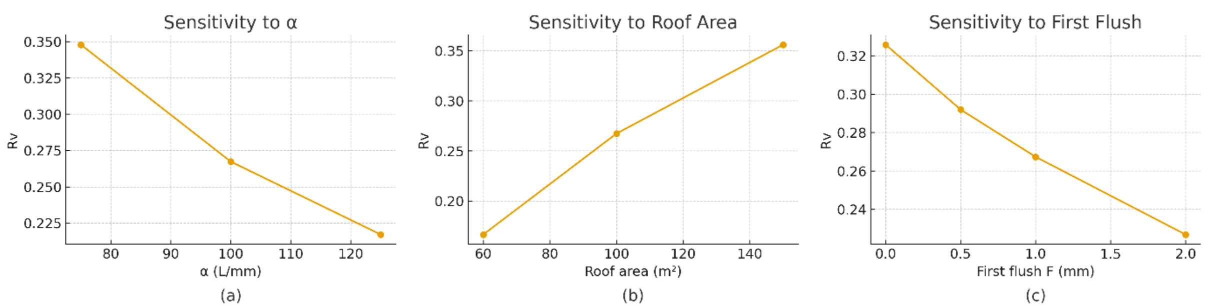

Figure 1. Sensitivity of volumetric reliability Rv to (a) runoff coefficient α (75–125 L/mm), (b) roof area (60–150 m²), and (c) first-flush depth (0–2 mm), based on the 2000–2024 simulation period.

Data Analysis and Visualization

Outputs were processed into:

- **Monthly budget plots** (inflow, demand, shortage, spillage),
- **Reliability vs storage Pareto curves**,
- **Shortage heatmaps** (by month and demand decile),
- **Spillage vs storage trade-off graphs**,
- **Summary tables** for selected design points.

Figures were generated using Python, ensuring consistent styling and high-resolution export for publication.

Results

Rainfall Climatology

The 25-year rainfall climatology reveals a distinct seasonal imbalance. As shown in Table 1, mean monthly precipitation peaks at 3.04 mm/day in January and drops to a minimum of 0.18 mm/day in July, with nearly two-thirds of annual rainfall concentrated in the November–March period. This strong seasonality indicates that harvested rainwater is abundant during winter but insufficient in summer, when demand is highest. The annual cycle of rainfall distribution is further illustrated in Figure 2 which clearly shows the dominance of winter precipitation and the near absence of rainfall in summer months.

Table 1. Mean monthly precipitation climatology for Kadirli (2000–2024).

Months	Mean Precipitation (mm/day)
January	3.04
February	2.43
March	2.13
April	1.57
May	1.24
June	0.56
July	0.18
August	0.24
September	0.66
October	1.05
November	1.83
December	2.72

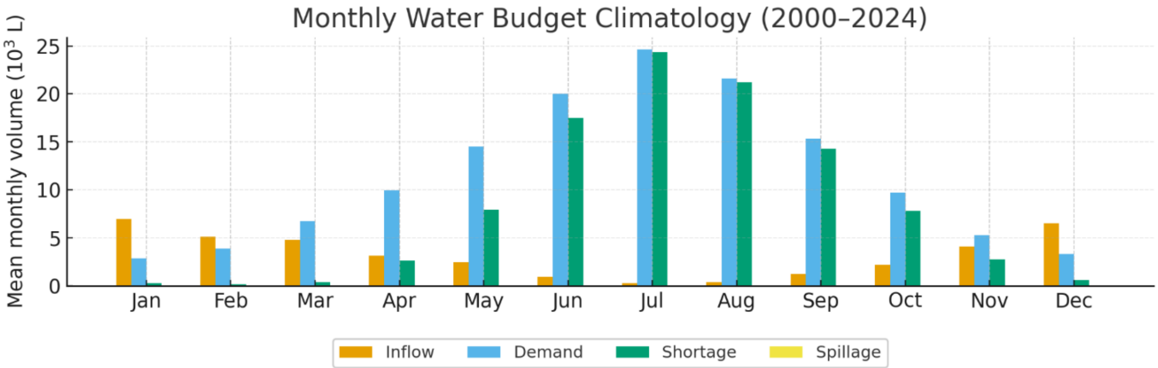

Figure 2. Monthly mean rainfall climatology for Kadirli district over the period 2000–2024, based on NASA POWER data.

Beyond monthly averages, descriptive statistics of daily precipitation were computed to assess variability and distributional characteristics. As summarized in Table 2, daily rainfall exhibits high variability and strong positive skewness, confirming the uneven distribution of rainfall between wet and dry seasons.

Table 2. Descriptive statistics of daily precipitation for Kadirli district (2000–2024).

Statistic	Value
Mean (mm/day)	1.467
Median (mm/day)	0.010
Standard Deviation	3.850
Variance	14.820
Range	59.810
Minimum	0.000
Maximum	59.810
Coefficient of Variation	2.624
Skewness	4.547
Kurtosis	29.226

Reliability–Storage Relationships

System reliability increases with tank volume and quickly reaches saturation. As illustrated in Figure 3 volumetric reliability (Rv) rises steeply from ~0.05 at 2 m³ to ~0.20 at 10 m³, but further expansion yields diminishing gains. At 30 m³, reliability levels off at ~ 0.28 for F = 0.0 mm and <0.25 for F = 2.0 mm, demonstrating the negative effect of first-flush diversion. These results confirm that Kadirli is a supply-limited rather than storage-limited environment. Comparable storage–performance behavior has been reported in many other studies of rainwater harvesting which have taken place in both Mediterranean and semi-arid type climates. For example, Liuzzo et al. (2016), studied domestic rainwater harvesting systems in southern Italy and found that the reliability of the system increased as the size of the tank increased, however, the performance was limited by the seasonal rainfall regime. Notaro et al. (2017), and subsequent Mediterranean studies also indicated that the greatest gains can be achieved when small to moderate sized tanks are used and diminishing returns are experienced with larger tank capacities due to long dry spells during the summer months. The results of reliability-storage curves generated using stochastic or optimization based methods in similar climates (Angrill et al., 2011; Baek & Coles, 2011; Monteiro et al., 2016; Muklada et al., 2016; Alamdari et al., 2018; Molaei et al., 2018; Nguyen et al., 2018; Al-Khafaji et al., 2022; Ruso et al., 2024) also indicate a rapid initial increase in reliability followed by a plateau. The results obtained in Kadirli, where Rv increases rapidly up to about 15-20m³ and then becomes saturated at around 0.28 for a 100m² roof, are thus consistent with previous literature indicating that rainwater harvesting performance in environments of the Mediterranean type is generally constrained by seasonal rainfall variability rather than solely by tank size.

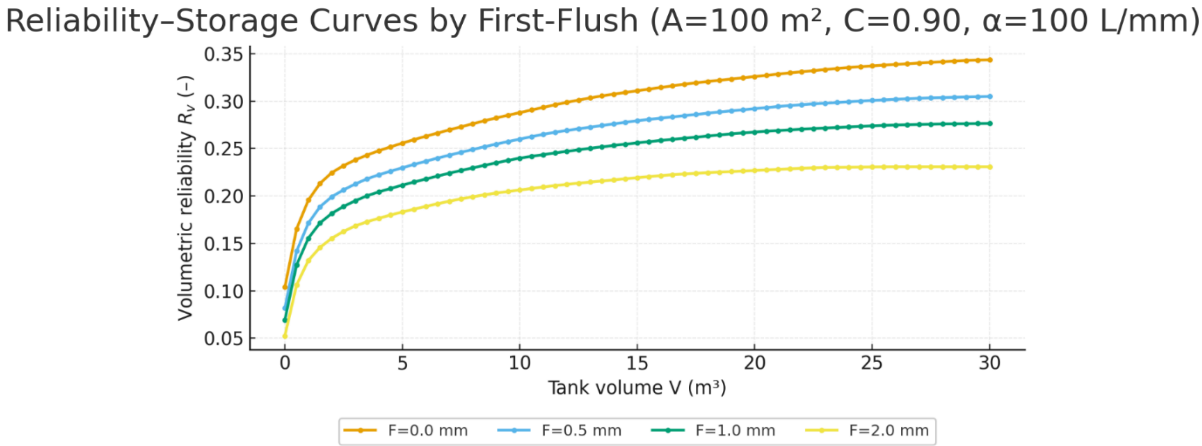

Figure 3. Volumetric reliability as a function of storage volume for four first-flush depths (0.0, 0.5, 1.0, and 2.0 mm).

Reliability increases with tank size and saturates beyond 20 m³, with higher first-flush penalties reducing overall performance.

Temporal Dynamics of Water Balance

The simulated monthly water budget highlights the mismatch between supply and demand. As shown in Figure 4 inflows (blue) regularly exceed demand (orange) during winter, leading to small spillage (yellow), whereas in summer, demand dominates inflow, generating persistent shortages (green). Shortages reach more than 20,000 L/month in August–September, while winter spillage events rarely exceed 5,000 L/month.

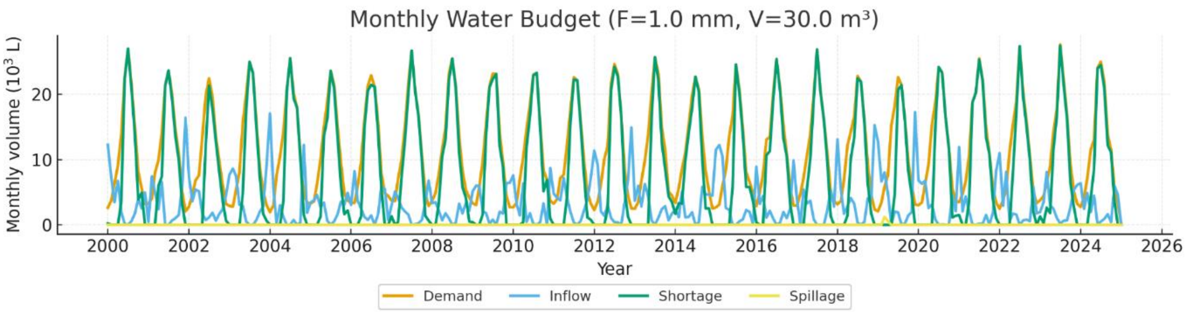

Figure 4. Monthly water budget time series showing inflow, demand, shortages, and spillage for the 25-year simulation

Shortages dominate late summer, while spillage events are limited to winter.

Shortage Seasonality

Seasonal distribution of shortages is further detailed in the heatmap. As presented in Figure 5 shortages are absent between December and April but become frequent from July to October. Even with the maximum tank volume of 30 m³, shortages remain nearly unavoidable in August and September, highlighting the structural imbalance between rainfall and water demand during the dry season.

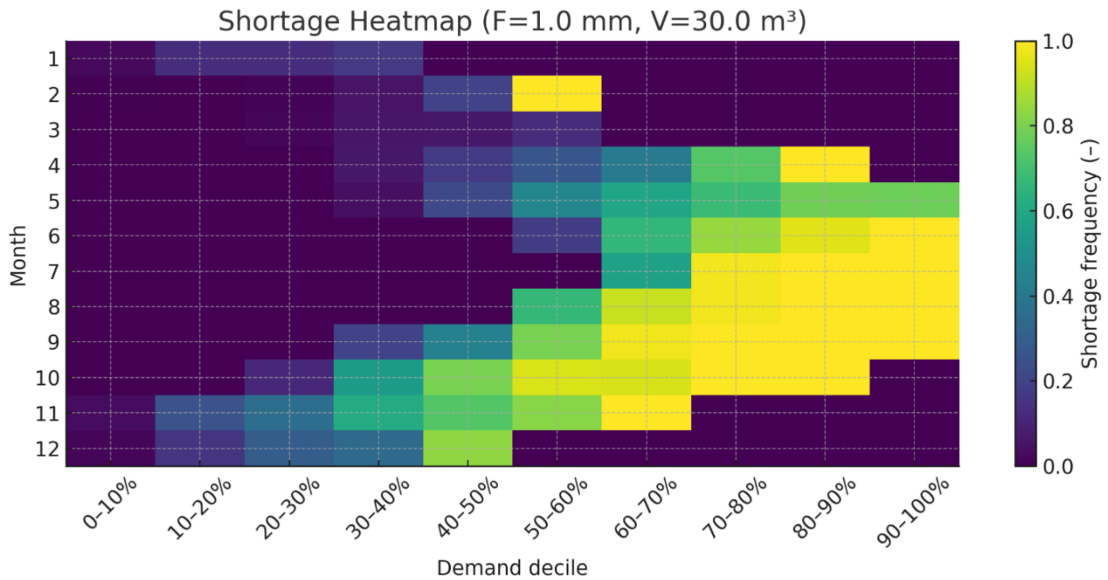

Figure 5. Heatmap of shortage frequency across tank volumes (0–30 m³) and months.

Shortages are concentrated between July and October, persisting even at maximum storage capacity.

Spillage–Storage Trade-offs

The relationship between spillage and storage size shows that inefficiencies remain despite larger tanks. As depicted in Figure 6 spillage ratios exceed 60% at 1 m³, but decline to <5% once storage surpasses 20 m³. Increasing first-flush depth slightly reduces spillage but simultaneously lowers reliability, emphasizing the inherent trade-off between water quality assurance and system performance.

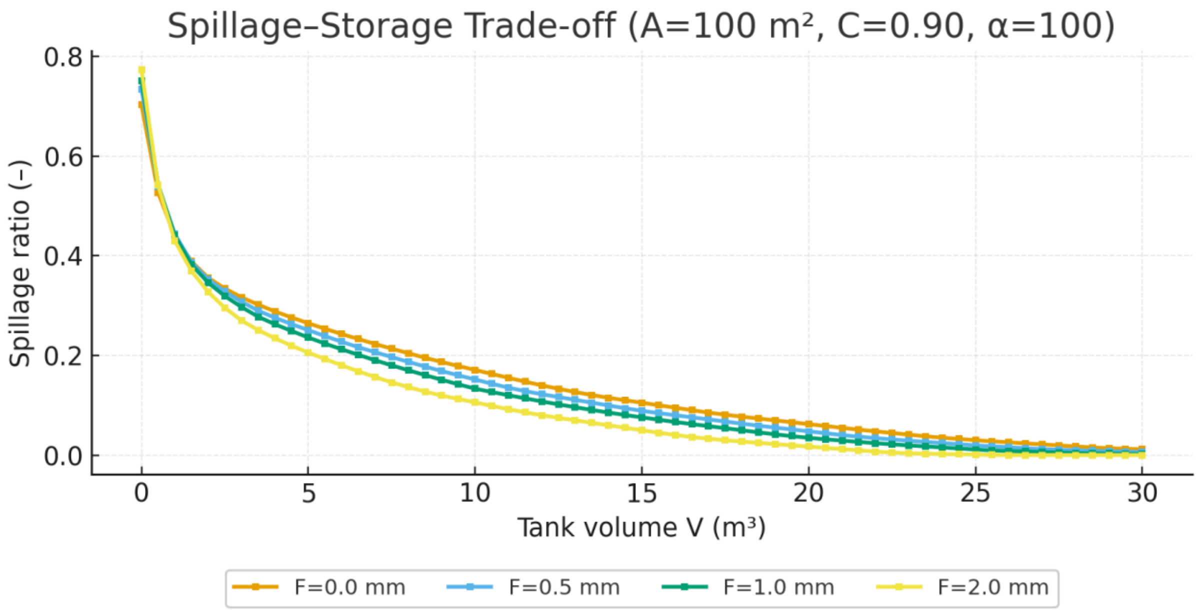

Figure 6. Spillage ratio as a function of storage volume and first-flush depth.

Spillage exceeds 60% for very small tanks but declines below 5% for tanks larger than 20 m³.

Pareto-Optimal Design Points

The design matrix evaluation enabled identification of Pareto-optimal solutions. As summarized in Table 3, at 10 m³ storage and F = 1.0 mm, volumetric reliability is ~0.18 with a spillage ratio of 1.5%. Increasing tank size to 20 m³ raises reliability to ~0.25 with spillage reduced to 0.6%. Beyond this point, gains are marginal: at 30 m³, reliability reaches ~0.28 with spillage falling to only 0.2%. These findings indicate that the optimal design range is between 10–20 m³, where the balance between reliability and efficiency is most favorable.

Table 3. Performance metrics of rainwater harvesting system for selected tank volumes.

Tank Volume (m³)	Volumetric Reliability (Rv)	Day-based Reliability (Rd)	Spillage Ratio (%)
10	0.18	0.22	1.5
20	0.25	0.29	0.6
30	0.28	0.31	0.2

Discussion

The analysis of rainfall patterns and RWH system performance in Kadirli district revealed critical insights into the feasibility and limitations of rooftop-based water supply in semi-humid Mediterranean climates. Descriptive statistics of daily precipitation (Table 2) clearly indicate a highly irregular rainfall distribution. While the mean precipitation is 1.47 mm/day, the median is close to zero, demonstrating that most days remain dry. Statistical analysis reveals that the coefficient of variation is greater than 2.6; in addition, the high value for skewness (4.55), and very high value for kurtosis (29.23), indicate that there are frequent low precipitation levels and infrequently large amounts of precipitation. From a design perspective, these values suggest a dual problem; first, as a result of the high positive skewness, most days will be dry and require large amounts of storage to cover the time between rain events, secondly, the high kurtosis suggests that there are rare large pulses of flow into the system requiring large and reliable overflow systems and sufficient storage volume to endure the prolonged dry periods.

The reliability–storage relationship (Figure 3) further illustrates these constraints. Volumetric reliability (Rv) improves rapidly with tank capacity up to approximately 15–20 m^3, beyond which additional storage yields diminishing returns. This saturation effect reflects the imbalance between inflow and demand: even oversized tanks cannot compensate for the lack of rainfall during summer months. Day-based reliability (Rd) follows a similar trajectory, reinforcing the conclusion that system performance is fundamentally supply-limited rather than storage-limited. Spillage ratios, meanwhile, increase with tank volume, signifying that larger tanks are unable to prevent overflow during winter storms. Thus, trade-off analysis between reliability and spillage identifies Pareto-optimal configurations that balance performance against redundancy, supporting efficient and cost-effective system sizing.

Reliability saturation and summer shortfalls that are persistent in Kadirli support many prior studies in the Mediterranean and semi-humid regions. Most Mediterranean rooftop RWH research has demonstrated that storage expansion can only marginally correct for a large seasonal difference between winter inflow and summer demand (Angrill et al., 2011; Adham et al., 2016; Liuzzo et al., 2016; Monteiro et al., 2016; Muklada et al., 2016; Notaro et al., 2017; Kisakye et al., 2018). Semi-arid and cold–semi-arid multi-year simulation and optimization-based sizing studies have also indicated that increased tank volume will increase reliability, but rarely to full capacity, especially during extreme dry periods (Baek and Coles, 2011; Alamdari et al., 2018; Molaei et al., 2018; Nguyen et al., 2018; Ruso et al., 2024). As such, all design-oriented RWH assessments for detached homes, public facilities and greenhouses in Turkey have similarly found that while systems may be able to significantly decrease the amount of potable water and stormwater discharged into the main water supply system, they are generally used to supplement rather than replace the use of conventional water supplies (Karakoçak et al., 2013; Ülker and Tasci, 2022; Ertop et al., 2023; Müftüoğlu, 2024; Muftuoglu, 2025; Müftüoğlu and Oral, 2025). Thus, the results from Kadirli, which include an average reliability value of about 0.28 and unavoidable shortfalls during late summer despite having a 30 m³ tank, are consistent with results from previous studies and provide further evidence that rooftop RWH is generally intended to provide some relief to drought conditions, and not to completely substitute the use of traditional water resources.

The monthly water budget (Figure 4) shows this disparity between supply and demand. For the winter months, inflows generally exceed household-equivalent demand, leading to spills and the loss of volume. In the summer months extending from July to September, while the demand reaches its highest point, the inflows are nearly zero which causes critical shortages. The shortage heatmap (Figure 5) identifies these seasonal risks for all tanks and sizes, showing that the same deficits exist in late summer regardless of storage size. Even at maximum tested volumes (30 m³), the system fails to achieve full reliability, underscoring the insufficiency of rainfall as a standalone source during drought months. The spillage–storage trade-off curve (Figure 6) confirms this duality: as tanks grow larger, reliability gains plateau but spillage escalates, revealing the inefficiency of oversizing in climates dominated by seasonal rainfall asymmetry.

These findings align with prior studies in Mediterranean and semi-humid regions, where RWH has been shown to provide partial relief rather than complete substitution of conventional water sources. The positive role of RWH is most evident in reducing winter runoff, moderating stormwater impacts, and partially supplementing domestic or irrigation demand during transitional months. However, reliance on RWH alone cannot guarantee water security without complementary strategies such as conjunctive use of groundwater, demand management, or hybrid supply systems. The distinctive statistical properties of rainfall in Kadirli, particularly the extreme skewness and kurtosis, further emphasize the importance of integrating climate variability into reliability-based design frameworks.

Conclusion

This study developed a 25-year reliability-based framework for evaluating rooftop RWH in Kadirli, Türkiye, using NASA POWER daily climate data as inputs. The results demonstrate that while RWH offers tangible benefits, system performance is fundamentally constrained by the seasonal rainfall regime. Descriptive statistics confirmed that precipitation is highly irregular, with most days dry and only a few extreme events contributing the majority of annual rainfall. Consequently, volumetric reliability saturates around 0.28 despite increasing tank volumes, and shortages remain unavoidable during summer.

Pareto-optimal analysis identified a practical design range of 10–20 m^3 for rooftop tanks under first-flush depths of 0.5–2.0 mm, where reliability and spillage are most balanced. Beyond this range, larger storage volumes produce limited additional benefits while substantially increasing overflow losses. The monthly budget and shortage heatmap confirmed that deficits are concentrated in late summer, highlighting that system limitations stem from supply scarcity rather than storage capacity.

In conclusion, rooftop RWH in Kadirli can play a valuable role as a supplementary water source, particularly for non-potable uses such as cleaning, irrigation, or landscape management, while also mitigating stormwater impacts in winter. However, it cannot be relied upon as a standalone supply strategy due to the intrinsic rainfall variability of the region. Future research should explore hybrid water supply systems, cost–benefit analyses of tank sizing under uncertainty, and integration of RWH with urban planning to enhance resilience against climate variability in semi-humid Mediterranean settings.

Conflict of Interest Statement

The author of the article declares that there is no conflict of interest.

Contribution Statement Summary

The author declares sole responsibility for the entirety of the article.

References

Adham A, Riksen M, Ouessar M, Ritsema CJ., 2016. A methodology to assess and evaluate rainwater harvesting techniques in (semi-) arid regions. Water, 8(5): 198. doi:10.3390/w8050198.

Al-Khafaji DS, Abdulkareem AK, Al-Kubaisi QY., 2022. Determining the best rainwater harvesting system in Al-Muthanna Governorate, Iraq. Iraqi Journal of Science, 63(6): 2525–2537. doi:10.24996/ijs.2022.63.6.39.

Alamdari N, Sample DJ, Liu J, Ross A., 2018. Water supply and runoff capture reliability curves for hypothetical rainwater harvesting systems for locations across the U.S. for historical and projected climate conditions. Data in Brief, 17: 226–232. doi:10.1016/j.dib.2018.03.024.

Allen RG, Pereira LS, Raes D, Smith M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome.

Angrill S, Farreny R, Gasol CM, Gabarrell X, Prat BV, Josa A, Rieradevall J., 2011. Environmental analysis of rainwater harvesting infrastructures in diffuse and compact urban models of Mediterranean climate. The International Journal of Life Cycle Assessment, 17: 25-42.

Baek CW, Coles N., 2011. Defining reliability for rainwater harvesting systems. doi:10.36334/modsim.2011.i9.baek.

Bojer AK, Bekalo DJ, Debelee TG, Nadarajah S, Fadhil Al-Quraishi AM., 2024. Rainwater harvesting site selection for drought-prone areas in Somali and Borena Zones, Oromia Regional State, Ethiopia. Water, 16(13): 1789. doi:10.3390/w16131789.

Brião VB, Cadore JS, Graciola S, da Silva RV, Moraes Giubel GO, Barbizan LD, Shaheed MH., 2024. Rainwater for drinking purposes: An overview of challenges and perspectives. Wiley Interdisciplinary Reviews Water, 11(3): e1746. doi:10.1002/wat2.1746.

Chubaka CE, Whiley H, Edwards J, Ross K., 2018. Microbiological values of rainwater harvested in Adelaide. Pathogens, 7(1): 16. doi:10.3390/pathogens7010021.

Ertop H, Kocięcka J, Atılgan A, Liberacki D, Niemiec M, Rolbiecki R., 2023. The importance of rainwater harvesting and its usage possibilities: Antalya example (Turkey). Water, 15(12): 2194. doi:10.3390/w15122194.

Ferrand EA, Cecunjanin F., 2014. Potential of rainwater harvesting in a thirsty world: A survey of ancient and traditional rainwater harvesting applications. Geography Compass, 8(11): 830–845. doi:10.1111/gec3.12135.

Hanafiah MM., 2018. Rainwater harvesting system (MyRAWAS): Towards upscaling water-conserving practice at university level. Environment and Ecosystem Science, 2(1): 10–12. doi:10.26480/ees.01.2018.10.12.

Hijrawadi SN, Setiacahyandari HK., 2025. Assessment of rainwater harvesting for household water demand in Lancang Island, Kepulauan Seribu DKI Jakarta. IOP Conference Series Earth and Environmental Science, 1462: 012007. doi:10.1088/1755-1315/1462/1/012007.

Igbinosa IH, Osemwengie OV., 2016. On-site assessment of environmental and sanitary qualities of rainwater harvesting system (RWH) in a rural community in Benin City, Nigeria. Journal of Applied Sciences and Environmental Management, 20(2): 259–263. doi:10.4314/jasem.v20i2.12.

Jha MK, Markande Y, Markandey DK, Dev M., 2024. A cornerstone to sustainable development in the evaluation of the state of the ground water supply and its recharge through rainwater harvesting for the NCR and surrounding areas. International Journal of Latest Engineering and Management Research, 9(4): 1–10. doi:10.56581/ijlemr.9.04.01-10.

Judeh T, Shahrour I., 2021. Rainwater harvesting to address current and forecasted domestic water scarcity: Application to arid and semi-arid areas. Water, 13(24): 3583. doi:10.3390/w13243583.

Karakoçak BB, Yenigün O, Toraman RT., 2013. An integrated approach to water management in Kayseri: Rainwater collection and use in an amusement park. Water Science and Technology, 68(12): 2640–2647. doi:10.2166/wst.2013.656.

Karmilah M, Madrah MY., 2024. Coping strategies to address water scarcity through local knowledge in tidal flood and erosion-prone areas. IOP Conference Series Earth and Environmental Science, 1321: 012005. doi:10.1088/1755-1315/1321/1/012005.

Kim J, Latos A., 2016. Non-drinking water self-sufficiency of residential buildings utilizing rainwater harvesting. WIT Transactions on the Built Environment, 165: 153-163.

Kisakye V, Akurut M, Van der Bruggen B., 2018. Effect of climate change on reliability of rainwater harvesting systems for Kabarole District, Uganda. Water, 10(1): 71. doi:10.3390/w10010071.

Liuzzo L, Notaro V, Freni G., 2016. A reliability analysis of a rainfall harvesting system in Southern Italy. Water, 8(1): 18. doi:10.3390/w8010018.

Mbarep DPP, Apelabi GO, Bolly YY, Nurhidayat A., 2022. The potency of obtained clean water from rainwater harvesting in Sikka District. Jurnal Pengelolaan Sumberdaya Alam dan Lingkungan (Journal of Natural Resources and Environmental Management), 12(2): 237–245.

Milinga K, Chachage B, Matonya J., 2023. Influence of institutional forces on the intention to harvest rainwater in Tanzania. European Journal of Business and Management, 15(19): 51–61. doi:10.7176/ejbm/15-19-05.

Molaei O, Kouchakzadeh M, Fashi FH., 2018. Evaluation of rainwater harvesting performance for water supply in cities with cold and semi-arid climate. Water Science and Technology Water Supply, 18(6): 1931–1938. doi:10.2166/ws.2018.193.

Monteiro C, Calheiros C, Pimentel-Rodrigues C, Silva-Afonso A, Castro P., 2016. Contributions to the design of rainwater harvesting systems in buildings with green roofs in a Mediterranean climate. Water Science & Technology, 73(8): 1842-1847. doi:10.2166/wst.2016.034.

Muftuoglu TD., 2025. A preliminary investigation of rainwater harvesting potential in emergency healthcare facilities: Case study of Yeşilköy Prof. Dr. Murat Dilmener Hospital. Kadirli Uygulamalı Bilimler Fakültesi Dergisi, 5(1): 145–172.

Muftuoglu TD, Oral HV., 2024. The hydraulic approach relevant to circularity on sustainable water catchment. In: Nature-based solutions for circular management of urban water. Springer, Cham, 353–370.

Müftüoğlu TD., 2024. Evaluating rainwater harvesting potential of concrete and tile roofings for detached houses in Aydın, Turkey. Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 7(3): 1096-1115. doi:10.47495/okufbed.1369970.

Müftüoğlu TD, Oral HV., 2025. Implementing rainwater harvesting in blocks for a sustainable university campus. Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 8(2): 543–565.

Muklada H, Gilboa Y, Friedler E., 2016. Stochastic modelling of the hydraulic performance of an onsite rainwater harvesting system in a Mediterranean climate. Water Science & Technology: Water Supply, 16(6): 1614–1623. doi:10.2166/ws.2016.082.

Nguyen VM, Ichikawa Y, Ishidaira H., 2018. Exploring optimal tank size for rainwater harvesting systems in Asian tropical climates. Hydrological Research Letters, 12(1): 1–6. doi:10.3178/hrl.12.1.

Notaro V, Liuzzo L, Freni G., 2017. Evaluation of the optimal size of a rainwater harvesting system in Sicily. Journal of Hydroinformatics, 19(6): 853–864. doi:10.2166/hydro.2017.150.

Ogolla B, Olal FO., 2022. Physicochemical and microbiological quality of roof-harvested rainwater in urban areas: A review. Journal of Environment and Earth Sciences, 12(10): 37–45. doi:10.7176/jees/12-10-05.

Oladele EM, Ojo O, Adewuyi AS., 2021. Variation of rain water quality with storage time for different coloured storage containers. Journal of Applied Sciences and Environmental Management, 25(9): 1447–1452. doi:10.4314/jasem.v25i9.22.

Omokpariola DO, Nduka JK, Omokpariola PL., 2024. pH precursors as a factor for assessing rainwater quality in roofing sheets: A case study of Rivers State, Nigeria. IntechOpen. doi:10.5772/intechopen.1004027.

Patil D., 2023. A strategic design approach for implementing rainwater management system using an integration of GIS and BIM tool. CIC International Conference on Civil Engineering, Doha, Qatar, 168. doi:10.29117/cic.2023.0168.

Ruso M, Akıntuğ B, Kentel E., 2024. Rainwater harvesting system analysis for semi-arid climate: A daily linear programming model. Turkish Journal of Civil Engineering, 1(2): 41–54. doi:10.18400/tjce.1326198.

Sakati SN, Mallongi A, Ibrahim E, BBB, SSS, Palutturi S., 2024. Utilization of rainwater as consumable water with rainwater harvesting methods: A literature review. Pharmacognosy Journal, 15(2): 227. doi:10.5530/pj.2023.15.227.

Saplıoğlu K, Küçükerdem Öztürk TS, Senel F., 2018. Determining rainwater harvesting storage capacity with particle swarm optimization. Preprints, 2018080348. doi:10.20944/preprints201808.0348.v1.

Steffen J, Jensen MA, Pomeroy C, Burian SJ., 2013. Water supply and stormwater management benefits of residential rainwater harvesting in U.S. cities. Journal of the American Water Resources Association, 49(4): 810–824. doi:10.1111/jawr.12038.

Syarifuddin M, Masria M, Oktaviantoro D., 2024. A GIS-based approach to determine the priority area for rainwater harvest in Kupang. IOP Conference Series Earth and Environmental Science, 1311: 012032. doi:10.1088/1755-1315/1311/1/012032.

Tahera JK, Nasimi MN, Nasimi MN, Boyce SE., 2022. Identifying suitable sites for rainwater harvesting using GIS and multi-criteria decision making techniques in Badghis Province of Afghanistan. Central Asian Journal of Water Research, 8(2): 46–69. doi:10.29258/cajwr/2022-r1.v8-2/46-69.eng.

Ülker E, Tasci H., 2022. Determining rainwater harvesting potentials in municipalities by a semi-analytical method. Journal of Water Supply Research and Technology-Aqua, 71(2): 106–116. doi:10.2166/aqua.2022.106.

Villar-Navascués R, Pérez-Morales A, Gil-Guirado S., 2020. Assessment of rainwater harvesting potential from roof catchments through clustering analysis. Water, 12(9): 2623.

Yulistyorini A, Idfi G, Fahmi ED., 2018. Enhanced rooftop rainwater harvesting quality through filtration using zeolite and activated carbon. MATEC Web of Conferences, 204: 03016. doi:10.1051/matecconf/201820403016.

Zarikos I, Politi N, Vlachogiannis D, Sfetsos A, Vakondios D., 2025. Communal rainwater harvesting framework for reducing water scarcity and desalinated water production in arid and semi-arid islands. 12th International Conference on Urban Climate (ICUC12), Sydney, Australia, p. 668. doi:10.5194/icuc12-668.

Zia S, Shirazi SA, Nasar-u-Minallah M, Batool M., 2023. Urban floods and suitability analysis of rainwater harvesting potential areas in Lahore City, Pakistan. International Journal of Economic and Environmental Geology, 12(2): 11–22. doi:10.46660/ijeeg.v12i2.97.

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Türkiye ve Sırbistan'da Meyve İşleme Verimliliği ve Posanın Değerlendirme Potansiyelinin Veriye Dayalı Analizi

Arzum IŞITAN[1,2,3*], Mihailo MILANOVIC[4], Cem GÖK[5,6], Vladimir PAVLOVIC[7], Aleksandra SKNEPNEK[8], Dunja MILETIĆ[9], Mahmut KUŞ[10], Nataša MILOSAVLJEVIĆ[11], Massimo BERSANI[12], Ahmet KOLUMAN[13]

[1*,13] Pamukkale Üniversitesi, Teknoloji Fakültesi, Denizli
[2,12] Fondazione Bruno Kessler, Center for Sensors and Devices, Trento, Italy
[3] Bilgece Mühendislik Geri Dönüşüm Ltd Şti, Denizli
[4,7,8,9,11] University of Belgrade, Faculty of Agriculture, Belgrade, Serbia
[5] İzmir Bakırçay Üniversitesi, Mühendislik ve Mimarlık Fakültesi, İzmir
[6] İzmir Bakırçay Üniversitesi, Biyomedikal Teknolojiler Tasarım Uygulama ve Araştırma Merkezi, İzmir
[10] Konya Teknik Üniversitesi, Mühendislik ve Doğa Bilimleri Fakültesi, Konya

[1*,2,3] https://orcid.org/0000-0002-5228-9788
[4] https://orcid.org/0000-0002-7702-1120
[5,6] https://orcid.org/0000-0002-8949-8129
[7] https://orcid.org/0000-0002-1138-0331
[8] https://orcid.org/0000-0001-7730-3120
[9] https://orcid.org/0000-0002-3743-9418
[10] https://orcid.org/0000-0002-6998-6459
[11] https://orcid.org/0000-0003-4056-089X
[12] https://orcid.org/0000-0003-4062-5286
[13] https://orcid.org/0000-0001-5308-8884
*Sorumlu yazar: aisitan@pau.edu.tr

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ÖZ

Bu çalışma, üzüm (*Vitis vinifera L.*) ve erik (*Prunus domestica L.*) üretiminde önde gelen üretici ülkelerden Türkiye ve Sırbistan'da ortaya çıkan üzüm ve erik posalarının üretim, işleme ve değerlendirme potansiyelini veri temelli bir yaklaşımla incelemesi amaçlanmıştır. Çalışma kapsamında elde edilen bulgular, bu yan ürünlerin döngüsel biyoekonomi çerçevesinde sürdürülebilir ancak büyük ölçüde değerlendirilmeyen biyokütle kaynakları olduğunu göstermektedir. Çalışmada, açık erişimli ulusal ve uluslararası istatistik veri tabanları ile literatüre dayalı olarak geliştirilen veri temelli bir metodolojik çerçeve kullanılmıştır. Tüm veri işleme, istatistiksel analizler ve görselleştirmeler, yapılandırılmış tarımsal veri setlerine uygunluğu, hesaplamaların şeffaf biçimde izlenebilmesi ve kullanıcılar arasında tekrarlanabilirliği nedeniyle tercih edilen Microsoft Excel (Microsoft Corp., Redmond, WA, ABD) yazılımı kullanılarak; ağırlıklı olarak tanımlayıcı istatistikler ve formül tabanlı hesaplamalar aracılığıyla gerçekleştirilmiştir. 2020–2024 dönemine ait tarımsal üretim verileri, endüstriyel işleme oranları, posa miktarları ve atık yönlendirme düzeyleri bu kapsamda değerlendirilmiştir. Bulgular, Türkiye'de yılda yaklaşık 451×10³ ton üzüm posası, Sırbistan'da ise 34×10³ ton erik posası üretildiğini; buna karşın her iki ülkede de değerlendirme oranlarının %5'in altında kaldığını göstermektedir. Biyokimyasal veriler, her iki posanın da selüloz, hemiselüloz, pektin ve fermente edilebilir şekerler açısından zengin olduğunu ve bu nedenle bakteriyel selüloz, nanoselüloz ve pektin bazlı biyopolimer üretimi için uygun ve sürdürülebilir hammaddeler olduğunu ortaya koymaktadır. Ancak yetersiz biyorafineri altyapısı ve sınırlı endüstriyel entegrasyon, bu potansiyelin hayata geçirilmesini engellemektedir.

Data-Driven Analysis of Fruit Processing Efficiency and Pomace Valorization Potential in Türkiye and Serbia

Research Article

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ABSTRACT

This study examines the production, processing, and valorization potential of grape and plum pomaces generated in Türkiye and Serbia, two leading producers of grapes (*Vitis vinifera* L.) and plums (*Prunus domestica* L.), using a data-driven approach, and demonstrates that these by-products represent sustainable yet largely underutilized biomass resources within the framework of the circular bioeconomy. The findings obtained within the scope of this study indicate that these by-products represent sustainable yet largely underutilized biomass resources within the framework of the circular bioeconomy. All data processing, statistical analyses, and visualizations were performed using Microsoft Excel (Microsoft Corp., Redmond, WA, USA), primarily through descriptive statistical methods and formula-based calculations, selected for its suitability for structured agricultural datasets, transparent traceability of calculations, and reproducibility across users. Agricultural production data for the period 2020–2024, including industrial processing ratios, pomace quantities, and waste diversion levels, were evaluated within this framework. The findings indicate that approximately 451×10^3 tons of grape pomace are generated annually in Türkiye, while Serbia produces about 34×10^3 tons of plum pomace; however, valorization rates in both countries remain below 5%. Biochemical evidence shows that both pomaces are rich in cellulose, hemicellulose, pectin, and fermentable sugars, making them suitable and sustainable feedstocks for the production of bacterial cellulose, nanocellulose, and pectin-based biopolymers. Nevertheless, insufficient biorefinery infrastructure and limited industrial integration continue to hinder the realization of this potential.

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Introduction

Large volumes of organic waste are produced by the food processing and agricultural sectors worldwide, which not only present environmental challenges but also offer valuable resources for the development of sustainable materials (Casquete et al., 2022; Galante et al., 2025). Agricultural and food processing wastes represent a major environmental and economic challenge in both Türkiye and Serbia.

Agricultural residues can be valorized in several ways to provide energy, biomaterials, and soil additives that benefit both the environment and the economy. Conventional management practices including open burning and landfilling not only waste valuable resources but also emit particulate matter and greenhouse gases (Yaman, 2012; Ünlü et al., 2023). Recent advances in biotechnology and materials science have made it feasible to convert lignocellulosic residues into biofuels (biogas, bioethanol, and biodiesel), biopolymers, and activated carbons (Dhyani and Bhaskar, 2018; Awogbemi and Von Kallon, 2022a; Işıtan, 2025). Composting and anaerobic digestion remain key biological routes, reducing organic load while producing nutrient-rich fertilizers and renewable energy (Negi et al., 2022; Ivanović et al., 2025). While chemical and enzymatic procedures facilitate the manufacture of nanocellulose, activated carbon, and other high-value bioproducts, thermal conversion techniques like pyrolysis and gasification enable the recovery of bio-oils and syngas (Ioannidou and Zabaniotou, 2007; Dhyani and Bhaskar, 2018; Koul et al., 2022; Bednárek et al., 2024; Zielińska and Bułkowska, 2024).

Agricultural residues and food industry by-products accounted for a significant share of Türkiye's total waste generation, which reached 109,200×10^3 tons in 2022, yet much of this potential resource remains underutilized (CEIC, 2021). According to the Biomass Energy Potential Atlas (EIGM, 2021), approximately 74.6% of Türkiye's renewable biomass potential originates from agricultural residues, corresponding to nearly 34,000×10^3 tons of oil equivalent per year. Despite this, biomass contributes only about 1% of national electricity generation (IRENA, 2019), revealing a considerable gap between potential and utilization. This underlines the need for sustainable conversion routes such as composting, biogas production, and biopolymer synthesis from lignocellulosic residues (Yaman, 2012; Ünlü et al., 2023).

Similarly, in Serbia, annual food waste is estimated at 770×10^3 tons (UNECE, 2022) with more than 90% disposed in landfills due to limited recovery infrastructure. In addition, the agricultural sector generated 88.2×10^3 tons of waste in 2022 (STAT, 2025). Fruit production represents a cornerstone of Serbian agriculture, contributing around 6% of national GDP (Zelenović et al., 2023). Serbia ranks among Europe's leading producers of plums (430.2×10^3 tons) and raspberries (127×10^3 tons) (Subić et al., 2021; FAOSTAT, 2023). Despite this enormous output, only a small fraction of agro-industrial residues is valorized, primarily through local composting or use as animal feed (Ketin et al., 2021). Serbia's sustainable biogas potential is largely derived from livestock manure, crop residues and fruit by-products, and it is estimated that if all these wastes are used properly, the country's electricity needs could be met by 15%. Nevertheless, infrastructure limitations and policy fragmentation hinder large scale adoption of circular economy practices (Vukelić et al., 2023).

The economic potential of agricultural waste valorization is equally significant. In Türkiye, utilizing even 20% of agricultural residues for bioenergy could offset nearly 5% of national natural gas imports (EİGM, 2021), while biocomposite production using crop-based fillers can reduce manufacturing costs by up to 30% compared to synthetic materials (Avşar and Çevik, 2023). Similarly, in Serbia, expanding biogas facilities to process available agro-residues could generate rural employment and contribute to national energy independence (Vukelić et al., 2023; Belošević et al., 2024).

Among the various agro-industrial residues, grape and plum pomaces stand out as abundant and compositionally rich substrates for biotechnological valorization. Grape pomace, consisting mainly of skins, seeds, and stems, accounts for nearly 20–25% of the total grape weight after processing, and is rich in cellulose, hemicellulose, lignin, pectin, phenolic compounds, and residual sugars (Varış et al., 2000; Bekar, 2016; Malićanin et al., 2025; Milinčić et al., 2025; Chedea et al., 2025). Similarly, plum residues, generated during juice, jam, and brandy production, are composed of fibrous pulp, stone fragments, and carbohydrates that can serve as feedstocks for microbial fermentation and enzyme-assisted hydrolysis (Subić et al., 2021). Both residues have been traditionally discarded or used as low-value animal feed, yet their biochemical composition provides a promising foundation for conversion into bio-based materials such as bioplastics, biochar, or bacterial cellulose.

The objective of this study is to present a thorough quantitative evaluation of the production of grapes (*Vitis vinifera L.*) and plums (*Prunus domestica L.*) together with their industrial processing levels and valorization potential in Türkiye and Serbia. In addition to assessing the sustainability implications in relation to the EU Green Deal framework (EC, 2019) and the United Nations Sustainable Development Goals (SDGs) 9, 12, and 13 (UN, 2019), the research incorporates agricultural production information for the years 2020–2024 with industry-specific processing ratios, pomace yield models, and economic contribution calculations. This study is the first cross-national quantitative analysis that simultaneously estimates pomace quantities for two major fruit industries, models the economic outputs and contributions of industrial processing, identifies pathways for valorization based on the biochemical properties of grape and plum residues, and connects agricultural production patterns with circular bioeconomy indicators pertinent to regional sustainability transitions.

Materials and Methods

Materials

Grape (*Vitis vinifera L.*) and plum (*Prunus domestica L.*) have been selected as target materials in Türkiye and Serbia due to their high production volumes, significant processing rates, and their substantial sectoral contribution and export relevance. As shown in Figure 1a, Türkiye ranks among the world's top grape-producing countries (typically within the top six), with an annual production exceeding $3{,}500\times10^3$ tons, while Serbia is one of the world's leading plum producers, generally ranking among the top five globally with an annual production exceeding 400×10^3 tons (FAOSTAT, 2023). These production levels contribute significantly to national revenues (Figure 1b) and also generate large quantities of industrial by-products: Grape pomace constitutes approximately 20-25% of processed fruit and contains cellulose, hemicellulose, lignin, pectin, and phenolic compounds (Bekar, 2016; Megías-Pérez et al., 2023), while plum processing produces 12-18% solid residue rich in pectin and fermentable sugars suitable for biopolymer synthesis (Subić et al., 2021; Nirmal et al., 2023). The high availability and favorable biochemical composition make these residues particularly suitable for evaluating biopolymer valorization potential in both countries.

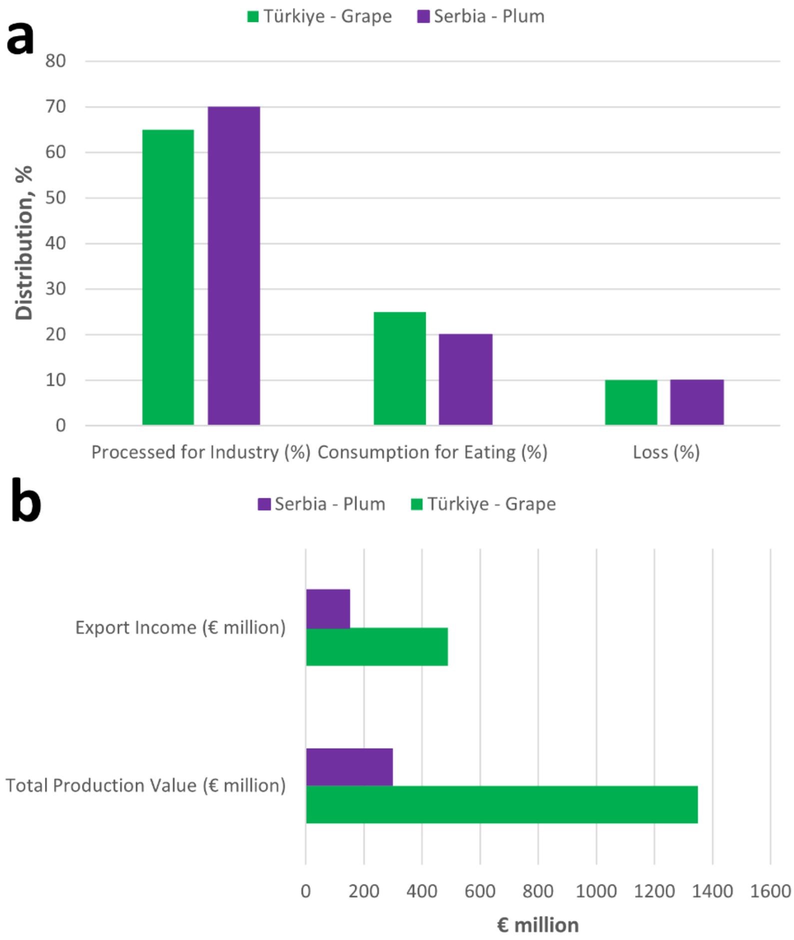

Figure 1. Comparative global production profiles of grapes and plums (a) and corresponding sectoral economic indicators for Türkiye (grapes) and Serbia (plums) (b) (FAOSTAT, 2023; UN, 2023; StatAgri, 2024)

Data Sources and Methodological Framework for Data Collection and Processing

In this study, a data-driven methodological framework was adopted to evaluate fruit processing efficiency and pomace valorization potential. All of the data utilized in this study were obtained from publicly accessible secondary sources. From 2020 to 2024, agricultural production data for grapes and plums were gathered from publicly accessible national and international databases, such as FAOSTAT, TÜİK, and the Statistical Office of the Republic of Serbia (STAT). These databases provided annual national-level production figures. All production statistics were standardized into uniform annual units (tons) to ensure cross-country comparability. Industrial processing ratios (R_{proc}) for grapes and plums were obtained from sector-specific reports and peer-reviewed literature rather than statistical databases. These ratios reflect dominant processing pathways, such as the production of wine, juice, and vinegar for grapes in Türkiye and brandy for plums in Serbia.

FAOSTAT provided country-level data on grape and plum production for the years 2020–2023, and CEIC and the Turkish Statistical Institute (TÜİK) provided supplementary agricultural indicators for Türkiye. The Statistical Office of the Republic of Serbia (STAT) provided corresponding agricultural output and processing data for Serbia (IRENA, 2019, 2020, 2022; TÜİK, 2020; CEIC, 2021; EİGM, 2021; UNECE, 2022; FAOSTAT, 2023; StatAgri, 2024; STAT, 2025). Sectoral reports and peer-reviewed scientific literature were used to determine processing ratios, pomace generation rates, and the average biochemical makeup of grape and plum wastes (Bekar, 2016; Tarım ve Orman Bakanlığı, 2020; Subić et al., 2021; Megías-Pérez et al., 2023; Tariş Üzüm, 2025;). In order to facilitate cross-national comparability and subsequent residue-potential calculations, all statistics were harmonized to annual production units (tons).

Sectoral averages were used to calculate the percentage of harvested produce that entered industrial processing for each fruit species. Because grapes are widely used in the production of wine, juice, molasses, and vinegar, they generally showed higher processing rates than plums. According to published studies, pomace generation rates are between 20-25% for processed grapes and between 12-18 % for plums, depending on the type of product. In this study, fixed residue coefficients of 20% (grape) and 15% (plum) were applied.

Modeling Industrial Processing Levels

Production trends of grapes and plums and their total economic contribution (EC)

Each fruit category's industrial processing levels were determined by multiplying annual production numbers by country-specific processing ratios. Grape processing in Türkiye comprises the manufacturing of wine, vinegar, pekmez (molasses), dried grapes, and industrial juice extraction. Brandy or plum spirit (rakija), jam, juice, compotes, and dried fruits are the main products of plum processing in Serbia. Plum spirit, which represents the dominant end use of plums in Serbia, was inscribed on the UNESCO Representative List of the Intangible Cultural Heritage of Humanity in 2022, reflecting its cultural and socio-economic importance (Trajković et al., 2025). These fruit processing chains generate considerable pomace residues, which are currently treated as waste despite their high biochemical potential. The percentage of residue left over after industrial extraction was represented by literature-based factors that were used to estimate pomace generation. Depending on the processing route, reported pomace yields range from 20–25% for grapes and 12–18% for plums. Economic analysis included two components: Raw product economic value, based on average market prices (€/ton) and value-added industrial contribution, reflecting the revenue generated through processed products. Value-added multipliers were derived from national wine industry reports (Türkiye), plum brandy sector statistics (Serbia), export price datasets, and previously published studies (Pecot and Watt, 1975; Salunkhe and Kadam, 1995; Ioannidou and Zabaniotou, 2007; Keshk, 2014; Tarım ve Orman Bakanlığı, 2020; Ataseven, 2025; Tariş Üzüm, 2025).

All data processing, statistical analyses, and visualizations were performed using Microsoft Excel (Microsoft Corp., Redmond, WA, USA), primarily through descriptive statistical functions and formula-based calculations, which was selected due to its suitability for structured agricultural datasets, transparent traceability of calculations, and reproducibility across users.

The industrial processing output (IPO) and pomace yield coefficient (PM)

The percentage of yearly fruit production that goes into the wine, brandy, juice, vinegar, jam, and other fruit-processing operations is known as the industrial processing output, or IPO. IPO was determined using:

$$IPO = P_{total} \times R_{proc} \tag{1}$$

where P_{total} and R_{proc} refer to the total annual fruit production ($\times 10^3$ tons) and industrial processing ratio (decimal) accordingly.

The amount of solid residue (annual produced pomace mass, PM) remaining after industrial processing was calculated using the pomace yield coefficient (Y_{pom}) :

$$PM = IPO \times Y_{pom} \tag{2}$$

The values used in the calculations were obtained from the literature (Salunkhe and Kadam, 1995; Tarım ve Orman Bakanlığı, 2020; Subić et al., 2021).

Waste Diversion Rate (WDR)

The waste diversion rate (WDR, %) quantifies the proportion of pomace that is valorized ($PM_{valorized}$) (e.g., composting, animal feed, extraction, energy use), compared to the total pomace generated (PM_{total}):

$$WDR = \frac{PM_{valorized}}{PM_{total}} \times 100 \tag{3}$$

Approximately 2–5% of grape pomace in Mediterranean and European wine industries is valorized, while plum pomace is even more underutilized, with only small fractions used for feed or fuel (Subić et al., 2021; Carpentieri et al., 2023; Kokkinomagoulos and Kandylis, 2025).

Results

Grape and plum production trends in Türkiye and Serbia and their total economic contribution

As illustrated in Figure 2, both Türkiye and Serbia rank among the world's top producers of grapes and plums, respectively. In Türkiye, the annual grape production is around 4,200×10^3 tons, ranking the country sixth worldwide (TÜİK, 2020). Manisa, Mardin, and Denizli rank first in terms of vineyard area (Ataseven, 2025). Fruit production is currently Serbia's most competitive agricultural industry and plums are the most significant fruit species in terms of both production volume and land area covered by plantations (Subić et al., 2021; Katarina et al., 2024; Gajić et al., 2025).

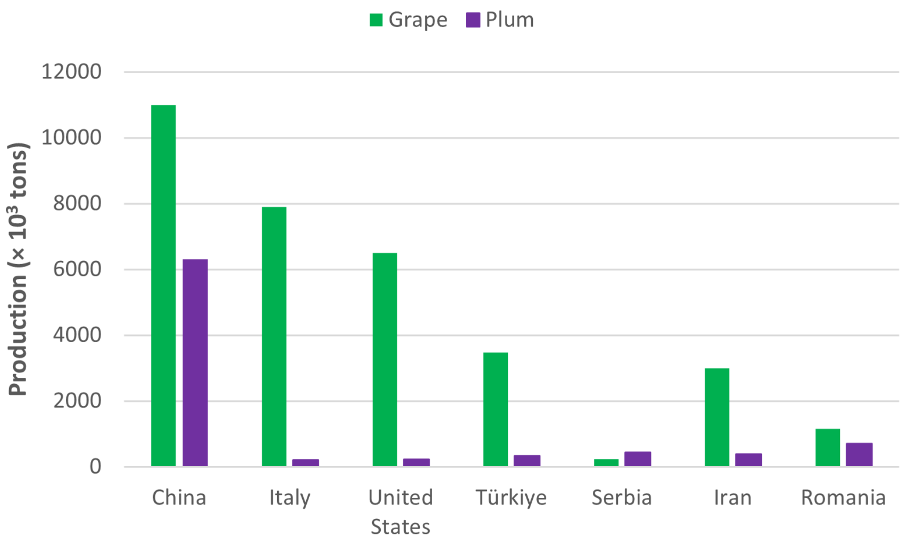

Figure 2. Global Production Comparison of Grapes and Plums (Average 2020–2024, ×10^3 tons) (TÜİK, 2020; FAOSTAT, 2023; UN, 2023; StatAgri, 2024; Tariş Üzüm, 2025)

Grapes are among Türkiye's most important fruit crops, generating large quantities of pomace during wine, juice, vinegar, and jam production. These residues are rich in sugars, cellulose, and lignin, making them excellent candidates for microbial fermentation and bacterial cellulose (BC) production. Approximately 3,400×10^3 tons of grapes were produced on 3.7 million decares of land during the 2023/2024 production season. According to FAO data, grapes are one of the most produced fruits globally, with a total yield exceeding 87,000×10^3 tons per year, generating approximately 20% solid waste (grape pomace) during wine and juice production (Bekar, 2016; FAO, 2025). Approximately 11–12% of this production is used for wine, vinegar, and molasses manufacturing, leading to the generation of nearly 600×10^3–800×10^3 tons of grape pomace annually (Bekar, 2016; Tarım ve Orman Bakanlığı, 2020). After processing, depending on the grape variety and processing step, 15–25% of the remaining material consists of grape pomace, comprising approximately 50% skins, 25% seeds, and 25% other solid residues (Bekar, 2016; Varış et al., 2000) (Bekar, 2016; Varış et al., 2000).

In Serbia, over 80% of the plums that are produced is utilized to make brandy, with the remainder being used for freezing, drying, or making jam and other confections. Fresh consumption accounts for only a small proportion (Direk and Spahic-Vukojevic, 2021; Subić et al., 2021). Plum pomace contains a soluble fraction of 7–13% and a total dietary fiber content of 38–49% (Milala et al., 2013). A large number of by-products, including plum stones with high potential value for sustainable utilization, are produced during the processing of plums. Because of their advantageous structure and chemical characteristics, plum stones, which are mostly composed of cellulose, hemicellulose, and lignin and contain about 61.1% carbon, are regarded as a promising lignocellulosic biomass for numerous uses (Usmonova and Salikhanova, 2024; Gajić et al., 2025).

Figure 3a, compiled from TÜİK, and STAT data, shows the annual grape and plum production in Türkiye and Serbia between 2020 and 2024. Türkiye consistently maintained high grape production levels (>3,000×10^3 tons/year), while Serbia remained a major global producer of plums (>325×10^3 tons/year). Observed interannual variations support the reliability of both residues as continuous feedstock sources.

As shown in Figure 3b, approximately 2,200×10^3 tons of grapes and 300×10^3 tons of plums are processed annually in Türkiye and Serbia, respectively. Following industrial processing, approximately 20% of the grape mass and 15% of the plum mass remain as pomace. Despite their rich lignocellulosic composition, these by products are not sufficiently utilized. These residues have the potential to be important raw materials for the circular economy. Currently, most of grape and plum pomace residues in both Türkiye and Serbia are disposed of in landfills, used as low-value animal feed, or left to decompose in open fields. These practices fail to utilize the biochemical potential of these residues and often result in environmental burdens. Improperly managed food and fruit processing wastes undergo uncontrolled microbial degradation, leading to the release of methane (CH_4) and carbon dioxide (CO_2), both potent greenhouse gases contributing to climate change (USDA, 2024). Additionally, leachates generated during decomposition can contaminate soil and groundwater, while excessive organic matter accumulation can result in eutrophication in nearby water bodies (EEA, 2025).

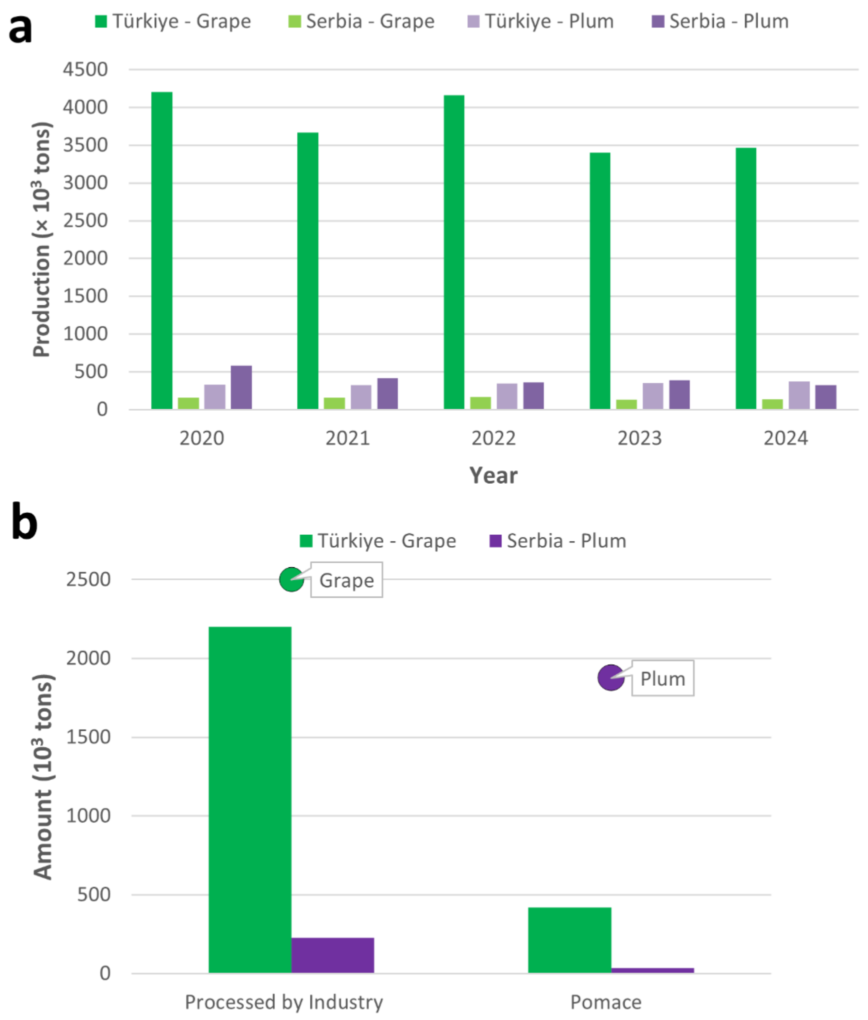

Figure 3. (a) Annual grape and plum production in Türkiye and Serbia (2020–2024) and (b) Industrial processing and pomace generation of grape and plum in Türkiye and Serbia ($\times 10^3$ tons) (Milala et al., 2013; TÜİK, 2020; Direk and Spahic-Vukojevic, 2021; Subić et al., 2021; FAOSTAT, 2023; UN, 2023; StatAgri, 2024; Tariş Üzüm, 2025).

Therefore, the valorization of grape and plum residues in Türkiye and Serbia represents not only an environmental necessity but also a strategic economic opportunity that is related to sustainability with regional development. The following sections present the quantitative results of production trends, processing levels, residue generation, and the biopolymer valorization potential of these residues.

Country-based industrial processing yield (IPO), pomace yield coefficient (PM), and waste diversion rate (WDR) for grapes and plums

The industrial processing output (IPO) was calculated using Equation (1) and 2024 grape and plum production values (Figure 3a): For Türkiye $P_{total}=3468\times10^3$ and for Serbia $P_{total}=325\times10^3$ tons. As can be seen in Figure 1a, for Türkiye grapes ($R_{proc}= 0.65$) driven by wine, vinegar, pekmez, and industrial juice processing (Bekar, 2016; Tarım ve Orman

Bakanlığı, 2020). For Serbian plum, (R_{proc}= 0.80), reflecting the dominance of brandy production (Direk and Spahić-Vukojević, 2021; Subić et al., 2021). The amounts of grapes and plums used in industry, along with their respective pomace quantities (Y_{pom}), were assumed to be 20% and 15% for Türkiye and Serbia, respectively (Figure 3b).

WDR is widely used in circular economy and waste management frameworks as an indicator of material recovery efficiency and resource circularity. However, at present, only a very small portion of grape residues (approximately 3% in the Mediterranean region) is used for compost, animal feed, or low-value fuel, while the majority is underutilized or managed as waste (Carpentieri et al., 2023). According to recent estimates for the EU wine industry; the wast majority of residues is still dumped in landfills or scattered over fields as low-value waste (Kokkinomagoulos and Kandylis, 2025). Despite this biochemical richness, plum pomace is still largely underutilized in Serbia and other producing nations; the majority of residues are inefficiently burned, dumped in the open, or used as animal feed. Studies frequently characterize plum pomace as a "under-exploited" or "low-value" by-product in relation to its chemical potential, while quantitative evaluations of valorized fractions are still rare in the literature (Milala et al., 2013; Subić et al., 2021).

Based on these studies, $PM_{valorized}$ was assumed to be 22×10^3 tons for grape pomace and 1.7×10^3 tons for plum pomaces for Türkiye and Serbia, respectively (WDR =5% for both fruit pomaces) as summarized in Table 1 (Milala et al., 2013; TÜİK, 2020; Direk and Spahic-Vukojevic, 2021; Subić et al., 2021; FAOSTAT, 2023; UN, 2023; StatAgri, 2024; Tariş Üzüm, 2025). Strengthening the valorization pathways for these large quantities of waste, particularly those related to biopolymer synthesis, bioactive extraction, and carbon-neutral material production, will significantly support regional bio-based industries and circular economy plans.

Table 1. Parameters used to estimate industrial processing output, pomace generation, valorization level, and waste diversion rate for grapes (Türkiye) and plums (Serbia)

	Units	Türkiye - Grape	Serbia - Plum
The industrial processing output (IPO)	10^3 tons	2254	228
Annual generated pomace (PM)	10^3 tons	451	34
Valorized pomace ($PM_{valorized}$)	10^3 tons	22	1.7
The waste diversion rate (WDR)	%	5	5

Biochemical Characteristics and Valorization Potential of Grape and Plum Pomaces for Biopolymer Applications

Thermal conversion techniques such as pyrolysis and gasification allow for the recovery of bio-oils and syngas, while chemical and enzymatic methods support the production of nanocellulose and other high-value bioproducts. These processes collectively align with circular economy principles by maximizing resource recovery and minimizing environmental impacts. Recent studies have demonstrated that lignocellulosic residues from fruit processing can serve as efficient feedstock not only for bacterial cellulose, but also for biogas, bioethanol, and biochar production—offering a closed-loop solution within the circular economy (Awogbemi and Von Kallon, 2022a; Chilakamarry et al., 2022).

Beyond direct energy and material value, agricultural waste utilization enhances rural livelihoods, stimulates innovation in small and medium enterprises, and supports carbon-neutral growth strategies under the European Green Deal (EC, 2019). In recent years, both Türkiye and Serbia have aligned their agricultural strategies with the European Green Deal and the Circular Economy Action Plan, emphasizing the recovery and reuse of organic residues. As emerging economies with rich agricultural outputs, they share similar challenges, including inadequate biorefinery infrastructure, low public awareness, and limited financial incentives for waste valorization. Yet, their combined potential for bio-based innovation, particularly in fruit waste utilization, offers a promising pathway toward achieving the UN Sustainable Development Goals (SDGs 12 and 13) (UN, 2019).

Bacterial cellulose (BC), a nano-structured polysaccharide synthesized by certain acetic acid bacteria such as *Komagataeibacter xylinus*, has attracted significant attention due to its high purity, crystallinity, tensile strength, and biocompatibility (Iguchi et al., 2000; Shah et al., 2013). It serves as a sustainable alternative to plant-derived cellulose for applications in biomedical materials, food packaging, and environmental remediation. The production of BC typically relies on glucose-based substrates, but fruit processing wastes rich in fermentable sugars can serve as cost-effective and eco-friendly alternatives, substantially lowering production costs (Ul-Islam et al., 2012; Shah et al., 2013; Jozala et al., 2016; Khan et al., 2023). Recent studies have demonstrated successful BC production using grape, apple, and citrus pomaces as carbon sources, achieving yields comparable to or higher than those obtained from synthetic media (Çakar et al., 2014; Keshk, 2014).

Mechanical characteristics (e.g., tensile strength, elongation at break), thermal stability (glass transition, melting, and decomposition temperatures), barrier performance (moisture and oxygen permeability), and biodegradability and sustainability attributes (renewable resource, carbon footprint) are the main factors that determine the biopolymer potential of biomass feedstock. These criteria are frequently applied in the literature to evaluate whether biopolymers are appropriate for specific applications in environmental technologies, biomaterials, and packaging (Shah et al., 2013; Jozala et al., 2016). As a result, the overall "potential" of a polymer or precursor feedstock is often assessed case by case, based on the demands of the intended application in biopolymer research.

Nevertheless, when assessing food and agricultural waste as raw materials for the production of biopolymers, the emphasis shifts from final material properties (mechanical or thermal) to the biochemical composition of the raw biomass, specifically its structural polysaccharide content that can be transformed into biopolymers based on cellulose or pectin. Thus, biochemical composition (cellulose, hemicellulose, and pectin), extractives, ash, and lignin ratios are also considered as key feedstock quality indicators in current biorefinery and residue valorization studies (Awogbemi and Von Kallon, 2022a; Awogbemi and Von Kallon, 2022b; Chilakamarry et al., 2022).

In this regard, the biochemical properties of grape and plum pomace, specifically their cellulose, hemicellulose, pectin, and fermentable sugar content, can be used to evaluate the biopolymer valorization potential of these materials. Thus, three criteria commonly reported in the literature were used in this study to assess the potential for valorization: (i) pomace availability; (ii) biochemical compatibility; and (iii) practical valorization capability, all of which are supported by recent studies on bio-based material production.

The main biochemical and operational variables that determine the possibility for producing biopolymers from grape and plum pomace are compiled in Table 2. Türkiye's grape pomace is particularly well suited for BC production due to its higher usability and sugar-rich composition. Despite being generated in relatively lower quantities, Serbian plum pomace offers significant prospects for nanocellulose and pectin-based biopolymers due to its high dietary fiber and lignocellulosic content. Both wastes currently exhibit very low valorization rates (below 5%), indicating substantial untapped potential within circular bioeconomy frameworks.

Table 2. Biochemical and practical indicators for evaluating grape (Türkiye) and plum (Serbia) pomace valorization potential for biopolymer production

Criterion	Indicator and Relevance for Biopolymer Production	Pomace		Key References
		Grape	Plum	
Availability	PM - Determines feedstock supply for continuous biopolymer production	High (≈451×10³ tons/year)	Moderate (≈34×10³ tons/year)	Bekar, 2016; Subić et al., 2021
	WDR - Indicates extent of underutilization and circularity potential	Very low (~3–5%)	Very low (<5%)	Carpentieri et al., 2023; Kokkinomagoulos and Kandylis, 2025
Biochemical Suitability	Cellulose (%) - Structural polysaccharide essential for BC, NC, bioplastics	~20–25%	~18–22%	Gajić et al., 2025; Ul-Islam et al., 2012; Milala et al., 2013; Çakar et al., 2014; Keshk, 2014; Ogrizek et al., 2021; Megías-Pérez et al., 2023; Usmonova and Salikhanova, 2024; Kokkinomagoulos and Kandylis, 2025
	Hemicellulose (%) - Supports biopolymer formation	12–18%	14–20%	
	Pectin (%) - Key precursor for pectin films, hydrogels, edible coatings	~6–10%	~10–15%	
	Fermentable sugars - Direct carbon source for BC fermentation	High (glucose, fructose)	Moderate (sorbitol, polyols)	
Valorization Feasibility	Existing industrial pathways - Lower processing cost if compatible with industry infrastructure	Wine, juice, and vinegar industries provide continuous feedstock	Brandy production	Subić et al., 2021
	Suitability for BC fermentation - Determines feasibility of microbial valorization	Demonstrated high BC yields	Limited studies and high potential but under-investigated	Çakar et al., 2014; Keshk, 2014
	Suitability for nanocellulose - Depends on cellulose/lignin balance and extractability	Good (skin/seed lignin manageable)	Good (lignocellulose high but extractable)	Chilakamarry et al., 2022

Conclusion

In conclusions, grape and plum pomace in Serbia and constitute high-volume, composition-rich biomass streams that are severely underutilized and possess substantial potential for integration into a circular bioeconomy. Although Serbia produces more than 34×10³ tons of plum pomace annually and Türkiye produces more than 451×10³ tons of grape pomace annually, the rates of valorization are still remarkably low (≤5%). Given the biological suitability of these wastes, this production-utilization gap presents a significant opportunity for the development of innovative biopolymer-oriented valorization pathways.

Both pomaces are attractive substrates for the production of bio-based materials due to their high lignocellulose content. High-yield BC production has been reported to be supported by the abundance of structural polysaccharides and residual glucose/fructose found in grape pomace. In a similar vein, plum pomace is suitable for applications such as edible films, nanocellulose extraction, and pectin-based bioplastics due to its increased pectin and dietary fiber content. These findings also corroborate prior studies showing fruit-based wastes are promising feedstocks for biochar synthesis, biopolymer manufacturing, and biogas upgrading within low-cost and scalable biorefinery systems.

Despite the availability of biochemical pathways and demonstrated laboratory-scale feasibility, practical limitations continue to represent a major barrier in Serbia and Türkiye. Grape pomace is produced year-round by Türkiye's wine, vinegar, and pekmez sectors, which increases the feedstock's dependability for bio-based production. On the other hand, Serbian plum pomace is highly seasonal because brandy production is concentrated in a short processing window. Logistical issues with storage, stability, and ongoing microbial processing result from this. Despite the high biochemical richness of plum residues, these temporal constraints partially explain Serbia’s lower level of technological adoption.

Both countries have acknowledged the need to expedite the use of organic waste and have connected their agriculture plans with the EU Green Deal and the Circular Economy Action Plan at the policy and system level. However, there is still a lack of the infrastructure needed for large-scale biopolymer synthesis, such as fermentation facilities, biorefineries, and effective pre-treatment systems. Despite solid scientific evidence supporting the widespread usage of residue-based biological products, this structural deficiency leads to low recovery rates. In addition to lessening the negative effects of unchecked decomposition on the environment (methane emissions, leachate formation, eutrophication), increasing these capacities will make it possible to produce high-value materials, including BC, nanocellulose, and pectin-based composites domestically.

The comparative analysis also reveals that Türkiye has a quantitative and infrastructural advantage due to its large-scale fruit processing industry, whereas Serbia has a qualitative advantage driven by the high fiber content of plum pomace. This complementarity demonstrates how cooperative biorefinery models and information sharing between nations may be crucial in hastening regional bioeconomic changes. This complementary relationship emphasizes the potential contribution of exchange of information, shared biorefinery models, and cross-border cooperation to the acceleration of regional bioeconomic development. Both countries show outstanding potential for creating integrated value chains that promote rural economic growth, reduce the burden on waste management systems, and assist in achieving SDGs 12 and 13.

Overall, the study indicates that grape and plum pomace have high biochemical suitability for biopolymer-focused value recovery; however, targeted advancements in infrastructure, technology, and policy frameworks are required to fully unlock this potential. Both in Türkiye and Serbia, the conversion of these waste materials into BC, nanocellulose and pectin-based biopolymers offers a technically feasible and strategically compatible path towards sustainable industrial development.

Several limitations should be considered when interpreting these findings. First, the analysis is mostly reliant on secondary datasets (FAOSTAT, TÜİK, and STAT), which may introduce variability due to differences in reporting standards, crop classifications, or data update frequencies among agencies. Variation associated with climate conditions, processing techniques, and storage conditions may not be fully captured, as biochemical composition data were compiled from direct experimental analysis. Moreover, the lack of government information on waste recovery in the fruit processing industry is reflected in the recovery rates described in the literature, which are generalized estimates rather than country-specific measures. Finally, economic metrics like value-added multipliers may not accurately reflect small-scale producers or the informal processing sector because they are dependent on national reports that are currently available.

To enable more accurate modeling of biochemical conversion efficiencies, future research should experimentally evaluate biopolymer yields at the laboratory scale using grape and plum pomace collected from Türkiye and Serbia. Cross-raw material comparisons could be enhanced by creating a common biopolymer compatibility index that incorporates polysaccharide content, extraction capacity, fermentation performance, and pretreatment energy requirements. To quantify the economic and environmental benefits of the proposed valorization pathways under realistic industrial conditions, techno-economic analysis and life cycle assessment (LCA) are also required. Pilot-scale biorefinery design that emphasizes continuous processing and seasonal stabilizing techniques will be made possible by cooperation with nearby vineyards, brandy manufacturers, and food processing facilities. Including other regional fruits like pomegranate, apricot, and apple residues could further enhance bio-based innovation capacity and facilitate more extensive circular economy transitions in both nations.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Contributions

The authors declare that they have contributed equally to the article.

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References

Ataseven ZY., 2025. Tarım ürünleri piyasaları raporu (Üzüm) Temmuz-2025.

Avşar Y, Çevik B., 2023. Biyokompozit üretiminde takviye elemanı olarak kullanılan tarımsal atıkların incelenmesi ve Türkiye'deki tarımsal atık potansiyeli. Düzce Üniversitesi Ziraat Fakültesi Dergisi, 1(1): 15–25. https://dergipark.org.tr/en/pub/jafdu/issue//1467094

Awogbemi O, Von Kallon DV., 2022a. Valorization of agricultural wastes for biofuel applications. Heliyon, 8(10). https://doi.org/10.1016/j.heliyon.2022.e11117

Awogbemi O, Von Kallon DV., 2022b. Pretreatment techniques for agricultural waste. Case Studies in Chemical and Environmental Engineering, 6: 100229. https://doi.org/10.1016/J.CSCEE.2022.100229

Bednárek J, Matějová L, Koutník I, Vráblová M, Cruz GJF, Strašák T, Šiler P, Hrbáč J., 2024. Revelation of high-adsorption-performance activated carbon for removal of fluoroquinolone antibiotics from water. Biomass Conversion and Biorefinery, 14(2): 2585–2599. https://doi.org/10.1007/S13399-022-02577-Z/FIGURES/10

Bekar T., 2016. Bağcılıkta atık teknolojisi. Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 6(1). https://www.academia.edu/download/80516463/17-24.pdf

Belošević S, Tomanović I, Milićević A, Crnomarković N, Stojanović A., 2024. Valorization of waste agricultural biomass as a fuel for sustainable power production by co-firing. Serbian Journal of Engineering Management, 9(2): 9-19. https://doi.org/10.5937/SJEM2402009B

Çakar F, Katı A, Özer I, Demirbağ DD, Şahin F, Aytekin AÖ., 2014. Newly developed medium and strategy for bacterial cellulose production. Biochemical Engineering Journal, 92: 35–40. https://doi.org/https://doi.org/10.1016/j.bej.2014.07.002

Carpentieri S, Ferrari G, Pataro G., 2023. Pulsed electric fields-assisted extraction of valuable compounds from red grape pomace: Process optimization using response surface methodology. Frontiers in Nutrition, 10: 1158019. https://doi.org/10.3389/FNUT.2023.1158019/BIBTEX

Casquete R, Benito MJ, Martín A, Martínez A, Rivas M. de los Á, Córdoba M. de G., 2022. Influence of different extraction methods on the compound profiles and functional properties of extracts from solid by-products of the wine industry. LWT, 170: 114097. https://doi.org/10.1016/J.LWT.2022.114097

CEIC., 2021. Turkey Waste generation: Total. https://www.ceicdata.com/en/turkey/environmental-waste-generation-by-sector-oecd-member-annual/waste-generation-total

Chedea VS, Tomoiagă LL, Ropota M, Marc G, Ranga F, Muntean MD, Sîrbu AD, Giurca IS, Comșa M, Bocsan IC, Buzoianu AD, Kisher H, Pop RM., 2025. Transylvanian grape pomaces as sustainable sources of antioxidant phenolics and fatty acids-A study of white and red cultivars. Antioxidants, 14(10), 1152. https://doi.org/10.3390/ANTIOX14101152/S1

Chilakamarry CR, Mimi Sakinah AM, Zularisam AW, Sirohi R, Khilji IA, Ahmad N, Pandey A., 2022. Advances in solid-state fermentation for bioconversion of agricultural wastes to value-added products: Opportunities and challenges. Bioresource Technology, 343: 126065. https://doi.org/https://doi.org/10.1016/j.biortech.2021.126065

Dhyani V, Bhaskar T., 2018. A comprehensive review on the pyrolysis of lignocellulosic biomass. Renewable Energy, 129: 695-716. https://doi.org/https://doi.org/10.1016/j.renene.2017.04.035

Direk M, Spahic-Vukojevic S., 2021. An economic analysis of plums production: The case of Gradacac, Bosnia and Herzegovina. Selcuk Journal of Agricultural and Food Sciences, 35(3): 202–209. https://doi.org/10.15316/sjafs.2021.249

EC., 2019. The European green deal. https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

EEA., 2025. Leachate pollution from landfills (Signal). https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/emission-from-waste-management-facilities

EİGM., 2021. Biyokütle enerjisi potansiyel atlası (BEPA). https://bepa.enerji.gov.tr/

FAO., 2025. Grape. Food and Agriculture Organization of the United Nations Https://Www.Fao.Org/Land-Water/Databases-and-Software/Crop-Information/Grape/En/. https://www.fao.org/land-water/databases-and-software/crop-information/grape/en/

FAOSTAT., 2023. Crops and livestock products: Plumbs and sloes. https://www.fao.org/faostat/en/#data/QCL

Gajić N, Radovanović D, Đokić J, Jelić I, Jevtić S, Sokić K, Štulović M., 2025. Optimization of milling process parameters for waste plum stones for their sustainable application. Processes 2025; 13(9): 2759. https://doi.org/10.3390/PR13092759

Galante M, Brassesco ME, Maragoni Santos C, Beres C, Fai AEC, Cabezudo I., 2025. Grape pomace as a natural source of antimicrobial agents for food preservation. Frontiers in Nutrition, 12: 1650450. https://doi.org/10.3389/FNUT.2025.1650450/ENDNOTE

Ignjatovic J, Dordevic A, Robinic J., 2025. Potential for applying circular economy principles in compost production in Serbia. 107–116. https://doi.org/10.53486/SER2025.11

Iguchi M, Yamanaka S, Budhiono A., 2000. Bacterial cellulose - a masterpiece of nature's arts. Journal of Materials Science, 35(2): 261–270. https://doi.org/10.1023/A:1004775229149/METRICS

Ioannidou O, Zabaniotou A., 2007. Agricultural residues as precursors for activated carbon production-A review. Renewable and Sustainable Energy Reviews, 11(9): 1966-2005. https://doi.org/10.1016/J.RSER.2006.03.013

IRENA., 2019. Global energy transformation : a roadmap to 2050 (2019 Edition). International Renewable Energy Agency. www.irena.org

IRENA., 2020. Recycle: Bioenergy (Circular Carbon Economy, 05). www.irena.org

IRENA., 2022. Scaling up biomass for the energy transition: Untapped opportunities in Southeast Asia. www.irena.org

Işıtan A., 2025. Sustainable adsorption of amoxicillin and sulfamethoxazole onto activated carbon derived from food and agricultural waste: Isotherm modeling and characterization. Processes, 13(8): 2528. https://doi.org/10.3390/PR13082528

Ivanović N, Vučinić A, Marinković V, Krajnović D, Ćurčić M., 2025. Towards sustainable food waste management in Serbia: A review of challenges, gaps, and future perspectives. Sustainability; 17(7): 2961. https://doi.org/10.3390/SU17072961

Jozala AF., de Lencastre-Novaes LC, Lopes AM, de Carvalho Santos-Ebinuma V, Mazzola PG, Pessoa-Jr A, Grotto D, Gerenutti M, Chaud MV., 2016. Bacterial nanocellulose production and application: a 10-year overview. Applied Microbiology and Biotechnology, 100(5): 2063–2072. https://doi.org/10.1007/S00253-015-7243-4

Katarina Đ, Simin Mirela T, Trbić Danica G, Bulatović Mirjana L., 2024. State and perspective of fruit production in Serbia. Ekonomija: Teorija i Praksa, spec issue, 53–65. https://doi.org/10.5937/ETP243-2053K

Keshk SM., 2014. Bacterial cellulose production and its industrial applications. Journal of Bioprocessing and Biotechniques, 04(02). https://doi.org/10.4172/2155-9821.1000150

Ketin S, Kostić B, Plojović Š., 2024. Agricultural waste and statistics. Ekonomija-Teorija i Praksa, 17 (Special Edition): 66–81. https://doi.org/10.5937/etp243-2066K

Khan S, Ul-Islam M, Fatima A, Manan S, Khattak WA, Ullah MW, Yang G., 2023. Potential of food and agro-industrial wastes for cost-effective bacterial cellulose production:

An updated review of literature. ES Food and Agroforestry, 13. https://doi.org/10.30919/esfaf905

Kokkinomagoulos E, Kandylis P., 2025. Sustainable wine fining: Evaluating grape pomace as a natural alternative to commercial agents. Beverages, 11(2): 31. https://doi.org/10.3390/BEVERAGES11020031

Koul B, Yakoob M, Shah MP., 2022. Agricultural waste management strategies for environmental sustainability. Environmental Research, 206: 112285. https://doi.org/10.1016/J.ENVRES.2021.112285

Krunić N, Josimović B, Gajić A, Nenković-Riznić M., 2019. Territorial analysis as support to the Strategic Environmental Assessment process for agro-waste management planning. Spatium, 42(42): 16–22. https://doi.org/10.2298/SPAT1942016K

Malićanin MV, Švarc-Gajić J, Lević SM, Rac VA, Salević-Jelić AS, Pešić MB, Milinčić DD, Pasarin D, Rakić VM., 2025. Valorization of grape seed cake by subcritical water extraction. Processes, 13(5): 1597. https://doi.org/10.3390/PR13051597/S1

Megías-Pérez R, Ferreira-Lazarte A, Villamiel M., 2023. Valorization of grape pomace as a renewable source of techno-functional and antioxidant pectins. Antioxidants, 12(4): 957. https://doi.org/10.3390/ANTIOX12040957/S1

Milala J, Kosmala M, Sójka M, Kołodziejczyk K, Zbrzeâniak M, Markowski J., 2013. Plum pomaces as a potential source of dietary fibre: Composition and antioxidant properties. Journal of Food Science and Technology, 50(5): 1012–1017. https://doi.org/10.1007/s13197-011-0601-z

Milinčić DD, Stanisavljević NS, Pešić MM, Kostić A, Stanojević SP, Pešić MB., 2025. The bioaccessibility of grape-derived phenolic compounds: An overview. Foods, 14(4): 607. https://doi.org/10.3390/FOODS14040607

Negi T, Kumar Y, Sirohi R, Singh S, Tarafdar A, Pareek S, Kumar Awasthi M, Alok Sagar N., 2022. Advances in bioconversion of spent tea leaves to value-added products. Bioresource Technology, 346. https://doi.org/10.1016/j.biortech.2021.126409

Nirmal NP, Khanashyam AC, Mundanat AS, Shah K, Babu KS, Thorakkattu P, Al-Asmari F, Pandiselvam R., 2023. Valorization of fruit waste for bioactive compounds and their applications in the food industry. Foods, 12(3): 556. https://doi.org/10.3390/FOODS12030556

Ogrizek L, Lamovšek J, Čuš F, Leskovšek M, Gorjanc M., 2021. Properties of bacterial cellulose produced using white and red grape bagasse as a nutrient source. Processes, 9(7): 1088. https://doi.org/10.3390/PR9071088

Pecot RK, Watt BK., 1975. Food yields - summarized by different stages of preparation (Y. J. Garrison and R. H. Matthews, Eds.). DIANE Publishing.

Salunkhe DK, Kadam SS., 1995. Handbook of fruit science and technology: Production, composition, storage, and processing. CRC Press. https://books.google.com/books/about/Handbook_of_Fruit_Science_and_Technology.html?hl=trandid=50ZZDwAAQBAJ

Shah N, Ul-Islam M, Khattak WA, Park JK., 2013. Overview of bacterial cellulose composites: A multipurpose advanced material. Carbohydrate Polymers, 98(2): 1585–1598. https://doi.org/https://doi.org/10.1016/j.carbpol.2013.08.018

STAT., 2025. Waste generation and treatment, 2022. Statistical Office of the Republic of Serbia. https://www.stat.gov.rs/en-us/vesti/statisticalrelease/?p=13623

StatAgri., 2024. Agricultural statistics. Https://Www.Statagri.Com/. https://www.statagri.com/#google_vignette

Subić J, Jeločnik M, Nastić L, Vasile Andrei J., 2021. Economic effects of plum plantation establishment. Sustainable Agriculture and Rural Development, 149–162. http://repository.iep.bg.ac.rs/543/1/Subi%C4%87%2C%20Jelo%C4%8Dnik%2CNasti%C4%87%2C%20Vasile.pdf

Suri S, Singh A, Nema PK., 2022. Current applications of citrus fruit processing waste: A scientific outlook. Applied Food Research, 2(1): 100050. https://doi.org/https://doi.org/10.1016/j.afres.2022.100050

Tariş Üzüm., 2025. Üzüm hakkında. S.S. Tariş Üzüm Tarım Satış Kooperatifleri Birliği. https://www.tarisuzum.com.tr/uzum_hakkinda.html#baslik6

Tarım ve Orman Bakanlığı., 2020. Dünyada üzüm.

Trajković D, Jojić A, Živojinović D., 2025. Sensory characteristics of Serbian plum spirit. Book of Abstracts : 3rd European Symposium on Phytochemicals in Medicine and Food, July 1-4, 2025, Belgrade, Serbia, 11–11. https://refri.institut-cacak.org/handle/123456789/987

TÜİK., 2020. Bitkisel üretim istatistikleri, 2020. https://data.tuik.gov.tr/Kategori/GetKategori?p=tarim-111

Ul-Islam M, Khan T, Park JK., 2012. Water holding and release properties of bacterial cellulose obtained by in situ and ex situ modification. Carbohydrate Polymers, 88(2): 596–603. https://doi.org/10.1016/j.carbpol.2012.01.006

UN., 2019. The 17 goals. Sustainable Development. https://sdgs.un.org/goals

UN., 2023. 2022 The International Trade Statistics Yearbook. https://comtradeapi.un.org/files/v1/app/publicationfiles/2022/VolI2022.pdf

UNECE., 2022. Accelerating circular economy in Serbia: UNECE supports action on agriculture and food loss and waste. https://unece.org/media/trade/uncefact/news/369099

USDA., 2024. Food waste and methane: What’s the Connection? www.usda.gov/foodlossandwaste

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Reducing Associated Resource Constraints in Erosion Risk Evaluation in Nigeria

Henry Emeka AHAMEFULE[1*], Mayowa Julius BABALOLA[2], Henry PEARL[3]

[1,2]Department of Agronomy, University of Ilorin, P.M.B.1515, Ilorin, Kwara State, Nigeria
[3]Department of Veterinary Public Health and Preventive Medicine, University of Ilorin, Ilorin, Kwara State, Nigeria

[1]https://orcid.org/0009-0001-6601-7206
[2]https://orcid.org/0009-0008-2629-2060
[3]https://orcid.org/0009-0007-6827-6301
[*]Corresponding author: : ahamefule.he@unilorin.edu.ng

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ABSTRACT

Erosion risk determination is time-consuming, cumbersome, and costly. To ensure food security, methods of estimating erosion risk that substantially reduces associated constrains are needed; therefore, this study determined the soil properties central to providing structural stability and using same to build empirical models to forecast possible response of soil structural framework to the shattering effects of raindrops (D). Five core and auger surface soil samples from five locations were collected across Central Nigeria. A chemical and physico-structural soil properties correlation matrix was produced; 'D' was then fitted to a linear multivariate model. Models with the highest coefficient of determination (R^2) and minimal standard error with interpretations applicable to real situations were selected for validation on 10 other test soils. Results indicate that the Ca content of soils and soil porosity were the single most important soil chemical and physical property respectively, determining 'D', whereas Na (-0.49) and bulk density (-0.73) where the most negatively correlated chemical and physical property to 'D'. Models 2, 11 and 12 best predicted 'D' with 'r' values between measured and predicted 'D' as 0.97, 0.94 and 0.95, and Model 2 predicted 'D' in 80 % of the test soils, whereas Models 11 and 12 did so in 70 % of test soils. However, the cost associated with model 2 was six and four folds higher compared to model 11 and 12 respectively. Based on the related cost, model 11 is the choice, whereas in terms of versatility model 2 is. All models developed were cheap and high in predictive accuracy for 'D'. The models (2, 11 and 12) with few entries (soil properties) are simpler than existing models.

Nijerya'da Erozyon Riski Değerlendirmesinde İlişkili Kaynak Kısıtlamalarının Azaltılması

Araştırma Makalesi

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ÖZ

Erozyon riskinin belirlenmesi zaman alıcı, zahmetli ve maliyetlidir. Gıda güvenliğini sağlamak için, ilgili kısıtlamaları önemli ölçüde azaltan erozyon riskini tahmin etme yöntemlerine ihtiyaç duyulmaktadır; bu nedenle, bu çalışmada, yapısal istikrarı sağlayan temel toprak

Anahtar Kelimeler:
Erozyon risk değerlendirmesi
Gine Savanı
Toprak yapısı
Toprak kimyasal özellikleri
Toprak fiziksel özellikleri
Nijerya

özelliklerini belirlemiş ve aynı özellikleri kullanarak, toprak yapısal çerçevesinin yağmur damlalarının parçalanma etkilerine olası tepkisini tahmin etmek için ampirik modeller oluşturmuştur (D). Orta Nijerya'da beş farklı konumdan beş adet karot ve burgu yüzey toprak örneği alınmıştır. Kimyasal ve fiziko-yapısal toprak özellikleri korelasyon matrisi oluşturulmuş; daha sonra 'D' doğrusal çok değişkenli bir modele uyarlanmıştır. En yüksek belirleme katsayısına (R2) ve en düşük standart hataya sahip, gerçek durumlara uygulanabilir yorumlara sahip modeller, 10 farklı test toprağı üzerinde doğrulama için seçilmiştir. Sonuçlar, toprakların Ca içeriğinin ve toprak gözenekliliğinin sırasıyla 'D'yi belirleyen en önemli toprak kimyasal ve fiziksel özelliği olduğunu, Na (-0,49) ve kütle yoğunluğunun (-0,73) ise 'D' ile en negatif korelasyon gösteren kimyasal ve fiziksel özellik olduğunu göstermektedir. Modeller 2, 11 ve 12, ölçülen ve tahmin edilen 'D' değerleri arasındaki 'r' değerleri sırasıyla 0,97, 0,94 ve 0,95 ile 'D' değerini en iyi şekilde tahmin etmiştir. Model 2, test edilen toprakların %80'inde 'D' değerini tahmin ederken, Modeller 11 ve 12 test edilen toprakların %70'inde bunu başarmıştır. Bununla birlikte, Model 2'nin maliyeti, Model 11 ve 12'ye kıyasla sırasıyla altı ve dört kat daha yüksektir. İlgili maliyete göre Model 11 tercih edilirken, çok yönlülük açısından Model 2 tercih edilmektedir. Geliştirilen tüm modeller ucuz ve 'D' için yüksek tahmin doğruluğuna sahiptir. Az sayıda girdiye (toprak özellikleri) sahip modeller (2, 11 ve 12), mevcut modellere göre daha basittir.

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Introduction

Soil is one of the important natural resources and a significant factor in global food production. More than 99% of human food comes from the land (Pimentel and Pimentel, 2000). Soil also supports plants and acts as a reservoir of water and nutrients, but not all soils suit these purposes. According to Buringh and Dudal (1987) the world's total land area is 14.9 billion hectares, 29% of the earth surface, the remaining 71% is covered with water. A part of the land, about 1.4 billion, is permanently covered with ice, and the remaining 13.4 billion is used for Agricultural purposes, which include grazing and forests. According to FAO (2013), a small fraction about 1.5 billion hectares is suitable for growing crops, yet about 10 million hectares of cropland are lost every year to accelerated erosion from the action of water and wind, which causes undesirable changes in soil structure leaving the soil degraded (Pimemtel, 2006).

Erosion was reported by Lal (1994) to be the most serious type of soil degradation undermining the long term viability of arable soils across the globe. Oldeman *et al*. (1991) estimated that erosion accounts for 84 % of total global area of degraded soils. United Nation (UN) Convention to Combat Land Degradation (CCD) opines that soil erosion leads to loss of chemical, biological, and economic productivity of terrestrial ecosystem diversity (Telles *et al*., 2011). Some researchers also argued that a significant area of cultivated land may be rendered biologically and/or economically unproductive if erosion continues unabated (Brown and Wolf, 1984; Lal, 1994; Pimental et al.1995; Eaton, 1996).

The process of soil erosion by water is initiated when the constituent particles of the aggregates are detached by the shearing force of raindrops incident on the soil surface. For an aggregate to be destroyed, the intrinsic force of resistance of soil aggregates must be overcome by the shearing force of raindrops. Therefore the extent of soil erosion depends on the binding forces that sustain the integrity of the structural units, enabling resistance to the shattering forces of raindrops (Meyer et al., 1975). Torri et al. (1987) reported that an aggregate detachment index (D) can be determined by the ratio of the raindrop detaching force (Fd) to the force of soil resistance (Fr), thus,

$$D = Fd / Fr = \Psi d\ Ad / \Psi s\ A_s$$

Where Ψd is the total shear stress of the average raindrop, Ψs, the soil cohesive force, Ad, the area over which Ψd acts and A_s, the area of soil aggregate over which Ψs acts.

From current reports, raindrop diameter, raindrop velocity of impact, surface tension, contact angle, duration and orientation of raindrops are the most important factors which affects 'Fd' (Nearing and Bradford, 1986; Nearing and Bradford, 1987; Truman et al., 1990; Barry et al., 1991; Kinnell, 2005; Wuddivira et al., 2009). Similarly, the force of resistance (Fr) refers to the ability of soil aggregates to withstand breakdown. The force of resistance (Fr) is influenced by the initial water content of the aggregate at impact (Cruse and Larson, 1977), the soil cropping history, with stability declining with continuous tillage (Ahamefule and Peter, 2013) compared to adjacent forest soils (Beare et al., 1994), and the nature and concentrations of microbial synthesized aggregate-stabilizing substances like resins and gums (Harris et al.,1966; Lynch and Bragg, 1985). Harris et al. (1966), Hamblin and Davies, (1977); Oades, (1984) and Lynch and Bragg, (1985) revealed that the significant properties of the soil which influence its stability can be grouped into invariant (intrinsic) and dynamic; and that the exhibition of their influence is related to type of soil, season and climate. Since water content is dynamic, by holding 'Fd' constant, a raindrop kinetic energy-based index of soil detachment (D) can be determined for correlating 'Fd' to some factors which affect 'Fr'. By doing this, a simple model of relating 'D' to some more-easily determined soil properties can be developed. Several studies have adopted the raindrop technique to compare soil's structural stability and erodibility of soils (McCalla, 1944; Low, 1954; Imeson and Vis, 1984; Ramos et al., 2003; Canton et al., 2009). It is generally known that no single determined soil property can completely stand for the bulk response that makes up soil erodibility (Lal, 1990); however, Bruce-Okine and Lal (1975) proposed the adoption of the multiplicative inverse of the total number of water drops needed to shatter an aggregate as an erodibility marker for tropical soils. De Vleeschauwer et al. (1978) and Mbagwu, (1986) reported highly correlated inverse relationships between the total kinetic energy of raindrops required to destroy aggregates and the quantity of soil lost from simulated rainfall.

A major setback to the adoption of ‘D’ for routine characterization of soil structural stability is the difficulty related to its determination. The apparatus for raindrop simulation must be arranged in such a way that the characteristics of raindrops are uniform while the investigation lasts. This is not readily achievable. A high coefficient of variation in ‘D’ which ranged from 38 to 47% was reported by Mbagwu (1986, 1989).

The need therefore arises for studies in which more-easily determined soil properties are related to ‘D’; Wustamidin and Douglas (1985) made such attempt, in which they put forward a model for estimating ‘D’, the model had 15 independent variables (co-variants included). This model is complex, time-consuming, and probably expensive, and its affordability with the present unfavourable economic realities may not permit its use, particularly in developing countries.

Therefore, the objectives of this study were to:

(a) Evaluate and characterize the invariant properties of the soil that influence soil aggregate stability, and

(b) Develop and validate simple empirical models for estimating the resistance of soil aggregates in the study areas and similar environments to water-drop impacts ‘D’ from soil properties that are more easily determined.

Material and Methods

The Study Area

Kwara state is located in a tropical region with a bi-modal rainfall pattern and a tropical wet and dry seasonal climate lasting about six months (Olanrewaju, 2009). Temperature is between 25^{o}C and 30^{o}C throughout the rainy season except in July – August when the is a rise in the temperature due to the formation of cloud in the sky, which prevents direct insolation (heatstroke) while in the dry season it ranges between 33^{o} C to 34^{o}C. It is sunny and the sun shines brightly for 6.5 to 7.7 hours daily from November to May (Oyegun,1982).

Soil Sampling

Soil samples were collected from five locations evenly spread across Kwara state. The locations were Irepodun (Kwara West), Ifelodun (Kwara South), Moro (Kwara North), Baruten (Kwara East) and Ilorin, which is situated in the centre of the state, as shown in Fig1. Cylindrical metal cores and augers were used for collection of samples from the five locations shown in Table 1. The auger samples were collected at 10 m regular intervals, bulked and a composite taken, giving a total of 25 composite samples. Three samples from each location (fifteen in total) were used to develop the models. In comparison, the remaining two from each location (ten samples in total) were used to validate the developed models. The soil samples were air dried, sieved using a 2 mm sieve and used for soil analyses.

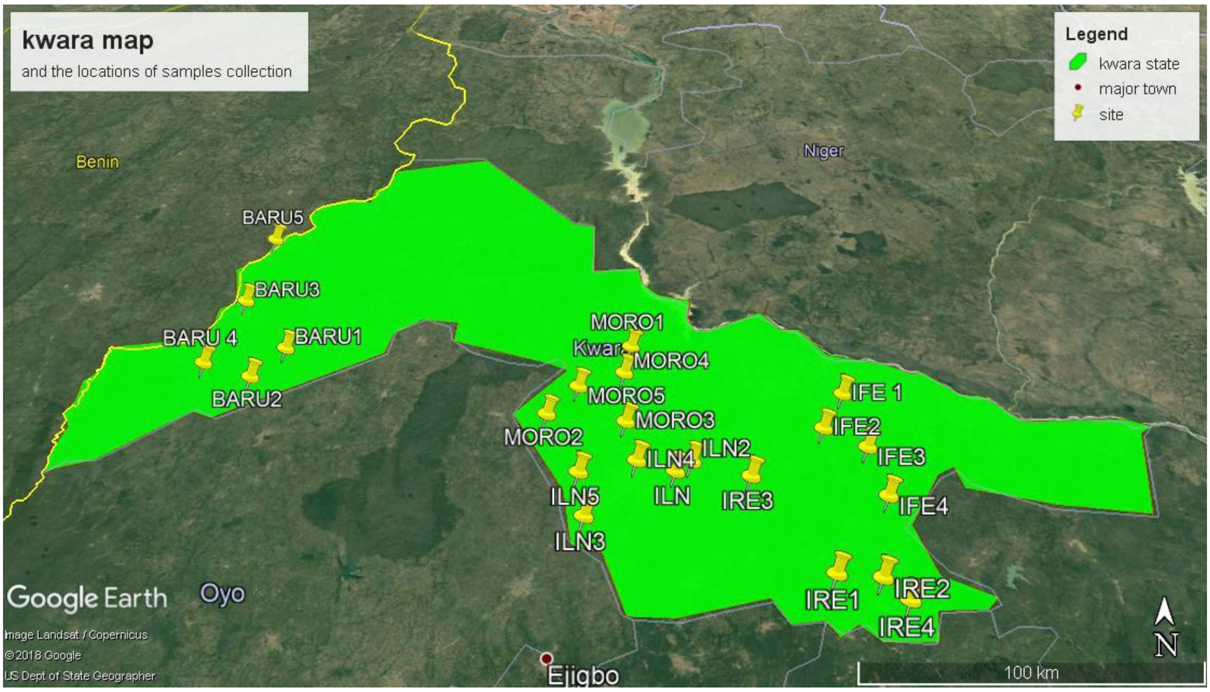

Figure 1. Map of Kwara State showing sampled locations

Table 1. Coordinates of sampled locations

Serial number	Name of location	Cardinal point of location
1	Ifelodun1	9° 1'13.77" N, 4° 59'13.27" E
2	Ifelodun2	8° 57'57.87" N, 5° 2'22.45" E
3	Ifelodun3	8° 53'7.08" N, 5° 7'18.01" E
4	Ifelodun4	8° 50'46.56" N, 5° 2'55.05" E
5	Ifelodun5	8° 57'17.07" N, 4° 54'14.70"E
6	Moro1	8° 36 '25" N, 4° 32'40" E
7	Moro2	8° 37 '18" N, 4° 31'58" E
8	Moro3	8° 39 '33" N, 4° 31'20" E
9	Moro4	8° 40'15" N, 4° 31'13" E
10	Moro5	8°42'49" N, 4° 27'57" E
11	Irepodun1	8° 7'51.17" N, 5° 6'9.06" E
12	Irepodun2	8° 7'9.65" N, 5° 7'45.20" E
13	Irepodun3	8° 15'0.22" N, 4° 55'0.20" E
14	Irepodun4	8° 4'17" N, 5° 5'36." E
15	Irepodun5	8° 3 '19" N, 5° 6'6." E
16	Baruten1	8° 53'43.80" N, 3° 23'21.98" E
17	Baruten 2	8° 53'43.80" N 3° 11'48.98" E
18	Baruten3	9° 0'57.12" N 3° 32'12.79" E
19	Baruten 4	9° 12'36.96" N 3° 27'29.44" E
20	Baruten 5	9° 4'31.41" N, 3° 15'46.80" E
21	Ilorin1	8° 34'44" N, 4° 42 '55" E
22	Ilorin 2	8° 27'28" N, 4° 43 '5" E
23	Ilorin 3	8° 34'1" N, 4° 34 '2" E
24	Ilorin 4	8° 29'48" N, 4° 32 '32" E
25	Ilorin 5	8° 29'48" N, 4° 35 '35" E

Laboratory Analyses

The Following Laboratory Analyses Were Conducted:

Soil Physical Properties

A constant head permeameter was used for the determination of saturated hydraulic conductivity (Ksat) according to Bouwer (1986), then applying the transposed Darcy's equation for vertical flows of liquid, thus:

$$K_{sat} = \frac{Q}{AT} \times \frac{L}{\Delta H}$$

Where Q is the stead state volume of flow (cm^3)

A is the cross-sectional area of the a core sample (cm^2)

T is the elapsed time (hr)

L is the length of the core sample (cm)

ΔH is the change in hydraulic head (cm)

The core method was used to determine of soil bulk density (Blake and Hartge, 1986). Total porosity was determined using the formula:

$$TP = (1 - \frac{Pd}{BD}) \times 100$$

Where TP is the total porosity

Bd is the bulk density

Pd is the particle density (2.65 g cm^{-3})

The wet –sieving method of Kemper and Rosenau (1986) was used to determine mean weight diameter (MWD) of water-stable aggregates. Particle size analysis (% sand, silt and clay) was determined by Bouyoucos (1932) hydrometer methods. Aggregated silt and clay (ASC) was determined according to the technique of Middleton (1930) as silt and clay in calgon-dispersed samples minus silt and clay in water-dispersed samples.

The clay dispersion index (CDI) was determined following the procedure of Dong *et al*. (1983), as clay in water-dispersed samples / clay in calgon-dispersed samples.

Moisture content at saturation was determined by saturating soil samples collected in a cylindrical metal core for 24 h and then weighing them. The soil samples were oven-dried for 24 h and weighed. Moisture content at saturation (MC) was then calculated thus:

$$MC = \frac{Mass\ of\ water\ at\ saturation}{mass\ of\ dried\ soil} \times 100$$

Soil structural index (SSI) was determined using the formula: $\frac{1.724 \times OC}{Si + Cl} \times 100$

Where OC = % soil organic carbon

Si = % silt

C = % clay

Moisture content at wilting point (-1.5megapascals) was determined by the use of pressure plate equipment.

Assessment of The Detachment Energy of A Water Drop (D)

Wustamidin et al. (1983) and Imeson and Vis, (1984) procedure was used to determine the detachment energy of a water drop (D). The 2 – 4 mm air-dried aggregates were weighed, and composite samples used to determine the residual gravimetric moisture content (θm) on oven-dry mass basis. The device for water drops simulation was consisted of a burette with an overflow device to maintain a constant pressure head. A silicon tube was fitted to the burette nozzle to deliver water drops of known mass and diameter at regular intervals. One gram of the dried aggregates (Wi) was placed on a fiberglass gauze of 1 mm aperture attached to a glass funnel. The aggregates of the samples were subjected to a maximum of 100 water-drops impacting from a 1 m height at a drop / s through a 15 cm diameter plexiglass tube. The frequency of water-drops completely destroyed an aggregate and was recorded, and total kinetic energy derived from the terminal velocity according to Laws (1941). The water-drop detachment energy 'D' defined as the kinetic energy required to break down and pass 1 g of aggregates through a 1 mm sieve aperture was calculated thus:

'D' = [Σni =1(0.5MV2)] / (Mi−Mb)

Where 'D' is in J / kg

M is the water drop mass (kg),

V is the water-drop velocity at impact (m / s),

n is the number of applied drops of water,

Mi is the initial mass of aggregates used (kg),

Mb is the leftover mass of aggregates on the sieve (kg) and

J is joule.

Twenty replicate determinations were made on each sample. The mass of the water drop was 0.03 g with a size of 1.5 mm, and the kinetic energy = 2×10^{-4}J per drop

Determination of Soil Erodibility Factor

The Wischmeier and Smith (1971) nomograph was used to estimate the soil erodibility factor.

Analyses of Chemical Properties of the Soil

Duplicate determinations were made for soil pH in both distilled water and in 0.1N KCl solution, using 5g of soil to water in the ratio 1:2.5 and stirred after 30 minutes, Beckman zeromatic pH meter was used to read off the pH values (Peech, 1965). The micro-Kjeldhal distillation method of Bremner (1996) was used to determine total nitrogen (N). The Ammonia evolved was distilled with 45 % NaOH into 2.5 % boric acid and determined by titrating with 0.05 N KCl. Available Phosphorus (P) was determined by the Bray II method, a procedure described by Bray and Kurtz (1945). The available phosphorous was read off from the standard curve after obtaining the optical density from the colorimeter. Organic matter was determined by the procedure of Walkley and Black using the dichromate wet oxidation method (Nelson and Sommers, 1982). Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ , Na^+) were extracted by leaching the soil with 1 N ammonium acetate solution. Exchangeable K^+ and Na^+ in the extract were determined using a flame photometer whereas an atomic absorption spectrophotometer was used to determine Calcium and Magnesium (Anderson and Ingram, 1993).

Data Analyses and Model Development

A matrix of correlation among each of the chemical, physical and structural data subsets was derived to determine soil properties that are auto correlated-'D' was subsequently transposed into a linear multivariate model of the form:

$$D = B_o + X_1B_1 + X_2B+_2 \ldots \ldots\ldots\ldots + B_n X_n + e$$

Where e is random error; X_1 to X_n, the independent variables in each data set, and B_o to B_n, the empirical constants using the IBM SPSS Statistic 21 package. Models with the highest coefficient of determination (r^2), the lowest standard error (SE) and having relevant physical interpretations over the range of determined values were validated with independent data from 10 other test-soils. The choice of regression model was predicated on the ease of determining the independent variables.

Results and Discussion

Characterization of Soils Used for Model Development

The characteristics of the soils used to develop the models are presented in Table 2. The results indicate that the study soils collected from different locations across Kwara State are predominantly sandy clay loam and sandy loam in texture, with exceptions in Baruten2 and Ilorin1 where a loamy sand and sandy clay texture were observed respectively. Soil pH varied from slightly alkaline to strongly alkaline across the state. Irepodun soil had the highest pH (mean pH = 8.5) while Baruten had the lowest (mean pH = 7.7). Organic matter (OM) content also varied across the state, with soils of Moro recording the lowest organic matter (mean OM = 0.55%) while Ilorin had the highest (OM = 2.99%).

The detachment energy (D) values staggered across the state. Ilorin had the widest 'D' range (0.05 – 0.52 $JKg^{-1} \times 10^{-3}$) and the highest mean value of 'D' (0.21 $JKg^{-1} \times 10^{-3}$), Irepodun had the lowest mean (0.07$JKg^{-1} \times 10^{-3}$) whereas Moro soils had the narrowest range of 0.07 – 0.1 $JKg^{-1} \times 10^{-3}$.

Relationship Between Selected Soil Chemical Properties with 'D'

The correlation of selected soil chemical properties with 'D' is shown in Table 3. The result indicates that only Ca (r = 0.8) was correlated ($P \leq 0.01$) with 'D' whereas sodium (r = -49) and pH (r = -0.46) were negatively correlated.

Table 2. Selected physico-chemical properties of soils of Kwara State used for model development

Local	Clay (%)	Silt (%)	Sand (%)	Txt Class	O.M (%)	pH	D (JKg^{-1} × 10^{-3})
Ife1	20.25	11.25	68.50	SCL	0.38	8.00	0.11
Ife 2	13.75	6.36	79.89	SL	0.95	8.20	0.22
Ife 3	21.68	18..07	60.25	SCL	0.91	8.30	0.11
Mor1	22.66	17.89	59.46	SCL	0.69	8.20	0.07
Mor 2	33.71	6.74	59.55	SCL	0.50	8.40	0.10
Mor 3	34.50	11.50	54.00	SCL	0.47	8.10	0.07
Ire1	23.04	18.44	58.52	SCL	1.53	8.20	0.10
Ire 2	25.69	17.84	56.48	SCL	1.07	9.00	0.05
Ire 3	14.57	19.77	65.66	SL	1.16	8.30	0.06
Bar 1	32.91	2.67	64.42	SCL	1.79	7.60	0.33
Bar 2	5.47	6.07	88.46	LS	2.29	8.10	0.07
Bar 3	20.34	16.95	6271	SCL	3.05	7.50	0.03
Iln 1	40.13	9.69	5019	SC	3.62	8.10	0.52
Iln 2	15.66	15.82	68.52	SL	3.05	8.10	0.07
Iln 3	26.10	14.72	59.18	SCL	2.29	8.30	0.05

D= Detachment energy of water drop, TXT CLASS = Textural class O. M = Organic matter, SCL = Sandy clay loam, SL = Sandy loam, SC = Sandy clay, Ire = Irepodun, Ife = Ifelodun, Bar = Baruten and ILN = Ilorin

Table 3. Correlation between selected chemical properties and water-drop detachment energy (D)

Soil Properties	Range	Correlation (r) With D
O.M (%)	0.38 – 3.65	0.45
A.P (%)	2.79 – 5.25	0.20
EA (cmol Kg^{-1})	0.28 – 0.76	0.15
EB (cmol Kg^{-1})	25.75 – 95.93	0.04
CEC (cmol Kg^{-1})	26.11 – 95.21	0.05
N (%)	0.35 – 0.99	0.36
Ca (cmol Kg^{-1})	0.09 – 62.98	0.80^{**}
K (cmol Kg^{-1})	0.09 – 1.33	0.38
Na (cmol Kg^{-1})	19.28 – 34.94	– 0.49
Mg (cmol Kg^{-1})	3.21 – 10.31	0.29
pH	7.6 – 9.0	– 0.46

OM = organic matter; CEC = cation exchangeable capacity; EA = exchangeable acidity; EB = exchangeable basicity; OC = organic carbon, AP = available phosphorus ** significant at P ≤ 0.01

There was non–significant ($P < 0.05$) positive correlation between OM and 'D'and moderate correlation of K^+ (r = 0.38) and Mg^{2+} (r = 0.29) with 'D'. Soil CEC was weakly correlated with 'D'.

Models Relating Selected Soil Chemical Properties With 'D'

Table 4 shows that Ca^{2+} increased the predictive ability of regression models that relate 'D' to soil chemical properties. Models with Ca^{2+} accounted for 67 – 80% (R^2 values) variability in 'D'. Based on the use of soil chemical properties for the prediction of 'D', model 2 is the best, considering that it had the highest predictive ability (80%) in the study soils. The standardized coefficient- beta (B) index (column 4 in Table 4) measures the effect of individual soil properties on ‘D’. The index reaffirms that Ca^{2+} had the highest influence on ‘D’ (predicted detachment energy) compared to other constituent soil properties of model 2.

Table 4. The regression models relating Detachment energy index (D) in $JKg^{-1}\times10^{-3}$ to chemical properties of soil

Model number	Equation	Coefficient of determination (R^2)	Standardized Coefficient (B)	Associated cost per sample (NGN)
1	$D = 0.0093(Ca) - 0.00034(Ca)^2 + 0.000005(Ca)^3 + 004$	0.71	Ca = 2.59 Ca^2 = 2.41 Ca^3 = 1.11	150
2	$D = 0.005(Ca) + 0.0001(Na^2) + 0.023(OM) - 0.064$	0.80	Na = 0.1 Ca = 0.71 OM = 0.11	1300
3	$D = 0.003(Ca) + 0.013(OM) - 0.00001(Na)^2 + 0.032$	0.74	Ca = 0.75 OM = 0.19 Na^2 = 0.036	1300
4	$D = 0.108(N) + 0.045(P) - 0.012(Mg) - 0.001(Ca) - 0.135$	0.73	N = 0.162 P = 0.3 Mg = 0.15 Ca = 0.82	2800
5	$D = 0.133(N) + 0.011(Mg) + 0.001(Ca) - 0.003(CEC) - 0.01$	0.72	N = 0.2 Mg = 0.14 Ca = 0.87 CEC = – 0.44	2800

CEC = Cation exchangeable capacity, NGN = Nigeria Naira (money)

Table 4. cont.: The regression models relating Detachment energy index (D) in $JKg^{-1} \times 10^{-3}$ to chemical properties of soil

Model number	Equation	Coefficient of Determination(R^2)	Standardized Coefficient (B)	Associated cost per sample (NGN)
6	D = 0.135(N)+ 0.032 (P) + 0.096 (K) – 0.154	0.22	K = 0.269 P = 0.213 N = 0.202	2650
7	D = 0.007(Ca) + 0.014 (OM) – 0.0350(P) – 0.026 (K) – 0.114	0.71	K = –0.074 P = 0.23 Ca = 0.81 OM = 0.11	2800
8	D = 0.05 (Acidity) – 0.15 (pH) + 0.012 (Mg) – 0.049 (OM) + 0.11	0.41	EA = 0.007 pH = 0.414 Mg = 0.17 OM = 0.049	2250
9	D = – 0.007 (Na) + 0.006 (Ca) – 0.009 (Mg) – 0.033(K) – 0.0303	0.67	Na = – 0.25 Ca = 0.77 Mg = – 0.11 K = – 0.093	600
10	D = 0.45 + 0.002(CEC) – 0.057(0M)	0.21	CEC = 0.014 OM = 0.45	2500

CEC = Cation exchangeable capacity, NGN = Nigeria Naira (money)

Relationship Between Selected Soil Physico-Structural Properties With ‘D’

The result in Table 5 showed that the correlation between sand and ‘D’ (r = – 0.19) was negative and weak whereas a moderately positive correlation existed between clay and ‘D’ (r = 0.51). There was moderately positive relationship between silt and ‘D’.

Porosity gave a significant positive linear relationship with ‘D’ (r = 0.733) whereas bulk density gave the reverse (r = – 0.729).

Moisture content at saturation and wilting point related positively with ‘D’ with ‘r’ values of 0.634 and 0.534 respectively. Table 5 further shows that MWD has strong correlation with ‘D’ (r = 0.71). Aggregate silt and clay (ASC) and clay dispersion index (CDI) were not significantly correlated with ‘D’. No significant correlation was established between saturated hydraulic conductivity and ‘D’ of the soil. There was negative (inverse) correlation (r = – 0.47) between ‘D’ and the erodibility factor (K) of Wischmeier *et al.* (1971).

Table 5. Correlation between some soil physico-structural properties with water-drop detachment energy (D)

Soil Properties	Range	Correlation (r) With D
Sand (%)	50.19 – 88.46	– 0.19
Clay (%)	5.47 – 40.13	0.51*
Silt (%)	2.67 – 19.77	0.51*
Porosity (%)	31.32 – 59.25	0.73*
Bulk Density (g cm^{-3})	1.29 – 1.82	– 0.73**
MWD (mm)	0.65 – 3.09	0.71**
ASC (%)	3.95 – 11.56	0.17
CDI (g/g)	0.65 – 1.24	– 0.36
K_{sat} (cmh^{-1})	6.44 – 102.50	0.32
MCS (%)	19.53 – 60.58	0.64*
WP (%)	7.90 – 22.6	0.53*
SSI (%)	1.01 – 19.87	0.03
Erodibility (t h MJ^{-1} mm^{-1})	0.03 – 0.21	– 0.47

BD = Bulk density, MC = Moisture content at saturation, K_{sat} = Saturated hydraulic conductivity, MWD_w = Mean weight diameter of wet soil aggregates, WP = Wilting point, CDI = Clay dispersion index, ASC = Aggregate silt and clay, SSI = Soil structural index. MCS = Moisture content at saturation * significant at $p \leq 0.05$ ** significant at $p \leq 0.01$

Models Relating Selected Soil Physical Properties With ‘D’

Models that relate ‘D’ to physical properties are shown in Table 6. Only model 11 and 12 best predicted ‘D’ with the models accounting for 91 % and 94 % variability in ‘D’ respectively. The standardized coefficient beta (B) indicate that among three physical properties water content at wilting point (WP) had the highest positive effect on ‘D’ (B = 7.72) in model 11, meaning that a unit increase in WP will increase ‘D’ by 7.72. Bulk density (BD) had negative influence (B = -8.43) on the strength of predicting ‘D’ by model 11. An increase in BD will cause a reduction in the value of ‘D’ by a factor of 8.43. In model 12, BD^2 had positive effect on ‘D’ indicated by a high B value of 8.54. While the effect of BD on ‘D’ was negative squaring its value gave a positive effect.

Models Relating Selected Soil Structural Properties With ‘D’

The models that relate ‘D’ to soil structural properties are presented in Table 7. Model 19 showed the highest predictive accuracy among other models developed from soil structural properties. This model is solely based on mean weight diameter (MWD) which is one out of four soils structural properties (ASC, CDI and SSI) determined. A strong correlation between MWD and ‘D’(r = 0.71) had earlier been shown. The ‘B’ values in Table 7 shows that MWD^2 had multiplier effect on ‘D’ whereas MWD^3 had negative effect on ‘D’ in model 19. Therefore increasing MWD^3 by 1 will cause reduction in the value of ‘D’ by 12.56.

Table 6. Regression models relating Detachment energy index (D) ($J/Kg\times10^{-3}$) to physical properties of the soils

MODEL NUMBER	Regression equation	Coefficient of Determination (R^2)	Standardized Coefficient (B)	Associated cost per sample (NGN)
11	$D = 0.000011(WP)^2 + 1.88(BD)^2 - 0.001(WP) - 5.99(BD) + 4.84$	0.91	$WP^2 = 7.72$ $BD^2 = 0.1$ $WP = -0.18$ $BD = -8{,}43$	200
12	$D = 7.49 - 7.44(BD) - 0.019(P) - 0.004(MC) + 2.08(BD)^2$	0.94	$BD = -10.46$ $P = -1.008$ $MC = -2.68$ $BD^2 = 8{,}54$	300
13	$D = 0.091(SC)^3 - 0.5(SC) - 0.04(SC)^3 + 0.83$	0.48	$SC = -13.78$ $SC^2 = 45.27$ $SC^3 = -32.08$	150
14	$D = 0.003(C) + 0.194(P) + 6.87(BD) - 18.63$	0.59	$C = 0.20$ $P = 10.27$ $BD = 9.67$	300
15	$D = 0.0002(C) + 0.0002(Ksat) - 0.47(BD) + 0.824$	0.54	$BD = -0.66$ $C = 0.07$ $Ksat = 0.086$	350
16	$D = 8.3(BD) + 0.001(K_{sat}) + 0.23(P) - 22.44$	0.50	$BD = 11.67$ $Ksat = 0.24$ $P = 12.33$	350
17	$D = 6.43(BD) + 0.18(P) + 0.005(WP) + 0.02(MC) - 17.45$	0.54	$BD = 9.04$ $P = 9.55$ $WP = 0.16$ $MC = 0.15$	400
18	$D = 0.009(WP) + 0.0003(K_{sat}) - 0.07(MC)$	0.45	$MC = 0.51$ $WP = 0.25$ $Ksat = 0.045$	350

WP = Water content at wilting point, BD = Bulk density, MC = Moisture content, Ksat = Saturated hydraulic conductivity, SC = Sand/ clay, P = Porosity, C = Clay, NGN = Nigeria Naira (money)

Table 7. The regression models relating Detachment energy index (D) in $JKg^{-1} \times 10^{-3}$ to structural properties of soil

Model number	Regression equation	Coefficient of determination (R^2)	Standardized coefficient (B)	Associated cost per sample (NGN)
19	$D = -0.21(MWD)^3 + 1.06(MWD)^2 + 1.33(MWD) + 0.54$	0.82	MWD = 7.12 MWD^2 = 19.99 MWD^3 = – 12.56	200
20	$D = 0.031(MWD^2) - 0.005(ASC) - 0.11(CDI) + 0.20$	0.43	ASC = 0.11 CDI = 0.2 MWD = 0.59	350
21	$D = 0.07(CDI) + 0.031(MWD^2) - 0.001(SSI) + 0.13$	0.42	CDI = 0.126 MWD^2 = 0.59 SSI = – 0.019	350
22	$D = 0.32(WP) - 0.072(CDI) - 0.003(SSI) - 0.009(ASC) - 0.1$	0.53	CDI = – 0.13 SSI = – 0.12 ASC = – 0.19 MWD = 0.73	350
23	$D = 0.15(MWD) - 0.003(SSI) - 0.005(ASC) + 0.012$	0.52	SSI = – 0.13 ASC = – 0.122 MWD = 0.73	350

MWD = Mean weight diameter, ASC = Aggregate silt and clay, CDI = Clay dispersion index SSI = Soil structural index, NGN = Nigeria Naira (money)

Models Relating The Most Influential Soil Properties With 'D'

Models developed from the most influential physico-chemico-structural soil properties are shown in Table 8. Model 24 developed from water content at wilting point and mean weight diameter accounted for about 87 % ($R^2 = 0.865$) of the effect of variables on which 'D' was dependent (predictive accuracy). The model was most influenced by MWD^2 (B = 1.06), followed by WP (B = 0.61) whereas MWD^3 exerted a negative influence (B = – 0.47) on 'D'. Model 25 - developed from Ca, MWD and BD (chemico-physico-structural properties) indicated 91 % ($R^2 = 0.905$) predictive accuracy for 'D'. The effect of MWD (B = 0.49) was of the most positive influence of the three soil properties used to develop the model.

Criterion for Model Validation, Characterization of the Soils and Model Validation

Validation was performed on models with R^2 values ≥ 80% with data generated from 10 other soil samples as shown in Table 9. Table 10 shows that Model 2 predicted 'D' in 80 % of the other soil samples used as test soils with 97 % correlation between the predicted and measured 'D', model 11 and model 12 predicted 'D' in 70 %, Models 19 and 24 predicted 'D' in 60 % and 50 % of the test soils respectively while model 25 had the least prediction of 10 % for 'D'. Predicted 'D' for Models 2, 11 and 12 had a very strong correlation with measured 'D'(r = 0.97, 0.94 and 0.95 respectively), models 19 and 24 strongly correlated with measured 'D'(r = 0.76 and 0.65 respectively). In contrast, model 25 predicted 'D' weakly with 23 % correlation between the predicted and measured 'D'. The correlation between the predicted D (PD) and measured D (MD) for the respective models developed was not proportional to their coefficient of determination (R^2). Model 2 which predicted 'D' in the highest number of soils (80 %), had the lowest coefficient of determination ($r^2 = 0.80$) while model 25, with the least prediction of 'D' (10%) in the test soils, had a very high coefficient of determination ($R^2 = 0.91$). As R^2 values approach 1.0, it indicates that most of the soil properties on which 'D' is dependent have been captured in the model; this determines the predictive reliability of models. Model 2 predicted 'D' in soils of Irepodun, Moro and Ilorin with a precision of 100 % whereas it predicted 'D' with 50 % precision in soils of Ifelodun and Baruten. Model 11 predicted 'D' with 100 % precision in soils of Moro and Baruten and 50 % in soils of Ifelodun, Irepodun and Ilorin. Model 12 predicted 'D' with100 % precision in soils of Ifelodun, Moro, and Baruten and 50% in soils of Ilorin but failed to predict 'D' in soils of Irepodun. Model 19 predicted 'D' in 100 % of soils in Moro and Irepodun, 50 % in soils of Ifelodun and Ilorin, but failed to predict 'D' in soils of Baruten. Model 24 predicted 'D' in

100 % of soils in Ilorin, 50 % of soils in Ifelodun, Moro, and Irepodun and failed to predict 'D' in soils of Baruten. Model 25 only predicted 'D' in 50 % of soils from Moro. All the models predicted 'D' in at least 50 % of the soils from Moro.

Generally, the results in Table 10 show that the model based on physico-chemical properties (model 25) is a poor predictor of 'D' in the test soils, model based on physico-structural (model 24) and structural (model 19) properties are fair predictors of 'D', models based on physical properties (models 11 and 12) and chemical properties (model 2) were the best predictors of 'D'. However, between the models that best predicted 'D', the cost associated with model 2 was more than six times and four times higher than that of model 11 and 12 respectively. Therefore, based on associated cost, model 11 should be the choice model whereas based on versatility, it should be model 2.

Table 8. Models that relate the most influential soil properties to detachment energy (D)

Model number	Soil properties	Regression equation	Coefficient of determination (R^2)	Standardized Coefficient (B)	Associated cost per sample (NGN)
24	Physical and structural	$D = -0.034(MWD)^3 + 0.001(WP)^2 + 0,14 (MWD)^2 + 0.13$	0.87	$MWD^3 = -0.47$ $MWD^2 = 1.059$ $WP = 0.606$	300
25	Chemical, physical and structural	$D = 0.02(Ca) + 0.03(MWD^2) -0.07(BD^2) + 0.164$	0.91	$MWD^2 = 0.49$ $Ca = 0.325$ $BD^2 = -0.494$	450

MWD = mean weight diameter WP = wilting point, NGN = Nigeria Naira (money)

Table 9. Selected physico-chemical properties of soils of Kwara state used for model validation

Sample	Sand (%)	Silt (%)	Clay (%)	Texture	OM (%)	CEC (Cmol/Kg	pH
Ife 4	67.95	15.41	16.64	SL	0.81	68.75	8.6
Ife 5	68.18	17.76	14.063	SL	3.42	51.28	9.0
Moro4	75.14	12.95	11.91	SL	0.76	41.51	8.0
Moro5	70.71	13.31	15.98	SL	1.16	37.54	8.2
Ire4	85.31	6.30	8.39	LS	0.91	47.58	8.1
Ire 5	86.13	6.67	7.20	LS	1.03	54.52	8.3
Baru4	49.68	26.21	24.11	SCL	1.82	54.65	8.0
Baru5	60.50	17.96	21.55	SCL	1.38	45.49	8.3
ILN4	57.56	17.40	25.045	SCL	3.62	46.09	8.7
ILN5	86.72	7.41	5.87	LS	1.41	39.41	8.2

CEC= cation exchangeable capacity, OM= organic matter SL = sandy loam, LS = loamy sand, SCL = sandy clay loam Ire = irepodun, Ife = Ifelodun, Baru = Baruten and ILN = Ilorin

Table 10. Comparison between measured (md) and predicted (pd) aggregate detachment energy (d)

Sample Number	MD	Model predicted 'D' (PD) Model 2	Model 11	Model 12	Model 19	Model 24	Model 25
Ife 4	0.13	0.19	0.09*	0.09*	0.15*	0.04	0.51
Ife 5	0.05	0.06*	0.09	0.05*	0.23	0.08*	0.33
Moro4	0.13	0.17*	0.17*	0.18*	0.11*	0.06	010*
Moro5	0.07	0.06*	0.07*	0.06*	0.04*	0.04*	0.01
Ire4	0.13	0.13*	0.07	0.05	0.12*	0.31	0.43
Ire 5	0.54	0.54*	0.68*	0.76	0.54*	0.58*	0.40
Baru4	0.08	0.14	0.07*	0.06*	0.67	0.29	0.46
Baru5	0.09	0.08*	0.09*	0.1*	0.21	0.04	0.27
ILN4	0.19	0.14*	0.06	0.04	2.56	0.17*	1.16
ILN5	0.07	0.06*	0.11*	0.04*	0.04*	0.04*	0.13
PSP (%)		80	70	70	60	50	10
C		0.97	0.94	0.95	0.76	0.65	0.23

MD = Measured detachment energy; PSP = Per cent of soils predicted; C (MD & PD) = Correlation(r) between measured and predicted D

Discussion

Variation in the soil properties used to develop models may be attributable to differences in agricultural land-use practices (Ameyan and Ogidiolu, 1989). Ahamefule et al., (2020) also reported differences in water transmission characteristics of the experimental soils due to parent materials (basement complex and sandstone) and land-use.

The relatively low 'D' values observed for Irepodun soils suggest they will be the most vulnerable to water erosion. Moro soils with the narrowest range of 'D' indicate less variability suggesting similar agricultural practices and soil-forming processes across the community.

The strong positive correlation between Ca and 'D' is attributable to the reported bridging role played by Calcium in the soil (Chan and Heenan, 1999). Similarly, Wuddivira and Camps- Roach (2007) reported that increase in soil structural stability following liming of soils results from strong bonds formed from Ca^{2+} bridges. Calcium also inhibits clay dispersion and soil aggregate breakdown by substituting primarily Na^{+} and sometimes Mg^{2+} in clay aggregate (Wuddivira and Camps- Roach, 2006). Hanke and Dick, (2017) reported that all soil flocculating (Mg, K and Ca) and binding agents (OM) were positively related to 'D'. However, according to Wuddivira and Camps-Roach (2006), high calcium content in the soil (calcareous soils), with low organic matter, could cause soil degradation (hard, dense surface crust), in which Ca^{2+} could displace acidic cations (Al^{3+} and Fe^{2+}) whose loss contributes to soil disaggregation. In soils with high pH, the concentration of acidic cations is usually low (Idowu, 2003). This was the reason for this study's negative correlation between soil pH and 'D'. Acidic cations (Al^{3+} and Fe^{2+}) are known as soil stabilizing agents. Romken et al, (1977) reported that iron stabilized soil aggregates in the temperate region and suggested that it should be included in models for the prediction of potential erodibility of soils.

The negative influence of Na^{+} on the soil is due to its ability to disperse soil aggregates and accelerate their breakdown by impacting raindrops. Warrence et al, (2002) reported that Na^{+} caused soil dispersion, clay platelets, and aggregate swelling by disrupting the force that binds clay particles together when they come in- between clay particles and bring about separation that leads to swelling of clay particles and soil dispersion. Thus, sodium in the soil leads to soil aggregates breaking down.

The positive correlation between OM and 'D' corroborates the report of Mbagwu and Bazzoffi, (1998) and Idowu, (2003) that organic matter relates positively with 'D'. The organic carbon pool of the soil is unarguably the most significant component of the soil influencing soil structure (Bullock, 2005) by binding the soil particles into bigger and stable aggregates (Picolo and Mbagwu, 1999). However, the non-significant positive correlation between OM and 'D' could be attributable to the low content of the soil organic matter. For organic matter to significantly affect soil structure, it should make up about10 % of the overall soil (DeBoodt, 1985). The organic matter content in the studied soils ranges between 0.38 to 3.65% and, therefore, is not expected to significantly correlate with 'D'. In addition, the binding potential of organic matter could be suppressed by the high pH recorded in the study soils (7.6 - 9.0).

Soil with high pH has low concentration of $Fe^{2+}$and Al^{3+} which reduces the effect of organic carbon pool on soil structural stability. Mbagwu and Bazzoffi (1998) submitted that in soils where the concentration of Fe^{2+} and Al^{3+} is low, the effect of organic matter in such soils is usually suppressed. Organic matter comprises two components responsible for soil aggregation: polysaccharides and humic substances. The polysaccharides cement soil particles by acting as glue in-between soil particles (Cheshire and Hayes, 1990). In contrast, humic substances interact with metallic ions, oxides (Iron and Aluminum), and hydroxyl to form water stable aggregates (Oades, 1989).

Moderate correlation of K^{+} and Mg^{2+} with 'D' is due to their ability to reinforce soil aggregates by inducing clay flocculation (Levy and Torrento, 1995), in addition, Mg^{2+} also neutralizes the phenolic acids and clay-dispersing polycarboxyls produced during the decomposition of organic substances in the soil (Oades, 1990; Emerson, 1983). Weak correlation between CEC and 'D' might be due to hydration of the cations. Nweke and Ijeh (2017) observed that CEC had less influence on wet than dry aggregate stability.

The correlation between sand and clay with 'D' corroborates the results of Bruce-Okine and Lal (1975) and Mbagwu and Bazzoffi (1998) that soil erodibility varied directly with sand but inversely with clay. Schoonover and Crim (2015) suggested that particles of sand are relatively easy to detach due to a lack of cohesiveness, while clay particles are difficult to detach since they readily bond together. On the other hand, there has been discordant reports on the relationship between silt and 'D', Igwe et al, (1995) are among the authors that reported a positive correlation which is consistent with the findings of this study; nevertheless, it was reported that certain amount of clay, silt and very fine sand are needed for the formation of good soil aggregate (Norhayati and Verloo, 1984).

The observation that porosity was positively ($r = 0.73$) correlated to 'D' whereas bulk density was negatively (-0.73) correlated indicates that as porosity increases, particularly with increasing organic matter content, soil particles become less prone to detachment and transportation by runoff as more water sinks. However, the case is reversed when the soil bulk density increases. Idowu (2003) gave possible reasons for an inverse relationship between bulk density and 'D'. He posited that continuous soil tillage results in soil compaction (which increases bulk density) and low organic matter content, leading to low soil aggregate stability. Mbagwu and Bazzoffi (1998) however, reported a contrary finding in which aggregate stability correlated positively with bulk density and negatively with porosity.

The positive correlation of water content at wilting point with 'D' was similarly reported by Mbagwu and Bazzoffi (1998), the authors surmised that this may be attributable to the impact of clay in the soil. Muawia (2013) established that increasing clay content will increase the soil moisture content due to its affinity for water. These last two authors held that the impact of clay is more pronounced in dry soils than in moist soils. In addition, Idowu (2003) reported that due to its high affinity for water, organic matter also contributes to moisture content determination, especially air-dry moisture content. This background, therefore, reaffirms that high moisture content in the soil suggests high organic matter and/or clay content.

The strong positive correlation of MWD to 'D' is the leverage in their interchangeable use for estimating of soil aggregate stability. The non-significant correlation of ASC and CDI with 'D' is premised on the fact that for CDI and ASC to show a significant effect on 'D', maximal dispersion of soil is required; this may, however, not have been achieved due to the dominant impact of calcium (an anti-dispersant) in the study soils.

The inverse relationship observed between 'K' and 'D' had earlier been reported by De Vleeschauwer et al., (1978) and Mbagwu, (1993), the authors had reported that 'D' could be used to evaluate soil susceptibility to erosion. Soil erodibility (K) explains the intrinsic susceptibility of a soil to breakdown by erosive raindrops and runoff, and it is the inverse of 'D'.

The presence of bulk density in most models (particularly model 11 and 12) relating soil physical properties to 'D' highlights the importance of bulk density in the predicting aggregate stability. Some reports indicate that an increase in the bulk density of the soil result in the sealing of the soil's surface which give rise to low infiltration leading to surface runoff and soil loss (Towhid, 2013).

Models with R^2 values ≥ 80 % were chosen for validation to ensure high precision in the models that would be subsequently recommended. However, Mbagwu and Bazzoffi (1998) had earlier chosen models with R^2 values ≥ 75 % for validation.

The fairly wide variation in the soil properties that was used for the development (Table 2) and validation (Table 9) of models 2, 11 and 12 and their good prediction of 'D' suggest: (1) that they may find applicability in similar soils where similar data is available and (2) that they may also be applied in a wide variety of other soils with similar intrinsic properties. In the same vein, the high multiple of soil properties associated with past models for predicting 'D', which made such models cumbersome, has been drastically reduced in the models derived in this study. This feat reduces time and financial inputs/resources needed, making these models deployable during economic booms and lean (post COVID-19). Be that as it may, these models will need re-validation across a range of other soils since the models were developed from a correlation and regression approach. These approaches adopted for this study may not guarantee similar levels of prediction in other soils when the values obtained for their properties do not fall within the range used for the models here-in developed.

Conclusions

This study concludes that: (1) the detachment energy of the soils of Kwara state, Nigeria (a typical Guinea Savanna soil) is low which predisposes soils of this area to erosion. (2) The Ca content of the study soils is the most critical soil property which determines ‘D’ (3) Based on associated cost, model 11 should be the model of choice, suitable for the predominantly peasant and resource poor farming population in the study area. In contrast, based on versatility, it should be model 2, which gives comparatively better prediction across all the study locations (4) All the models (beyond 2, 11 and 12) tested were at least fairly suitable for predicting ‘D’ in soils of Moro (5) The most important physico-structural soil properties relating to the prediction of ‘D’ mean weight diameter and bulk density, and (6) The models developed can also be used to determine potential erosion risk of other similar soils, particularly those in the southern Guinea agro-ecological zone of Nigeria.

Conflict of Interest Statement

Authors declare no conflict of interest

Authors Contribution

The authors contributed equally

References

Ahamefule HE, Umar MB, Adepoju AS, Amana MS, Wahab AA, Ukelina CU., 2020. Response of soil water transmission properties to three land-use systems in soils of contrasting origin in Ilorin, Nigeria. Bulgarian Journal Soil Science Agrochemistry and Ecology, 54(3): 15-27.

Ahamefule HE, Peter PC., 2014. Cowpea (Vignaunguiculata L. Walp.) response to phosphorus fertilizer under two tillage and mulch treatments. Soil and Tillage Research, 136: 70-75.

Ameyan O, Ogidiolu O., 1989. Agricultural landuse and soil degradation in a part of Kwara State, Nigeria. Environmentalist, 9: 285-290. https://doi.org/10.1007/BF02241829.

Anderson JM, Ingram JSI (Eds)., 1993. Tropical Soil Biology and Fertility Handbook of Methods (2nd edt.). CAB International, Wallington, UK.

Barry PV, Stott EE, Turco RR, Bradford JM., 1991. Organic polymers' effect on soil shear strength and detachment by single raindrops. Soil Science Society of America Journal, 55: 799-804.

Beare MH, Hendrix PR, Coleman DC., 1994. Water-stable aggregate and organic matter fractions in conventional and no-tillage soils. Soil Science Society of American Journal, 58: 777-786.

Blake GR, Hartage KH., 1986. In: methods of Soil analysis, part 1, Klute A. (Ed). Monograph No.9. American Society of Agronomy, Madison, Wisconsin, 363-375.

Bouwer H., 1986. Intake rate: cylinder infiltrometer. In Methods of soil analysis, part I. Physical and mineralogical methods. Agronomy Monograph no. 9 (2nd edition.). American Society of Agronomy, Soil Science Society of America.

Bouyoucos GJ., 1932. Hydrometer method for making particle size analysis of soils. Soil Science Society of America Proceedings, 26, 464-465.

Bray RH, Kurtz LT., 1945. Determination of total organic and available forms of phosphorus in soils. Soil Science Society of American Journal, 59: 39-45.

Bremner JM., 1996. Nitrogen-total. In: Sparks, D. L. (Ed.), Methods of Soil Analysis. Chemical Methods, Part 3. 2nd edition. Soil Science Society Of America, JournaL Book Series No. 5, ASA and Soil Science Society of America, Madison, WI, USA, pp. 1085 –1121.

Brown LR, Wolf EC., 1984. Soil erosion: Quiet Crisis in the World Economy. Worldwatch Paper 60.

Bruce-Okine E, Lal R., 1975. Soil erodibility as determined by a raindrop technique. Soil Science, 119: 149-159.

Buringh P, Dudal R., 1987. Agricultural land use in space and time. In: Wolman, M.G., Fournier, F.G.A. Eds., Land Transformation in Agriculture. SCOPE 32, Wiley, Chichester, pp. 9 – 43.

Canton Y, Sole-Benet A, Asensio C, Chamizo S, Puigdefabregas J., 2009. Aggregate stability in range sandy loam soils relationship with runoff and erosion. Catena, 77: 192-199.

Chan K, Heenan D., 1999. Microbial-induced soil aggregate stability under different crop rotations. Biology and Fertility of Soils, 30(1-2): 29-32. doi: 10.1007/s003740050583

Cheshire MV, Hayes MHB., 1990. Composition, origins, structures, and reactivities of soil polysaccharides. In: DeBoodt MF., Hayes MHB., Herbillon A., De Strooper EBA., Tuck

J.J. (Eds.) Soil Colloids and Their Associations in Aggregates.NATO ASI Series (SeriesB:Physics). Springer,214:4899-2611-1_11.https://doi.org/10.1007/978-1-

Cruse RM, Larson WE., 1977. Effect of soil shear strength on soil detachment due to raindrop impact. Soil Science Society of America Journal, 41: 777–781.

De Vleeschauwer D, Lal R, DeBoodt M., 1978. Comparison of detachability Zindices in relation to soil erodibility for some important Nigerian soils. Pedologie, 28: 5–20.

DeBoodt M., 1985. Principal factors in soil structure formation. Paper presented at College on Soil Physics, Trieste, Italy, 15 April – 3 May, 1985, pp. 39.

Dong A, Chester A, Simsiman GV., 1983. Soil dispersibility. Soil Science, 136: 208 – 212.

Eaton D., 1996. The economics of soil erosion: A model of farm decision-making. Environmental Economics Programme Discussion Paper 96-01. IIED, London.

Emerson WW., 1983. Inter-particle bonding in soils: an Australian viewpoint. Division of Soil CSIRO, Melbourne/Academic Press, London, pp. 477-498.

Food and Agriculture Organization., 2013. The State of Food and Agriculture. Food systems for better nutrition.

Hamblin AP, Davies DB., 1977. Influence of organic constituents and complexed metal ions on aggregate stability of some East Anglian soils. Soil Science Journal 28: 410-416.

Hanke D, Dick PD., 2017. Aggregate stability in soil with humic and histic horizons in atoposequence under Araucaria forest. Revista Brasileira Ciencia, 41: e0160369.

Harris RF, Chesters G, Allen ON., 1966. Dynamics of soil aggregation. In: N.C. Brady Ed., Advances in Agronomy. Academic Press, New York, NY 18, pp. 107 – 169.

Idowu OJ., 2003. Relationships between aggregate stability and selected soil properties in humid tropical environment. Communications in Soil Science and Plant Analysis, 34(5-6): 695-708.

Igwe CA, Zarei M, and Stahr K., 1995. Stability of aggregates of some weathered soils in south-eastern Nigeria in relation to their geochemical properties. Journal of earth system science, 122(5), 1283 – 1294.

Imeson AC, Vis M., 1984. Assessing soil aggregates stability by water-drop impact and ultrasonic dispersion. Geoderma, 34: 185-200.

Kemper DW , Rosenau RC., 1986. Aggregate stability and aggregate size distribution. In: Klute, A. Methods of soil Analysis part 1. ASA-SSSA, Madison, pp425 – 442.

Kinnell PA., 2005. Raindrop impact induced erosion processes and prediction: A review. Hydrological Processes, 19: 2815-2844.

Lal R., 1990. Soil erosion in the tropics: Principles and management. New York: McGraw-Hill.

Lal R., 1994. Soil erosion by wind and water: Problems and prospects. In “Soil Erosion Research Methods” (R. Lal, Ed.),. Soil Water Conservation Society, American. pp. 1-9.

Levy GJ, Torrento JR., 1995. Clay dispersion and macroaggregate stability as affected by exchangeable potassium and sodium. Soil Science, 160(5): 352-358.

Low AJ., 1954. The study of soil structure in the field and in the laboratory. Journal of Soil Science. 5: 57-74.

Lynch JM, Bragg E., 1985. Microorganisms and soil aggregate stability. Advances in Soil Science, 2: 133-171.

Mbagwu JSC., 1993. Testing the fit of selected infiltration models on soils with different land use histories. Internal report No IC/93/290, International Centre for Theoretical Physics Trieste, Italy.

Mbagwu J, Bazzoffi P., 1998. Soil characteristics related to resistance of breakdown of dry soil aggregates by water-drops. Soil and Tillage Research, 45(1-2): 133-145.

Mbagwu JSC., 1986. Erodibility of soils formed on a catenary toposequence in south-eastern Nigeria as evaluated by different indices. East African Agricultural and Forestry Journal, 52: 74-80.

Mbagwu JSC., 1989. Specific dispersion energy of soil aggregates in relation to field and laboratory measured stability indices and physical properties. East African Agricultural and Forestry Journal 54: 173-183.

McCalla,TM., 1944. Water drop method of determining stability of soil structure. Soil Sci. 58, 117–123.

Meyer LD., 1981. How rain intensity affects interrill erosion. Transactions of the American Society of Agricultural Engineers 24, 1472–1475.

Meyer LD, Foster GR, Nikolov S., 1975. Effect of flow rate and canopy on rill erosion. Transactions of the American Society of Agricultural Engineers, 18(5): 905-911.

Middleton HE., 1930. Properties of soils which influence soil erosion. USDA Technical Bulletin., 178

Nearing MA, Bradford JM, Parker SC., 1986. Soil detachment by shallow flow at low slopes. Soil Science Society of America Journal, 55(2): 339-344.

Nearing MA, Bradford JM., 1985. Single waterdrop splash detachment and mechanical properties of soils. Soil Science Society American Journal, 49: 547-552.

Nearing MA, Bradford JM., 1986. Measurement of force versus waterdrop impact. Soil Science Society of America Journal 50: 1532-1536.

Nearing MA, Bradford JM., 1987. Relationships between waterdrop properties and forces of impact. Soil Science Society of America Journal, 51: 547-530.

Nelson DW, Sommers LE., 1982. Total carbon, organic carbon and organic matter. In Methods of Soil Analysis, Part 3. 2nd edn, 961-1010. (Ed. D. L. Sparks) Soil Science Society of America Journal, Book Series No. 5, Soil Science Society of America, Journal, Madison, Wi., USA.

Nweke IA, Ijeh AC., 2017. Relationship between aggregate stability ındices of four contrasting textural classes of soils as ınfluenced by different periods of soaking. Greener Journal of Soil Science and Plant Nutrition, 4(4): 036-045.

Norhayati M, Verloo M., 1984. Characterization of organic matter in four soils of peninsular Malaysia. I. Extraction, fractionation and purification of humic substances. Journal of Rubber Resource Institute of Malaysia, 32: 30-39.

Oades JM., 1989. An introduction to organic matter in mineral soils. In Minerals in Soil Environments, 2nd Ed.; Dixon, J.B., Weed, S.B., Eds.; Soil Science Society of America: Madison, WI,; 89 – 159.

Oades JM., 1990. Association of colloids in soil aggregates. In: M.F. De Boodt, M.H.B. Hayes, A. Hambillon (Eds.), Soil colloids and their associations in aggregates. NATO. AI Series. Ser. B. Phys., Vol. 215. Plenum Press, New York, pp.463 – 483.

Olanrewaju RM., 2009. The climate effect of urbanization in a city of developing country: The case study of Ilorin, Kwara State, Nigeria. Ethiopian Jounal of Environmental Studies and Management, 2(2):67 - 72. DOI:10.4314/EJESM.V2I2.45921

Oldeman LR, Hakkeling RTA, Sombroek WG., 1991.World map of the status of human- ınduced soil degradation: An explanatory note. UNEP and ISRIC, Wageningen.

Oyegun RO.,1982. Water resources in Kwara State. Matanmi and Sons printing and publishing Co. Ltd. Ilorin. 113p.

Piccolo A, Mbagwu J., 1999. Effects of humic substances and surfactants on the stability of soil aggregates. Soil Science, 147(1): 47-54. doi: 10.1097/00010694-198901000-00008

Pimental D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267: 1117-1123.

Pimentel D., 2006. Soil erosion: a food and environmental threat. Environment, Development and Sustainability, 8(1): 119-137.

Pimentel D, Pimentel M., 2000. To improve nutrition for the world’s population. Science, 288: 1966-1967.

Ramos MC, Nacci S, Pla I., 2003. Effect of raindrop impact and its relationship with aggregate stability to different disaggregation forces. Catena, 53(4): 365-376.

Romkens MJM, Roth CB, Nelson DW., 1977. Erodibility of selected clay subsoils in relation to physical ¨ and chemical properties. Soil Science Society American Journal. 41: 954-960.

Schoonover JE, Crim JF., 2015.An introduction to soil concepts and the role of soils in watershed management. Journal of Contemporary Water Ressearch and Education. 154(1): 1-27.

Telles TS, Guimaraes MD, Dechen SC., 2011. The cost of soil erosion. Revista Brasileira Ciencia Solo. 35(2): 287-298.

Torri D, Sflanga M, Del Sett M., 1987. Splash detachment: runoff depth and soil erosion. Catena, 14: 149-155.

Towid K Osman., 2013. Soils: Principles, Properties and Management. Springer. Pp 65.

Truman CC, JM Bradford, Ferris JE., 1990. Antecedent water content and rainfall energy influence on soil aggregate breakdown. Soil Science Society of America Journal, 54: 1385-1392.

Warrence NJ, Bauder JW, Pearson KE., 2002. Basics of salinity and sodicity effects on soil physical properties. Departement of Land Resources and Environmental Sciences, Montana State University-Bozeman, MT, 1-29.

Wischmeier WH, Smith DD., 1971 Predicting rainfall erosion losses: A guide to Conservation Planning.Washington DC: US Department of Agriculture Hand Book 537 US Government Printer Office.

Wuddivira M, Camps-Roach G., 2006. Effects of organic matter and calcium on soil structural stability. European Journal of Soil Science, 58(3): 722-727. doi: 10.1111/j.1365-2389.2006.00861.x

Wuddivira MN, Stone RJ, Ekwue EI., 2009. Clay, organic matter and wetting effects on splash detachment and aggregate breakdown under intense rainfall. Soil Science Society of America Journal, 73: 226-232.

Wustamidin Douglas LA., 1985. Aggregate breakdown in relation to raindrop energy. Soil Science, 139: 239-242.

Wustamidin Douglas LA, Cummings DJ, Leslie TI., 1983. Comparison of the water-drop energy required to breakdown aggregates and soil loss caused by simulated rainfall. Soil Science, 136: 367-370.

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Doğu Anadolu Bölgesinden Toplanan *Achillea wilhelmsii* K. Koch Türünün Uçucu Bileşiklerinin GC-MS Analizi

Azize DEMİRPOLAT[1*], Pelin YILMAZ SANCAR[2]

[1]Department of Crop and Animal Production, Vocational School of Food, Agriculture and Livestock, Bingol University, Bingol, Türkiye
[2]Department of Biology, Faculty of Science, Fırat University, Elazığ, Türkiye

[1]https://orcid.org/0000-0001-7192-185X
[2]https://orcid.org/0000-0002-6134-622X
*Corresponding author: ademirpolat@bingol.edu.tr

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ÖZ

Bu çalışma, Türkiye'nin Bingöl yöresinde doğal olarak yetişen *Achillea wilhelmsii* K. Koch bitkisinin çiçekli üst kısımlarından elde edilen uçucu yağ bileşenlerini incelemeyi amaçlamaktadır. GC-MS analizleri sonucunda toplam 31 farklı bileşik tespit edilmiş; bunlar arasında özellikle kamfor (%48,2), 3-siklohekzen-1-ol (%14,2), borneol (%10,3) ve 1,8-sineol (%6,6) öne çıkmıştır. Elde edilen bu veriler, daha önce İran ve Türkiye'de yapılan benzer çalışmalarla genel anlamda örtüşmektedir. Ancak 3-siklohekzen-1-ol'ün bu denli yüksek oranda bulunması, Bingöl bölgesine özgü olabilecek yeni bir kemotipin varlığını düşündürmektedir. Bu bulgu, çevresel koşullar ve uygulanan yöntemlerin uçucu yağ bileşimi üzerindeki etkisini net biçimde ortaya koymakta; ayrıca bölgesel botanik araştırmaların önemini bir kez daha gözler önüne sermektedir.

GC-MS Analysis of the Volatile Compounds in *Achillea wilhelmsii* K. Koch Collected from Eastern Anatolia

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ABSTRACT

This study aims to analyze the essential oil composition of *Achillea wilhelmsii* K. Koch, collected from the Bingöl region of Turkey, using the GC-MS method. A total of 31 different compounds were identified, with camphor (48.2%), 3-cyclohexen-1-ol (14.2%), borneol (10.3%), and 1,8-cineole (6.6%) being the most abundant. These results are largely consistent with previous findings from Iran and Turkey; however, the notably high proportion of 3-cyclohexen-1-ol suggests a potentially unique chemotype specific to the Bingöl region. The study highlights the impact of environmental and methodological factors on essential oil profiles and underscores the importance of region-specific research.

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1. Introduction

The genus *Achillea* (Asteraceae), comprising between 110 to 140 species globally, predominantly originates from Southeast Europe and Southwest Asia, extending further across Eurasia into North America. In Turkey, this genus is represented by 48 species, classified under 54 distinct taxa, with 24 recognized as endemic to the region (Arabacı, 2012; Baser, 2016). This plant commonly thrives on dry slopes, plains, and steppe ecosystems, especially across Central Anatolia. It typically enters its flowering phase during July and August (Davis, 1972).

Members of the *Achillea* genus are widely acknowledged for their medicinal value worldwide. Their significance spans from traditional herbal practices to evidence-based modern phytotherapy. The essential oils, primarily concentrated in the flowers, constitute the key pharmacologically active constituents. However, the biosynthesis and concentration of these essential oils are modulated by a range of biotic and abiotic factors. As such, both interspecific and intraspecific chemical variations are influenced by morphogenetic development stages and the chosen method of extraction. Despite their longstanding role in folk medicine, *Achillea* species have broader applications—most notably, their blossoms and flowering tops are frequently used in the preparation of herbal teas with nutritional and therapeutic benefits (Kindlovits and Németh, 2012).

Species of *Achillea*, commonly known as "yarrow," have long been used in traditional folk medicine due to their numerous medicinal properties. Today, their therapeutic applications including wound healing, spasmolytic, anti-inflammatory, and cholinergic effects are increasingly supported by scientific research findings. In Turkey, various species of the genus are traditionally used to treat wounds, ulcers, the common cold, diarrhea, abdominal pain, and to relieve gastrointestinal gas (Turkmenoglu et al., 2015).

Achillea wilhelmsii C. Koch contains a variety of compounds, including flavonoids, alkaloids, borneol, and cineole. Traditionally, this plant has been used as a remedy for relieving stomach pain, fatigue, neurological disorder symptoms, and epilepsy. Moreover, the aerial parts of *A. wilhelmsii* possess antioxidant properties. Additionally, flavonoids have been reported to exhibit phosphodiesterase type 5 inhibitory (PDE5I) activity (Saravani et al., 2017).

The main bioactive components that contribute to the pharmacological actions of the plant are essential oils. The present study aims to characterize the essential oil profile of *Achillea wilhelmsii* and to evaluate the findings in comparison with existing literature data.

2.Material and Method

2.1. Sample of Plant

A. Demirpolat identified *Achillea wilhelmsii* (AD1007) K. Koch. using Flora of Turkey after the plant sample was dried using the herbarium process (Davis, 1972). *Achillea wilhelmsii* was obtained from Bingöl, Genç in July.

2.2. Essential Oil Extraction

Using a 2 L round-bottom flask and a modified Clevenger equipment, the essential oil was extracted by hydrodistillation. One liter of water and 100 grams of fresh plant material (aerial portions) were utilized in the extraction process. The Plant Products and Biotechnology Res. Lab. was where the chemical analysis was carried out. The extraction process took three hours to complete. The dry mass was used as the foundation for calculating the oil yields.

2.3. Analysis of Gas Chromatography (GC)

The HP 6890 GC with FID detector and an HP-5 MS capillary column (30 m x 0.25 mm I.d., film thickness 0.25 μm) were used to analyze the essential oil. As stated below, the column and analytical conditions were identical to those in the GC-MS. GC-FID peak regions were used to calculate the essential oils % composition without the use of correction factors.

2.4. Analysis of Gas Chromatography/Mass Spectrometry (GC-MS)

Hewlett Packard Gas Chromatography HP 6890 interfaced with Hewlett Packard 5973 mass spectrometer equipment with an HP 5-MS capillary column (30 m x 0.25mm id, film thickness 0.25 μm) was used to undertake GC-MS studies of the oils. The oven was set to operate between 70 and 240^0 at a rate of 5 degrees Celsius per minute. The electron ionization was set at 70 eV and the ion source was tuned at $24C^o$. The carrier gas, helium, was employed at a flow rate of 1 mL/min. 35 to 425 amu was the scanning range. The GC-MS was filled with 1.0 μL of diluted oil in n-hexane. Their mass spectra were compared to those from the NIST 98 Libraries (on ChemStation HP) and Wiley 7th Version in order to further identify them. Without the use of correction factors, the relative amounts of each component were determined using the GC peak area (HP5MS column). Table 1 lists the components of the essential oils that have been identified. Retention indices (RI) were determined by injecting a homologous series of *n*-alkanes (C8–C30) under identical GC–MS operating conditions. RI values were calculated according to the Van den Dool and Kratz method and compared with literature data and mass spectral libraries (NIST and Wiley) for compound identification.

Table 1. Essential oil components of *Achillea wilhelmsii*

No	Compound Name	Retention Index	Percentage (%)
1.	Tricyclene	1013	0,5
2.	α-Pinene	1021	1,5
3.	Camphene	1035	**7,9**
4.	Sabinene	1051	0,4
5.	β-Pinene	1055	1,1
6.	α-Terpinene	1085	0,3
7.	Benzene-1-methyl	1091	1,4
8.	Limonene	1094	0,5
9.	1,8-Cineole (Eucalyptol)	1098	**6,6**
10.	γ-Terpinene	1116	0,4
11.	trans-Sabinene Hydrate	1126	0,3
12.	α-Terpinolene	1136	0,2
13.	Camphor	1184	**48,2**
14.	Borneol	1201	**10,3**
15.	3-Cyclohexen-1-ol	1205	**14,2**
16.	Ethanone	1226	0,1
17.	Carveol	1230	0,2
18.	cis-Carveol	1240	0,4
19.	Endobornyl Acetate	1281	0,1
20.	Thymol	1286	0,2
21.	Eugenol	1339	0,1
22.	cis-Jasmone	1371	0,1
23.	trans-Caryophyllene	1392	0,2
24.	Aromadendrene	1420	0,2
25.	Naphthalene	1429	0,2
26.	β-Ionone	1432	0,1
27.	Germacrene D	1434	0,7
28.	Bicyclogermacrene	1444	0,5
29.	Spathulenol	1494	0,4
30.	Caryophyllene Oxide	1497	0,6
31.	α-Cadinol	1531	0,4
		% TOTAL	**98.3**

Results and Discussion

Using the GC–MS method, the essential oil composition of the flowering aerial portions of *Achillea wilhelmsii* K. Koch was examined in this study, oil yield %0.4 and 31 distinct components were identified based on a single analytical measurement. The predominant constituents were camphor (48.2%), 3-cyclohexen-1-ol (14.2%), borneol (10.3%), and 1,8-cineole (6.6%), respectively (Table 1). These findings are largely consistent with previous results obtained from *A. wilhelmsii* samples collected in Iran and Turkey (Motavalizadehkakhky et al., 2013; Salehi et al., 2025). The essential oil was predominantly composed of oxygenated monoterpenes (66.3%), followed by monoterpene hydrocarbons (12.8%), whereas sesquiterpenes were present only in minor proportions. This compositional pattern clearly indicates a camphor-rich oxygenated monoterpene chemotype (Table 2).

Table 2. Percentage Distribution of Chemical Classes Identified in the Essential Oil of *Achillea wilhelmsii*

Chemical Class	Number of Compounds	Percentage (%)
Monoterpene hydrocarbons	9	12.8
Oxygenated monoterpenes	8	66.3
Sesquiterpene hydrocarbons	4	1.6
Oxygenated sesquiterpenes	3	1.4
Other compounds*	7	16.2
Total identified	**31**	**98.3**

Rustaiyan et al. (1999) reported camphor (38.1%), borneol (14.5%), and 1,8-cineole (9.8%) as dominant constituents in *A. wilhelmsii* essential oil collected from northern Iran. Similarly, in a study by Sefidkon et al. (2002), camphor (42.3%) and 1,8-cineole (7.4%) were identified as primary components, supporting the current findings regarding chemotype dominance. Motavalizadehkakhky et al. (2013) analyzed oils from Iranian populations and observed lower levels of camphor (25.7%) but higher proportions of thujone and artemisia ketone, suggesting possible intraspecific chemical polymorphism.

Camphor, in particular, is one of the most common monoterpene ketones found in this species and is known for its local anesthetic, anti-inflammatory, and antimicrobial properties (Ertaş et al., 2014). Other major compounds such as borneol and 1,8-cineole have also been reported to exhibit expectorant and antiseptic effects in respiratory tract infections. The presence of flavonoid derivatives pharmacologically supports the traditional use of the plant in the treatment of stomach pain and neurological disorders (Ayoobi et al., 2017).

Several studies have highlighted how environmental influences might affect the composition of essential oils. Baser (2016) and Kindlovits and Németh (2012) have reported that geographic origin, harvesting time, and the distillation process significantly influence essential oil composition. In this context, the high camphor content observed in the sample collected from the Bingöl region highlights the chemotypic diversity of this species. The essential oil composition obtained in the present study shows similarities with previously reported *Achillea wilhelmsii* populations collected from different regions of Turkey, where camphor and 1,8-cineole were identified as dominant constituents (Baser, 2016; Tosun and Kürkçüoğlu, 2018). The essential oil composition of *Achillea wilhelmsii* obtained in the present study demonstrated notable similarities as well as quantitative differences when compared with previously reported Turkish populations. Earlier investigations conducted on *A. wilhelmsii* collected from different regions of Turkey revealed camphor, 1,8-cineole, borneol, and oxygenated monoterpenes as dominant constituents of the essential oil. Similar compositional patterns have been reported particularly for Central Anatolian populations, where camphor was identified as the major component, followed by 1,8-cineole and related monoterpenoids (Baser, 2016; Tosun and Kürkçüoğlu, 2018).

Furthermore, differences in extraction procedures, harvesting period, and analytical parameters may also contribute to quantitative discrepancies among studies. The observed compositional variation therefore supports the existence of regional chemotypes within Turkish *A. wilhelmsii* populations. These findings highlight the importance of local population-based analyses for evaluating the phytochemical diversity and potential pharmacological applications of this species.

One particularly striking result from this study is the high concentration of 3-cyclohexen-1-ol (14.2%), which stands out because such elevated levels of this compound have not been consistently reported in earlier research. This unusual abundance may reflect the presence of a distinct local chemotype, possibly unique to the Bingöl region of Turkey.

Conclusion

In general, the dominance of borneol and camphor remains in line with findings from previous studies, reinforcing their role as key constituents in *Achillea wilhelmsii*. However, the noticeable differences in the amounts of other components clearly demonstrate how environmental factors and methodological choices can influence the essential oil profile of the plant. These findings underscore the importance of regional studies in capturing the chemical diversity within a species.

Conflict of Interest

The authors declare no conflict of interest.

Authors' Contributions

The authors declare that they have contributed equally to the article

References

Arabacı T., 2012. *Achillea L.* Editörler: Güner A., Aslan S., Ekim T., Vural M., Babaç M.T., Türkiye Bitkileri Listesi (Damarlı Bitkiler), Sayfa: 108–112, Nezahat Gökyiğit Botanik Bahçesi ve Flora Araştırmaları Derneği Yayını, İstanbul.

Ayoobi F, Shamsizadeh A, Fatemi I, Vakilian A, Allahtavakoli M, Hassanshahi G, Moghadam-Ahmadi A., 2017. Bio-effectiveness of the main flavonoids of *Achillea millefolium* in the pathophysiology of neurodegenerative disorders-A review. Iranian Journal of Basic Medical Sciences, 20(6): 604.

Başer KHC., 2016. Essential oils of *Achillea* species of Turkey. Natural Volatiles and Essential Oils, 3(1): 1–14.

Davis PH., 1972. Flora of Turkey and the East Aegean Islands. Edinburgh University Press, 7(52), Edinburgh.

Ertaş A, Boğa M, Haşimi N, Yeşil Y, Gören AC, Topçu G, Kolak U., 2014. Antioxidant, anticholinesterase, and antimicrobial activities and fatty acid constituents of Achillea cappadocica Hausskn. et Bornm. Turkish Journal of Chemistry, 38(4): 592–599.

Kindlovits S, Németh E., 2012. Sources of variability of yarrow (Achillea spp.) essential oil. Acta Alimentaria, 41(1): 92–103.

Motavalizadehkakhky A, Shafaghat A, Zamani HA, Akhlaghi H, Mohammadhosseini M, Mehrzad J, Ebrahimi Z., 2013. Compositions and the in vitro antimicrobial activities of the essential oils and extracts of two Achillea species from Iran. Journal of Medicinal Plants Research, 7(19): 1280–1292.

Rustaiyan A, Mojab F., 1999. The composition of the essential oil of Achillea tenuifolia Lam. from Iran. Iranian Journal of Chemistry and Chemical Engineering, 18(2): 108-110.

Salehi M, Kalvandi R., 2025. Report of a new chemotype from Achillea santolinoides subsp. wilhelmsii (K. Koch) Greuter. Journal of Essential Oil Research, 37(6): 506–514.

Tosun, F, Kürkçüoğlu M., 2018. The essential oils of two Achillea L. Species from Turkey. Acta Pharmaceutica Sciencia, 56(2): 59-66.

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Rainwater Harvesting Design and Optimization in Semi-Arid Mediterranean Climates: A Technical Review with Focus on Türkiye

Tevfik Denizhan MUFTUOGLU[1*]

[1]Istanbul Aydin University, Engineering Faculty, Civil Engineering (English) Department, Kucukcekmece, Istanbul

[1]https://orcid.org/0000-0001-5836-3689
*Corresponding author: tmuftuoglu@aydin.edu.tr

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ABSTRACT

A comprehensive technical review of current literature regarding rainwater harvesting (RWH) systems in terms of design, feasibility and optimization in Türkiye and similar Mediterranean climates is presented here in. Research has been conducted through a peer-reviewed study process (2010-2026). It was created to provide hydraulic engineers with design specifications and sizing methodologies for use in urban settings. The results indicated that for optimal residential tank size in Türkiye would be dependent upon several factors including roof area (30-270 m^2), rainfall (292-1180 mm/year), and demand profile, but generally ranged from 2-21 m^3. Particle Swarm Optimization and Linear Programming were identified as the most effective sizing methods to achieve 90-98 % volumetric reliability while minimizing the total lifecycle cost. Potential water savings resulting from implementation of an RWH system range from 20-70 % of domestic water usage, which could result in discounted payback times ranging from 12-36 years based on the configuration of the RWH system and local water pricing structures. The review also emphasized the importance of hydrologic models, filtration requirements and optimization techniques for designing RWH systems in semi-arid Mediterranean climates.

Yarı Kurak Akdeniz İklimlerinde Yağmur Suyu Hasadı Tasarımı ve Optimizasyonu: Türkiye Odaklı Teknik Bir Derleme

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Yağmur suyu hasadı
Tasarım optimizasyonu
Depo boyutlandırma
Hidrolojik modelleme
Yarı kurak iklim

ÖZ

Bu çalışma, Türkiye ve benzeri Akdeniz iklimlerinde tasarım, fizibilite ve optimizasyon açısından Yağmur Suyu Hasadı (YSH) sistemlerine ilişkin mevcut literatürün kapsamlı bir teknik incelemesini sunmaktadır. Araştırma, 2010-2026 yılları arasındaki hakemli çalışmaların incelenmesi süreciyle yürütülmüştür. Çalışma, hidrolik mühendislerine kentsel alanlarda kullanım için tasarım kriterleri ve boyutlandırma yöntemleri sağlamak amacıyla oluşturulmuştur. Sonuçlar, Türkiye'deki optimum konut depo boyutunun çatı alanı (30-270 m^2), yağış miktarı (292-1180 mm/yıl) ve talep profili gibi çeşitli faktörlere bağlı olduğunu, ancak genellikle 2-21 m^3 arasında değiştiğini göstermiştir. Parçacık Sürü Optimizasyonu ve Doğrusal Programlama, toplam yaşam döngüsü maliyetini en aza indirirken %90-98 hacimsel güvenilirliğe ulaşmak için en etkili boyutlandırma yöntemleri olarak belirlenmiştir. Bir YSH sisteminin uygulanmasıyla elde edilecek potansiyel su tasarrufu, evsel su kullanımının %20-70'i arasında değişmektedir; bu durum, sistem konfigürasyonuna ve yerel su fiyatlandırma yapılarına bağlı olarak 12-36 yıl arasında değişen iskontolu geri ödeme süreleri ile sonuçlanabilmektedir. İnceleme ayrıca, yarı kurak Akdeniz iklimlerinde YSH sistemleri tasarlarken hidrolojik modellerin, filtrasyon gereksinimlerinin ve optimizasyon tekniklerinin önemini vurgulamıştır.

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Introduction

Rainwater Harvesting (RWH) is an important strategy for managing water resources in both Türkiye and throughout the Mediterranean region that are experiencing water shortages due to the impacts of population growth, urbanization, and seasonally varying climate conditions along with increased tourist activities. The semi-arid climate in Türkiye (characterized by variable precipitation, high rainfall during winter months, low rainfall during summer months), provides both opportunities and challenges for designing and implementing RWH systems. As part of this technical review, evidence based guidelines for designing and optimizing RWH systems in Turkish and comparable Mediterranean climates have been compiled by combining methodologies used for engineering design, optimization algorithms and design parameters that were reported in 189 peer reviewed studies.

The use of new optimization techniques-such as linear programming, particle swarm optimization, and stochastic simulations — have made recent improvements to the accuracy of tank size selection and systems configuration decisions (Okoye et al., 2015; Saplioglu et al., 2019). The above computational tools have enabled water engineering professionals to simultaneously optimize several conflicting goals: maximize the reliability of the water supply, minimize both the cost of construction and operation of a water system, and maximize the utilization of available storage in tanks under uncertain rainfall conditions (Russo et al., 2019; Okoye et al., 2015)

The main goal of this review is to combine the current body of technical knowledge relating to: (1) storage tank size optimization methods; (2) hydrologic model types used for arid environments; (3) component specification and hydraulic design criteria; (4) evaluation metrics and reliability analysis; and (5) economic viability framework options. The emphasis of the review will be on numerical design parameters; optimization algorithms that use mathematics; and performance based on empirical data available for residential and small scale urban rainwater harvesting (RWH) systems (Okoye et al., 2015; Ruso et al., 2024).

Material and Methods

Search Strategy and Data Collection

To provide transparent and replicable results, this systematic review followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), and thus, all the searches were done according to the PRISMA guidelines. A detailed literature search was executed on three main databases of science; Scopus, Web of Science, and Google Scholar. The research time frame included articles that were available from January 1st, 2010 through January 31st, 2026. The search strategy used a combination of the following terms and Boolean operators: ("Rainwater Harvesting" or "RWH") and ("Optimization" or "Tank Sizing" or "Design Parameters") and ("Turkey", “Türkiye”, "Mediterranean Climate", "Semi-Arid").

Inclusion and Exclusion Criteria

To ensure the technical quality of the review, the identified records were subjected to a two-stage screening process based on titles, abstracts, and full texts.

Inclusion Criteria: (1) Peer-reviewed journal articles and conference proceedings published in English or Turkish; (2) Studies providing quantitative data on tank sizing, water saving potential, or economic feasibility; (3) Research specifically focusing on residential or small-scale urban applications in semi-arid Mediterranean climates.

Exclusion Criteria: (1) Studies lacking technical design parameters (e.g., papers focusing solely on social acceptance without engineering data); (2) Duplicate records; (3) Review articles that did not contribute original data or synthesis relevant to the specific region.

From an initial identification of 189 records, 30 studies met all criteria and were selected for detailed analysis. These studies were categorized based on their primary focus: hydrological modeling, optimization algorithms, and economic assessment. Figure 1 illustrates the PRISMA flow diagram for the study selection process.

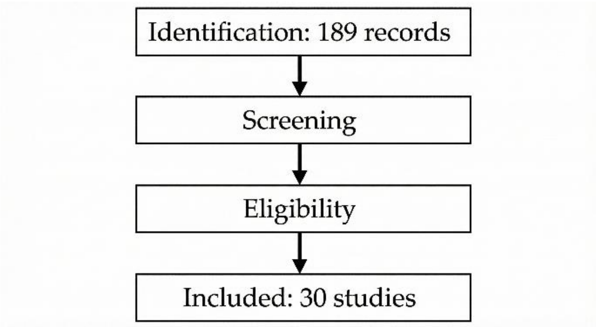

Figure 1. PRISMA flow diagram illustrating the literature selection and screening process.

Hydrological Context and Climate Characteristics

The hydrologic regime in Türkiye has a large degree of spatial and temporal variability. Annual rainfall varies significantly from 292 mm in semi-arid regions located in the interior of Türkiye to 548 mm in coastal Mediterranean regions (Ruso et al., 2019; Abdulla, 2020). A geographic representation of the diverse climates studied in this review can be seen in Figure 2.

Figure 2. Geographical distribution of the selected rainwater harvesting case studies evaluated in this review (highlighting Ankara, Antalya, Aydın, Burdur, Isparta, İzmir, Karabük, and Northern Cyprus).

The Mediterranean climate pattern creates an extreme challenge in designing a Rainwater Harvesting System (RWH); it is characterized as having 60-75 % of total annual rainfall occurring over the six-month period from november through march with a very defined or pronounced drought period during the summer months (Campisano and Modica, 2012; Muklada et al., 2016). Due to the extremely high amount of precipitation that falls during these winter months there needs to be a significantly larger storage capacity to fill the reservoirs prior to the start of the long dry season while at the same time avoid an excess of water overflowing into flood control areas when the rainy weather returns (Campisano and Modica, 2012; Okoye et al., 2015).

A comparative analysis using data from other arid and semi-arid areas in the Mediterranean region shows similar hydrologic limitations to those found in Türkiye. Jordan is another example of a semi-arid Mediterranean country which gets about 200-400 mm of rainfall annually. Also it gets a very large portion of its annual rainfall during the rainy season. Due to the similarities with the other semi-arid mediterranean regions of this study, we will be able to evaluate the effects of droughts on water supplies in Türkiye using data from these areas (Jaradat et al., 2024; Abdulla, 2020). In addition to Jordan, Sicily is also a semi-arid mediterranean coastal area receiving between 400-600 mm of rainfall annually with a similar distribution of rainfall during the winter as Türkiye (Campisano and Modica, 2012; Notaro et al., 2017). Therefore, Sicily provides another valuable analog for designing water resources management systems in Türkiye. Lastly, the northern part of Cyprus, which receives 292-350 mm of rain per year, is the most directly analogous area to evaluate semi-arid coastal conditions in Türkiye (Ruso et al., 2019).

The variable amount of rain that falls each day makes it even harder to determine what size of a system is needed. In analyzing stochastic rainfall in the Mediterranean area, researchers have found that there are large amounts of variability in the rainfall (coefficient of variation greater than 1.5) over a short time period (daily), as well as large amounts of rainfall occurring on the majority of rain days (70-85 %) and very little total rainfall for the year coming from the extreme rainfall events (>50 mm/day) that occur occasionally (Muklada et al., 2016). The variability of rainfall over a short time period necessitates a design approach that includes probability and does not include a design approach based solely on the average rainfall (Muklada et al., 2016; Snir et al., 2021).

System Design Methodologies and Optimization Approaches

Linear Programming Methods

Okoye et al. (2015) stated that the use of Linear Programming (LP) was the most effective and efficient method to date to optimize RWH tank sizes for semi-arid regions. LP is also discussed by Ruso et al. (2024). LP provides a method of optimizing tank sizes through the optimization process which will provide the lowest total system cost while meeting the reliability criteria of the RWH system.

A basic LP model was developed by Okoye et al. (2015) in order to develop an optimized RWH tank size for Türkiye. In this model, the authors used a time-step based approach using daily water balance equations. Decision variables are represented by the volume of the tank, the amount of water flowing over the top of the tank, and the amount of water supplied from the tank when it is empty. The objective function in the model represents the minimum cost associated with both the capital costs (construction, conveyance, filtration) and the operational costs over a 20-30 year design life.

Okoye et al. (2015) noted that the LP model included several critical constraints including: (1) continuity of the daily water balance, (2) maximum capacity of the tank, (3) non-negative storage, and (4) minimum reliability thresholds of 90-95 %.

The LP model was successfully applied to several Turkish case studies and demonstrated that there are significant benefits compared to traditional design methods for determining tank sizes. For example, in a residential analysis conducted by Okoye et al. (2015) on a single family dwelling in Ankara (150 m^2 roof area, 120 L/day demand), the authors determined the optimum tank size to be 8 m^3 with a volumetric reliability of 94 %. This compares to the 12 m^3 tank recommended by traditional design methods. Therefore, the authors concluded that the LP model resulted in a solution that was 33 % less expensive than the traditional design without any compromise in reliability. Additionally, Ruso et al. (2019; 2024) have demonstrated the effectiveness of LP models in determining optimal tank sizes for Northern Cyprus, as they have shown that reliability levels of 90-98 % can be achieved using storage tanks that are 20-40 % smaller than those determined using traditional design methods.

Stochastic and Simulation-Based Approaches

Stochastic modelling is used to capture uncertainty in rainfall through the application of probabilistic representations of the rainfall processes (Snir et al., 2021; Muklada et al., 2016); this permits reliability studies for a variety of climates (Snir et al., 2021; Muklada et al., 2016). To maintain the spatial detail of historical precipitation data while retaining the key features of precipitation, many stochastic models employ Markov Chain Monte Carlo (MCMC) techniques to generate synthetic rainfall sequences which possess historical statistical characteristics of precipitation such as the probability of occurrence of precipitation on a given day, the distribution of precipitation intensities and the temporal autocorrelation of precipitation.

The stochastic water balance model is developed by combining the MCMC rainfall generator with the daily mass balance equation to simulate the long term behavior of the system over thousands of simulations. Thus, reliability metrics including both volumetric and time-based reliability are expressed as probability distributions, and therefore provide confidence intervals for engineering design decisions. For example, Muklada et al. (2016) showed that deterministic designs based on average rainfall in the Mediterranean climate, tend to be conservative by approximately 15-25 percent compared to stochastic approaches with the same reliability target.

The use of a continuous simulation model, using historical rainfall records with at least daily time step resolution and/or sub-daily time step resolution, provides an alternative to the traditional method of generating synthetic rainfall scenarios (Jenkins, 2007). Jenkins (2007) demonstrates that the use of a continuous simulation model, in conjunction with the use of 30+ years of rainfall data, is able to provide reliable estimates of storage size requirements for tanks located within Australia's climatic zones; these are similar to those found in the Mediterranean climates of Türkiye. The study further illustrates that since continuous simulation includes all forms of natural rainfall variability including extremes such as extended durations of dryness and heavy storms, it eliminates the need to make any form of distributional assumption concerning the occurrence of precipitation.

Metaheuristic Optimization Algorithms

It was established that the particle swarm optimization (PSO) methodology can effectively identify the optimum tank sizes for the rainwater harvesting systems; especially where the goal is to find an optimal solution among multiple conflicting goals and nonlinear cost relations (Saplioglu et al., 2019). In order to do so, the PSO methodology uses a population-based search process that simulates the collective behavior of birds to provide near-optimal tank size configurations across the entire solution space. It was also established by Saplioglu et al. (2019), that PSO is very successful in finding solutions to nonlinear objective functions that exist within the problem (such as the economy of scale that exists with construction cost, or the threshold value that defines reliability metrics); such as they were able to determine the optimum tank size combination along with the appropriate first flush diversion and pump specifications in their case study of university buildings in Türkiye using a population based search process with 50-100 iterations that would result in a minimum total cost with a reliability level of at least 95 % for the water supply. Additionally, it was reported by the authors that a comparison of the lifecycle costs obtained using the PSO methodology versus those obtained using linear programming (LP) demonstrated that the inclusion of nonlinear cost factors would result in a reduction in lifecycle costs of 8-12 %.

The authors of Soh et al. (2023) emphasized that the application of multi-objective optimization frameworks allows the ability to address explicitly the multiple objectives that are often present in many engineering applications (for instance, minimizing cost while maximizing reliability, or minimizing flood damage while maximizing water savings).

Additionally, the authors emphasized that the results of the Pareto frontier analysis illustrated a collection of non-dominant options that represent the best possible design options that will allow engineers to select the most suitable option(s) for different stakeholders and localized conditions. Therefore, the results of this research demonstrate how multi-objective optimization can be utilized to develop optimum tank volume configurations for dual-purpose RWH systems by identifying the tank volume configuration that optimizes the trade-off between the amount of water saved and the height of the stormwater flood.

Water Balance Models

The fundamental water balance equation governs all RWH system sizing methodologies, relating storage volume to inflows (rainfall), outflows (demand, overflow, losses), and storage state over time (Campisano and Modica, 2012; Okoye et al., 2015). The daily water balance formulation is expressed as:

$$S(t) = S(t-1) + Q(t) - D(t) - O(t) - L(t) \quad (1)$$

where S(t) is storage volume at time t, Q(t) is harvested rainfall inflow, D(t) is water demand supplied from storage, O(t) is overflow, and L(t) represents losses (evaporation, leakage) (Campisano and Modica, 2012; Okoye et al., 2015). Boundary conditions include: $S(t) \geq 0$ (non-negative storage), $S(t) \leq V$ (tank capacity constraint), and $D(t) \leq \min[S(t-1) + Q(t), Demand(t)]$ (supply limited by availability) (Okoye et al., 2015).

Harvested rainfall Q(t) is calculated as:

$$Q(t) = P(t) \; x \; A \; x \; \eta \quad (2)$$

where P(t) is daily precipitation depth, A is effective catchment area, and η is the runoff coefficient accounting for losses during collection (Campisano and Modica, 2012; Müftüoğlu, 2024). Runoff coefficients for Turkish roof types range from 0.75-0.85 for tile roofs to 0.85-0.95 for concrete and metal roofs (Müftüoğlu, 2024). First-flush diversion typically removes the initial 1-2 mm of rainfall to improve water quality, effectively reducing η by 5-10 % (Müftüoğlu, 2024).

Behavioral simulation models implement the water balance equation over multi-year time series to evaluate system performance under historical or synthetic rainfall sequences (Jenkins, 2007). The yield-after-spillage (YAS) operating rule—where demand is met from storage before overflow occurs—represents the standard operating policy for domestic RWH systems (Jenkins, 2007). Alternative operating rules, such as yield-before-spillage or controlled release for flood mitigation, require modified water balance formulations (Soh et al., 2023).

Storage Tank Sizing: Technical Parameters and Design Criteria

Optimal Tank Volumes for Turkish Applications

The empirical study of optimal storage tank sizes through the use of examples from Türkiye has demonstrated that the three main variables have an empirical relationship as follows: the size of the roof catchment area, the total amount of annual rainfall in the catchment area and the total amount of water used on a daily basis (Okoye et al., 2015; Ruso et al., 2019; Müftüoğlu, 2024). For residential application in the semi-arid regions of Türkiye (annual rainfall of 300-400 mm), the most suitable volume of tanks ranges between 2-8 m^3 for one family houses (roof area ranging from 100-150 m^2, water consumption ranging from 100-150 L/day) and between 15-25 m^3 for multi-family dwellings (roof area ranging from 300-500 m^2, water consumption ranging from 400-600 L/day) (Okoye et al., 2015; Ruso et al., 2019).

Specific case studies provide quantitative design benchmarks:

- Ankara residential building (150 m^2 roof, 120 L/day demand, 415 mm annual rainfall): Optimal tank size 8 m^3, achieving 94 % volumetric reliability and 45 % water savings (Okoye et al., 2015).
- Northern Cyprus villa (180 m^2 roof, 150 L/day demand, 292 mm annual rainfall): Optimal tank size 12 m^3, achieving 90 % reliability and 38 % water savings (Ruso et al., 2019).
- Aydın detached house (120 m^2 roof, 100 L/day demand, 548 mm annual rainfall): Optimal tank size 6 m^3, achieving 96 % reliability and 52 % water savings (Müftüoğlu, 2024).
- Antalya residential complex (450 m^2 roof, 500 L/day demand, 1180 mm annual rainfall): Optimal tank size 21 m^3, achieving 98 % reliability and 68 % water savings (Himat and Dogan, 2023).

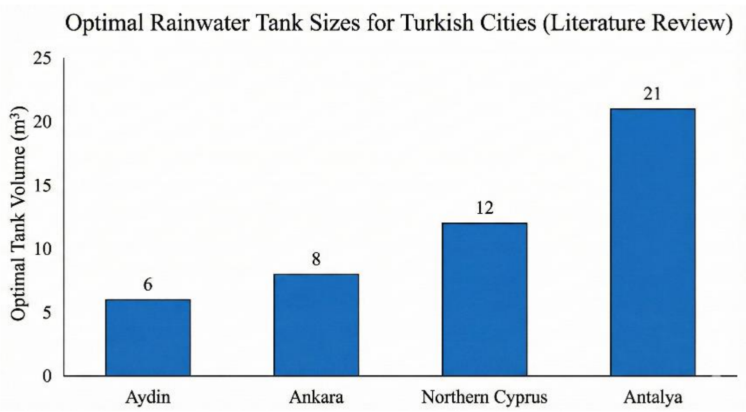

Figure 3. Comparison of optimal storage tank volumes derived from various case studies in Türkiye and Northern Cyprus.

Tank volume and reliability have a decreasing relationship as tank size exceeds an optimal tank volume that is usually around 60 – 70 percent of the average annual harvestable rainfall (Campisano and Modica, 2012; Okoye et al., 2015). Beyond the optimal tank size, there is little increase in reliability from additional tank volume, but there will be a large increase in the cost of the tank (Okoye et al., 2015). For semi-arid climates like those in Türkiye, the optimal tank volume corresponds to approximately 5 – 8 cubic meters of tank storage for a typical residential application (Okoye et al., 2015; Müftüoğlu, 2024).

Sizing Methods Comparison

In a comparative study of the performance of different tank sizing methodologies it has been found that there are significant differences in the way that different methodologies perform (Okoye et al. 2015; Campisano and Modica, 2012). Both linear programming (LP) and particle swarm optimization (PSO) have shown to be more cost-effective and reliable than traditional heuristics such as the demand-fraction methodology, rainfall-fraction methodology and empirical rule based methodologies (Saplioglu et al., 2019; Okoye et al., 2015).

The demand-fraction methodology is based on the idea of using a constant fraction (usually 5-10 %) of the annual demand to determine the required storage volume. This approach will typically result in tanks being over-sized in areas of high rainfall and under-sized in arid areas (Okoye et al., 2015). In comparison to the optimized tank sizes generated from LP methodologies, tank sizes determined by the demand-fraction methodology were found to be 25-40 % larger for Türkiye based applications (Okoye et al., 2015), although they provided comparable levels of system reliability.

Although the rainfall-fraction methodology provides more accurate results in semi-arid conditions than either the demand-fraction methodology or empirical rule based methodologies, it lacks explicit consideration of economics when determining tank sizes (Campisano and Modica, 2012).

As the use of behavioural simulation methodologies can provide the greatest level of detail regarding how a system will operate, as it evaluates the performance of the system under the full range of historical rainfall events (Jenkins, 2007); however, the use of simulation alone cannot identify the optimum tank size without the use of optimization algorithms (Jenkins, 2007).

Therefore, the best practice currently available for designing engineered systems is to combine the use of LP or PSO methodologies for optimization with the use of behavioural simulation methodologies to verify performance (Saplioglu et al. 2019; Okoye et al. 2015).

Reliability and Efficiency Metrics

Reliability in terms of volume is the principal way to measure the performance of RWH systems, which is represented as a percentage of all total demand met by harvesting rainwater during a specific time frame (Campisano and Modica, 2012; Okoye et al., 2015). Reliability of volume in residential applications in Türkiye, for example, can be anywhere from 90-95 percent depending on how much money the owner is willing to spend to save water (Okoye et al., 2015; Ruso et al., 2019). Reliability targets greater than 95 percent require that the tank be significantly larger than those with reliability targets less than 95 percent and this requires an increase in costs that diminishes with each additional percent of reliability (Okoye et al., 2015).

The reliability of time represents the ability of the system to provide water every day (Muklada et al., 2016) and, as such, it provides another piece of information regarding the continuity of supply (Muklada et al., 2016). Due to the fact that there are only two possible outcomes when determining if the system provided enough water on any given day (i.e. yes or no), the reliability of time is always less than the reliability of volume (typically 70-85 percent vs. 90-95 percent) (Muklada et al., 2016). Therefore, while volumetric reliability may be adequate for many applications (residential buildings), time reliability may be the limiting factor in designing RWH systems for applications where continuous supply of water is required (e.g. commercial buildings) (Muklada et al., 2016).

Efficiency of the system is the amount of water that was delivered divided by the total amount of rainwater collected, and it measures how well the storage has been utilized (Campisano and Modica, 2012). RWH systems that have been properly sized for semi-arid climate conditions should be able to operate at an efficiency level ranging from 60-75 percent (Campisano and Modica, 2012) . The losses of water through the system occur primarily due to overflow (15-25 %), first flush diversion (5-10 %), and evaporation or leakage (3-5 %) (Campisano and Modica, 2012; Müftüoğlu, 2024).

Generally speaking, as the size of the tank increases so does the loss of water due to overflow, thus creating a trade-off between the reliability of the system and the overall use of resources (Campisano and Modica, 2012).

Catchment System Design and Hydraulic Components

Roof Catchment Areas and Runoff Coefficients

The size of a rooftop's catchment area is the most important factor determining how much rainwater can be collected from it. The amount of effective space available on the roof is determined by the horizontal surface area of the roof. Single family home rooftops in Türkiye typically measure 80-150 square meters while those of multiple family homes are typically larger and can reach 200-500 square meters (Okoye et al., 2015; Müftüoğlu, 2024).

Turkish roof runoff coefficient values include: Galvanized Iron Sheets (0.90); Tile Roofs (0.75); Concrete Surfaces (0.70). In comparison to the other two types of surfaces evaluated, tile roofing generated more collectible water than did concrete roofing given the same precipitation amounts due to its runoff coefficient being greater than that of concrete surfaces (Müftüoğlu, 2024).

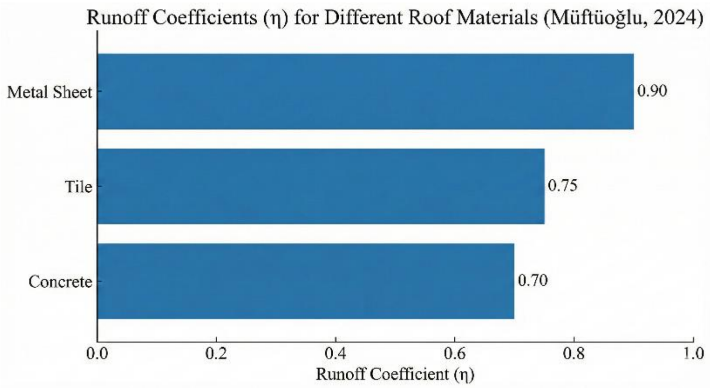

Figure 4. Runoff coefficients for common roof materials in Turkish residential buildings (adapted from Müftüoğlu, 2024).

Filtration and First-Flush Systems

The main purpose of the First-Flush Diversion Systems is to remove the first rainfall volume that has the greatest amount of contaminants from rooftops (Müftüoğlu, 2024). In terms of design recommendations for Türkiye, the author suggests using a diversion volume of 1 – 2 mm (1 – 2 L/m²) of storage that would be equivalent to 100 – 200 L of storage for the average residential roof area.

For filtration, Müftüoğlu (2024) recommends a standard multi-step process including: (1) coarse screen filter (1 – 2 mm mesh) at the inlet of the gutters; (2) finer filtration (0.2 – 0.5 mm mesh) before the water enters the tank; and (3) if applicable, disinfection for potable use. It is noted by the study that for the majority of non-potable uses of harvested rainwater (i.e., flushing toilets or irrigation), only the first two steps will be necessary. However, while pressure filtration systems (pore sizes 5 – 20 μm) can provide higher quality water than gravity fed systems, they also require more energy and maintenance. Therefore, according to Müftüoğlu (2024), gravity fed systems with 0.5 mm mesh screens provide the best cost effective and practical solution for residential rainwater harvesting in Türkiye. This is because they meet the required water quality standards while providing the simplest form of operation.

Conveyance and Pumping Systems

According to Müftüoğlu (2024), for a conveyance piping system designed to support the peak inflow rate into a water storage tank; however, it should be sized to provide sufficient head loss reduction that minimizes costs of installing piping; and at the same time, the sizing process should take into consideration the safety requirements of the piping system. For residential use, a common approach is to select PVC or HDPE pipe sizes ranging from 75 to 100 mm in diameter. Additionally, as an aid to the maintenance of clean conditions throughout the piping system, a slope of 1 to 2 percent is suggested to assure that the self-cleaning velocity of the fluid flowing through the system exceeds 0.6 m/s, which will preclude sediment from collecting in the system.

As for the pump design criteria, the system design needs to account for two types of head that need to be addressed: the static head, which includes the tank depth plus the height that the system needs to deliver water to the point of application, plus the dynamic losses due to friction and other fittings that the system encounters. In most cases for residential installations that have total heads ranging from 3 to 5 meters, a centrifugal type pump that has a rated horsepower of 0.5 to 1.0 kW and a flow capacity of 30 to 50 liters per minute will suffice. Additionally, using variable speed pumps with pressure sensors allow the system to operate on-demand, which reduces energy usage by about 20-30 % when compared to fixed speed systems; however, the variable speed pump can also contribute to maintaining pressure stability and extend the service life of the equipment (Müftüoğlu, 2024).

Dual supply systems require an automated switch control system to provide continuous supply to users once the rainwater in the storage tank is depleted (Judeh et al., 2022). The most common methods used to detect low levels of storage are float switches or pressure sensors that automatically turn on the municipal backup supply. Importantly, backflow prevention devices, i.e. air gaps or check valves, must be installed in dual supply systems to prevent cross-contamination of the municipal water distribution network and to meet all public health standards.

Performance Analysis and Water Savings Potential

The range of potential water savings from rainwater harvesting in Türkiye is estimated to be between 20-70 % of total domestic use based upon the size of the collection system, amount of rainfall collected and demand patterns (Okoye et al., 2015; Ruso et al., 2019; Abdulla, 2020; Müftüoğlu, 2024) for non-potable uses, such as flushing toilets, washing clothes, and irrigating plants which typically comprise 40-50 % of all residential demand (Okoye et al., 2015;

Müftüoğlu, 2024); thus properly designed systems can reduce total demand by 60-90 % in Mediterranean climate types (Okoye et al., 2015; Müftüoğlu, 2024).

Water savings from rainwater harvesting systems show significant variability over time. Typically, between November-March, rainwater harvesting systems will produce water savings of about 80-95% of total demand. However, due to the limited amount of rainfall available during this period, the production of water savings drops significantly during the dry summer months (June-September) and may only account for about 10-30 % of total demand (Ruso et al., 2019; Müftüoğlu, 2024). Thus, despite the ability of rainwater harvesting systems to provide water savings during certain times of the year, these systems continue to rely heavily on municipal supplies to meet base load demand during the dry summer months (Ruso et al., 2019).

In addition to providing water savings at specific points in time, rainwater harvesting systems also provide an opportunity to conserve potable water. In particular, for those households or commercial/industrial users with a high demand for water during the hot and dry summer months, such as for irrigation, rainwater harvesting systems have the potential to provide the largest portion of their water needs during the cooler and wetter months (Müftüoğlu, 2024). This results in a temporal mismatch between water availability and demand.

In terms of comparative analyses of rainwater harvesting system effectiveness across different parts of Türkiye, it has been found that there exists a significant correlation between the level of rainfall received each year and the amount of water savings achieved through rainwater harvesting systems (Ruso et al., 2019; Abdulla, 2020; Müftüoğlu, 2024). Specifically, for coastal areas of Türkiye with annual rainfall levels above 800 mm, moderate storage tank sizes of 8-12 m^3 can provide sufficient water savings to meet 60-70 % of non-potable household demand (Himat and Dogan, 2023). On the other hand, interior regions of Türkiye, such as the semi-arid regions, receive much lower levels of rainfall, averaging around 300-400 mm per year. As a result, even large storage tanks of 12-18 m^3 can only provide water savings of 30-45 % (Okoye et al., 2015; Ruso et al., 2019).

Based on these findings, it appears that rainwater harvesting systems are most economically viable for regions of Türkiye with annual rainfall levels greater than 500 mm (Campisano and Modica, 2012; Abdulla, 2020).

In terms of maximizing the efficiency of rainwater harvesting systems, effective demand management is essential. By prioritizing the use of rainwater harvested water for low-quality uses, such as toilet flushing and irrigation, rather than high-quality uses, such as drinking and cooking, the amount of water saved can be maximized, while minimizing the amount of treatment required to make the water safe for reuse (Judeh et al., 2022). Additionally, smart control systems that continuously monitor the current state of the water system and adjust the allocation of stored water to meet changing demands can provide additional water savings of up to 10-15% over simple priority-based allocation strategies (Behzadian et al., 2018).

Economic Feasibility and Lifecycle Cost Analysis

Residential Rain Water Harvesting Systems in Türkiye have three main factors influencing their long term economic viability - the cost of the initial investment (capital) for the system; the annual cost for municipal supplied water; and the anticipated service life of the system (Abdulla, 2020; Himat and Dogan, 2023; Okoye et al., 2015). There are many variables to consider when evaluating the costs of a residential Rain Water Harvesting System, including the cost of the storage tank(s), pump(s), treatment unit(s), piping, other components, and the cost of installation (Okoye et al., 2015; Himat and Dogan, 2023). The cost of each component of a residential Rain Water Harvesting System is typically dependent upon the storage capacity of the tank(s), as well as the design/manufacture of the system (Okoye et al., 2015; Himat and Dogan, 2023). For instance, the cost of a residential Rain Water Harvesting System, depending on storage capacity, ranges from $800 to $1,500 per cubic meter (Okoye et al., 2015; Himat and Dogan, 2023). A residential Rain Water Harvesting System having 8 cubic meters of storage capacity would thus cost anywhere from $6,400 to $12,000 (Okoye et al., 2015; Himat and Dogan, 2023), with the storage tank itself accounting for 50 % to 60 % of the cost of the entire system (Okoye et al., 2015; Himat and Dogan, 2023).

The costs associated with operating a residential Rain Water Harvesting System include the cost of pumping the collected water into the storage tank(s), estimated to be in the order of $20-$40 annually (Himat and Dogan, 2023); the cost of performing routine maintenance tasks associated with maintaining the operation of the system, estimated to be in the order of $50-$100 annually (Himat and Dogan, 2023); and the cost of replacing various components of the system over its 25-year service life (Himat and Dogan, 2023). Overall, during its 25-year service life, the cost of operating the system represents approximately 15 % to 25 % of the overall cost of owning and operating a residential Rain Water Harvesting System (Himat and Dogan, 2023), demonstrating that the majority of the cost of owning and operating a residential Rain Water Harvesting System relates to the purchase of the system and the ongoing costs of maintaining it.

Residential rainwater harvesting systems are typically evaluated for their economic viability based on discounted cash flow models utilizing discount rates of 5 % and 8 %, typical of those utilized when evaluating the economic feasibility of residential water infrastructure in

Türkiye (Himat and Dogan, 2023). Utilizing the above stated assumptions, the estimated simple pay-back periods for residential rainwater harvesting systems in Türkiye are estimated to be between 12 – 36 years, with the primary factor influencing the payback period being the local water tariff rates and the size of the system (Okoye et al., 2015; Abdulla, 2020; Himat and Dogan, 2023).

Systems located in coastal regions of Türkiye, such as Antalya, have the potential for achieving shorter simple payback periods (12 – 15 years), due to higher municipal water rates and larger annual rainfall (approximately 1180 mm/year) (Himat and Dogan, 2023).

Semi-arid inland areas of Türkiye have low municipal water tariffs ($0.80 – 1.20/m^3), resulting in long simple payback periods (25 – 35 years) for rainwater harvesting systems, often exceeding the expected life span of the system (Okoye et al., 2015; Ruso et al., 2019).

Net Present Value (NPV) calculations that account for the time value of money demonstrate that residential rainwater harvesting systems are economically viable (NPV > 0) only in those areas of Türkiye receiving high levels of rainfall, and where the municipal water tariff exceeds approximately $1.50/m^3 (Himat and Dogan, 2023). For many of the inland areas of Türkiye, the current municipal water tariffs result in a negative NPV calculation, implying that either an increase in water tariffs, a decrease in capital costs for the systems, or a combination of both and/or some form of incentive provided by government policies would need to occur to render the systems economically viable (Okoye et al., 2015; Himat and Dogan, 2023).

The sensitivity analyses indicate that the water price is the most significant variable affecting the economic viability of the systems. A 50 % increase in the water tariff reduces the simple payback period by approximately 30 – 40 % (Himat and Dogan, 2023). The cost of the storage tank is the next most significant variable affecting the economic viability of the systems, with a 30 % decrease in the cost of the storage tank potentially attainable through economies of scale, or through innovations in materials used for the storage tanks, improving the NPV by 25 – 35 % (Himat and Dogan, 2023). The impact of rainfall variability on the economic viability of residential rainwater harvesting systems is relatively small compared to the effects of water price and storage tank cost. For example, a 20 % increase or decrease in annual rainfall results in a 10 – 15% change in NPV values (Himat and Dogan, 2023).

Comparative Analysis: Mediterranean and Semi-Arid Regions

Comparative evaluation of rainwater harvesting performance in Mediterranean and semi-arid regions indicates common design practices regardless of regional differences in rainfall and demand patterns (Notaro et al. 2017; Campisano and Modica, 2012; Abdulla, 2020; Jaradat et al., 2024). The similarity in practices suggests that well-developed design heuristics can be adopted by other regions with similar climates if they account for their specific local rainfall distributions and demand profiles.

A case study conducted in Sicily demonstrates that optimal residential tank size is in the order of 6-12 cubic meters per dwelling, which is in line with recommendations published for the case of Türkiye (Notaro et al., 2017; Campisano and Modica, 2012). The agreement in optimal tank size supports the application of Mediterranean based design criteria to rainwater harvesting systems in Türkiye.

However, Jordan exhibits more pronounced aridity (rainfall 200-400mm/year), hence it is necessary to provide larger storage tanks (in the order of 10-18 cubic meters) to ensure comparable reliability to that of Mediterranean regions (Jaradat et al., 2024; Abdulla, 2020). The increase in storage tank size is related to the decrease in rainfall and increase in rainfall variability between years.

The ratio of the optimal tank volume to the annual amount of harvestable rainfall has been suggested as a dimensionless design parameter enabling cross-regional comparisons of system sizing (Campisano and Modica, 2012). For Mediterranean regions the ratio of the optimal tank volume to the annual amount of harvestable rainfall is in the order of 0.15-0.25 (Campisano and Modica, 2012; Notaro et al., 2017); therefore the corresponding optimal storage tank corresponds to approximately 15-25 % of the annual harvestable rainfall (Campisano and Modica, 2012; Notaro et al., 2017). In drier areas such as Jordan and the dry parts of Türkiye, the ratio is in the order of 0.25-0.35 because there is a greater concentration of rainfall in time and space and also due to the higher rainfall variability between years (Jaradat et al., 2024; Abdulla, 2020).

Reliability – cost trade-off relationships have similar properties for all Mediterranean climates; where the marginal cost of providing additional reliability is large when the volumetric reliability is higher than 90 – 95 % (Campisano and Modica, 2012; Notaro et al., 2017). Therefore the reliability – cost relationship suggests that a target reliability range of 90 – 95 % would represent an economical optimum for the design of residential rainwater harvesting systems in Mediterranean climates; thus balancing the benefits of water savings against the costs of capital investments (Campisano and Modica, 2012).

Only in cases of extreme water prices (> $2.50 /m³) or severe supply restrictions as those experienced in some arid areas (Abdulla, 2020), will reliability levels above 95 % be economically justifiable.

Projections of climate change for the Mediterranean region indicate increased rainfall variability and longer drought periods resulting in reduced reliability of rainwater harvesting systems by around 10 – 20 % by 2050 according to moderate emission scenarios (Jaradat et al., 2024). This projected trend implies that systems designed solely using past climate data could potentially perform poorly over the coming decades and therefore may require either increased storage volumes or a willingness to accept lower reliability levels (Jaradat et al., 2024).

Optimization methods that take into consideration climate uncertainty have been proposed to identify tank sizes that maintain reasonable performance levels over a range of potential future climate scenarios (Soh et al., 2023).

Synthesis of Optimization Methodologies and Economic Viability

Although the hydrological inputs are influenced by similar geographical conditions, the review finds a significant distinction in design methodology approaches. The advanced optimization techniques such as linear programming (LP), particle swarm optimization (PSO), have been shown to produce superior results compared to the heuristics (i.e. demand fraction), with an 8-12 % reduction in lifecycle cost and at least 90 % level of reliability (Saplioglu et al., 2019; Okoye et al., 2015). Nevertheless, the economic viability of these optimized systems in Turkey depends largely upon the price municipalities charge for water. Literature indicates that it will require a tariff of approximately $1.50/m³ for the system to be financially viable without subsidizing (Himat and Dogan, 2023). Below this tariff rate, the payback period can extend up to 25 years or longer, which makes residential rainwater harvesting (RWH) technically efficient but economically unattractive for most users (Ruso et al., 2019; Himat and Dogan, 2023).

Advanced Applications: Dual-Purpose Systems for Flood Mitigation

Dual-purpose rainwater collection systems which are a combination of both collecting rainwater and managing runoff from storms, have become a growing area of interest as they offer many benefits in regards to providing clean water supplies for communities and help to manage flooding in cities, especially in urban areas of Türkiye (Snir et al., 2022; Soh et al., 2023). Rainwater collection systems which provide multiple purposes use regulated orifice discharge mechanisms to conserve space to collect water from future rains and maximize water conservation (Snir et al., 2022; Soh et al., 2023).

In regards to controlling and optimizing dual-purpose rainwater collection systems, there is a need to weigh and meet two main conflicting goals: conserving enough stored water to maintain the dependability of your water supply and discharging the stored volume of water to handle the increased storm event flow (Soh et al., 2023). The results of Snir et al. showed that when using decentralized rainwater collection systems equipped with optimized algorithms for regulating water flow into sewers, you can expect to see about 20 – 40 % less urban drainage flow through the sewers during small to moderate-sized storm events (10 – 25 mm) while also meeting water supply dependability requirements of 85 – 90 % (Snir et al., 2022).

The control algorithm which was applied in the study utilizes short-term weather forecasting to pre-discharge water from the tank before the storm occurs so that there will be enough storage in the tank to capture the storm but it does not compromise the water conservation performance (Snir et al., 2022). When utilizing this type of dual function capability in combined sewer systems in urban areas of Türkiye, the dual-function capability will greatly increase the financial feasibility of investing in rainwater collection systems by decreasing the size of the necessary storm drain infrastructure and associated costs (Snir et al., 2022).

When developing robust optimization models for dual-purpose rainwater collection systems, the uncertainty in precipitation data affecting the ability to produce water for the community and uncertainty in storm intensities affecting the ability to mitigate flooding are explicitly accounted for (Soh et al., 2023). Through Pareto Frontier Analysis, it has been shown that systems which were optimized primarily for producing water will only result in minimal benefits for mitigating flooding, while systems optimized primarily for flood mitigation will lose approximately 30 – 40 % of possible water conservation benefits (Soh et al., 2023).

System design that balances the objective functions of water supply and flood mitigation can achieve approximately 70 – 80 % of the maximum achievable benefits for each objective function simultaneously, with typical system design having tanks that are 20 – 30 % larger than the design size needed to optimize the system for water supply alone (Soh et al., 2023). This highlights the need for multi-objective optimization in designing and implementing urban rainwater collection systems.

Operating the dual-purpose systems will require changes to the existing operating procedures and will require new control equipment beyond what would be required in traditional rainwater collection systems (Snir et al., 2022; Soh et al., 2023). Capital cost for real-time control systems with features such as integrating weather forecast information, automatically opening and closing valves, and remotely monitoring the systems will be approximately 15 – 25 % higher than that of a passive system (Snir et al., 2022). However, in urban areas where the cost of managing stormwater run-off is extremely high, the total benefits of both conserving water and mitigating flooding may be able to justify the added cost (Snir et al., 2022; Soh et al., 2023).

Design Recommendations and Engineering Guideline

Based on synthesis of the reviewed literature, the following design recommendations are provided for RWH systems in Turkish and comparable Mediterranean climates:

Tank Sizing:

- For residential projects located in semi-dry areas with precipitation rates ranging from 300-400 mm/yr: 6-10 m^3 (single-family home = 100-150 m^2 roof area) and 15-25 m^3 (multi-family building = 300-500 m^2 roof area) (Okoye et al., 2015; Ruso et al., 2019).
- For coastal Mediterranean areas (>600 mm/yr rainfall): 4-8 m^3 (single-family home) and 10-18 m^3 (multi-family building) (Campisano and Modica, 2012; Notaro et al., 2017).
- The target volumetric reliability is: 90-95 % for cost optimal designs (Campisano and Modica, 2012; Okoye et al., 2015).
- The tank volume should not exceed 25 % of the annually collectible rainfall to limit excessive excess flow losses (Campisano and Modica, 2012).

Optimization Methodology:

- Perform linear programming or use particle swarm optimization to size tanks, while using a behavioral model to simulate performance (Saplioglu et al., 2019; Okoye et al., 2015).
- Use a water balance model with at least 10 years of historical rainfall data in daily time steps (Okoye et al., 2015; Jenkins, 2007).
- Analyze the sensitivity of water prices, rainfall variations and changes in demand to the system's performance (Himat and Dogan, 2023).

Catchment and Conveyance:

- Roof runoff coefficients are as follows: 0.90 for metal; 0.75 for tile roofs; 0.70 for concrete roofs (Müftüoğlu, 2024).
- Diversion of first flush is 1-2 mm of rainfall or in terms of volume approximately 100-200 litres per average residential roof area (Müftüoğlu, 2024).

- Gutters should be sized to provide a minimum of a 100-150 mm/hr peak intensity, with an additional 20-30 % freeboard (Müftüoğlu, 2024).
- The conveyance pipes used for conveying stormwater should have diameters of 75-100 mm (PVC/HDPE) and slopes of at least 1-2 % (Müftüoğlu, 2024).

Filtration and Treatment:

- Coarse filtration (1-2mm) of roof surface runoff by means of gutter screens followed by a second stage of finer filtration (0.2-0.5mm) immediately prior to entering into the storage tank (Müftüoğlu, 2024).
- Screened (0.5 mm) gravity fed systems for use in non-potable applications (Müftüoğlu, 2024).
- Potable applications may require additional treatment such as UV disinfection or chlorine addition to achieve a minimum 0.5 - 1.0 mg/L free residual (Judeh et al., 2022).

System Integration:

- Dual-supply configuration with automatic switching between rainwater and municipal backup (Judeh et al., 2022).
- Backflow prevention mandatory for municipal connection (Judeh et al., 2022).
- Variable-speed pumps with pressure control for energy efficiency (Müftüoğlu, 2024).

Economic Considerations:

- RWH is a financially feasible option when water pricing is at least $1.50/m³ and rainfall totals 500mm of precipitation annually (Himat and Dogan, 2023).
- When water prices or rainfall in an area do not allow RWH to be financially feasible then it will require policy incentives (such as subsidies or rebates) to make it financially feasible (Okoye et al., 2015; Himat and Dogan, 2023).
- Prioritize RWH for new developments to take advantage of the fact that installation costs will be between 30-40 % lower than retrofit installations (Himat and Dogan, 2023).

Research Gaps and Future Directions

In spite of significant advances in RWH system design and optimisation there are still a number of areas of study which require further investigation:

- Climate Change Adaptation: Although there have been some studies into RWH system design to take account of potential future changes in rainfall patterns and drought duration (Jaradat et al., 2024) very few studies have examined how such changes will affect the performance of RWH systems over time (Soh et al., 2023). The need for robust optimisation tools that can be used to determine RWH system designs based on current estimates of climate uncertainty is becoming increasingly important as an increasing number of RWH systems come into operation.
- Water Quality and Treatment: Although the majority of studies relating to RWH systems in Türkiye have focused on determining suitable system sizes and hydraulic designs for RWH systems, most studies have paid little if any attention to the effects of the characteristics of roof type and local climatic conditions on water quality and required treatment processes (Müftüoğlu, 2024). Furthermore, no comprehensive water quality monitoring has been undertaken at a national level in Türkiye to provide data to support the design of water treatment systems (Müftüoğlu, 2024).
- Smart Control Systems: Advanced control methods for dual purpose RWH systems have shown great potential for use in smart RWH systems (Snir et al., 2022; Behzadian et al., 2018), however, studies examining the practicality of implementing such smart control methods for RWH systems in Türkiye have yet to be published (Behzadian et al., 2018). Research is required to develop low-cost sensor networks, integrate forecasts into smart control systems and investigate the benefits of using adaptive control methods to improve the widespread uptake of smart RWH systems (Behzadian et al., 2018).
- Social and Institutional Dimensions: Studies examining the technical feasibility of RWH systems dominate the current literature, whilst few studies have examined the role of user acceptance, behavioural factors and institutional barriers to RWH adoption in Türkiye (Himat and Dogan, 2023). To develop policies to support RWH adoption, interdisciplinary research is required to examine the technical, economic and social dimensions of RWH (Himat and Dogan, 2023).
- Life Cycle Assessment: There is a lack of comprehensive assessments of the environmental impacts associated with RWH systems during all phases of their life cycles, including material usage, operational emissions and end-of--life disposal (Morales-Pinzón et al., 2012). The completion of life cycle assessments of RWH systems will allow them to be compared with other alternative water management strategies (Morales-Pinzón et al., 2012).

- Coordinating Decentralized Systems: The research on coordinating decentralized RWH systems for a neighborhood or district level to manage both potable water and stormwater at the same time is currently still in its early stages but has a large potential as a whole (Snir et al., 2022). Techniques can be created to find the possible synergy's of optimizing multiple decentralized RWH systems at once (Snir et al., 2022).

Conclusion

The results of the above Integrated Technical Review represent an aggregation of the present state-of-the-art in engineering-related knowledge about the design and optimization of rainwater harvesting (RWH) systems for residential applications in Türkiye and in Mediterranean climates.

Some important findings of this synthesis include:

1. The appropriate size of a storage tank for RWH application in the residential sector in arid-semiarid regions of Türkiye varies between 6–10 cubic meters, while the appropriate size in coastal areas where there are high precipitation values ranges between 4–8 cubic meters. Both sizes result in volumetric reliabilities ranging from 90 to 95 percent, while also producing between 30–50 percent savings in the consumption of domestic potable water (Okoye et al., 2015; Ruso et al., 2019; Müftüoğlu, 2024).
2. Optimization methods such as linear programming and particle swarm optimization result in smaller tank sizes than conventional design practices, while reducing costs by 20–40 percent (Okoye et al., 2015; Saplioglu et al., 2019).
3. Depending on the amount of local precipitation (typically >600 mm/yr) and type of use (potable versus non-potable uses such as toilet flushing and irrigation) domestic water conservation via RWH systems can vary between 20–70 percent of the total water used in a house (Okoye et al., 2015; Müftüoğlu, 2024).
4. The economic viability of installing RWH systems is contingent upon water prices exceeding $1.50/cubic meter and annual rainfall amounts of >500 mm/year (Himat and Dogan, 2023). Regions with lower prices and/or rainfall amounts may need additional financial incentives (such as tax credits or low-interest loans) to encourage people to adopt them (Okoye et al., 2015; Himat and Dogan, 2023).
5. Urban RWH systems capable of providing both a source of domestic water supply and flood mitigation can provide combined benefits that can make up for the expenses of developing these systems, but require sophisticated control systems and storage tank sizes

that are 20–30 percent larger than those necessary for single-purpose RWH systems (Snir et al., 2022; Soh et al., 2023).

6. Some general design recommendations include the use of daily time-step optimization models, multi-stage filtration systems, dual-supply configurations (with municipal backup supplies), and sensitivity analyses based on different design parameters (Campisano and Modica, 2012; Okoye et al., 2015; Müftüoğlu, 2024).

As a result of the referenced studies, a technically feasible framework for optimizing the performance of RWH systems in Türkiye and in other similar Mediterranean climates has been developed. Nonetheless, to foster the adoption of RWH systems, a favorable policy environment must be established to support the installation of RWH systems and to provide financial incentives to individuals and organizations to install RWH systems. It is equally important to develop institutional frameworks that enable the effective implementation of RWH systems. Future research should focus on adapting RWH systems to climate change, determining the effect of using collected rainwater for irrigation and other uses on the quality of the water, developing smart control systems to manage both the quality and quantity of rainwater that has been harvested, and encouraging interdisciplinary research to assess both the technical and non-technical elements of successfully implementing RWH systems (e.g., economics, social considerations).

Conflict of Interest Statement

The author of the article declares that there is no conflict of interest.

Contribution Statement Summary

The author declares sole responsibility for the entirety of the article.

References

Abdulla F., 2020. Rainwater harvesting in Jordan: potential water saving, optimal tank sizing and economic analysis. Urban Water Journal.

Behzadian K, Kapelan Z, Mousavi SJ, Alani AM., 2018. Can smart rainwater harvesting schemes result in the improved performance of integrated urban water systems. Environmental Science and Pollution Research, 25: 19271-19282.

Campisano A, Modica C., 2012. Optimal sizing of storage tanks for domestic rainwater harvesting in Sicily. Resources, Conservation and Recycling, 63: 9-16.

Himat A, Dogan S., 2022. Rooftop rainwater harvesting optimization in Antalya, Türkiye. Akdeniz University, Master's thesis, Türkiye.

Himat A, Dogan S., 2023. The impact of the regularization on the economic analysis of rooftop rainwater harvesting system. Water Science and Technology: Water Supply.

Jaradat RA, Al-Zboon MM, Alqadi KM., 2024. Assessment of rainwater harvesting potential from rooftops in Jordan's Twelve Governorates. Environmental Science and Pollution Research, 31: 52896-52912.

Jenkins GA., 2007. Use of continuous simulation for the selection of an appropriate urban rainwater tank. Australian Journal of Water Resources, 11(2): 231-246.

Judeh T, Shahrour I, Comair F., 2022. Smart rainwater harvesting for sustainable potable water supply in arid and semi-arid areas. Sustainability, 14(15): 9271.

Morales-Pinzón T, Lurueña R, Rieradevall J, Gasol CM, Gabarrell X., 2012. Financial feasibility and environmental analysis of potential rainwater harvesting systems: A case study in Spain. Resources, Conservation and Recycling, 69: 130-140.

Muklada H, Gilboa Y, Friedler E., 2016. Stochastic modelling of the hydraulic performance of an onsite rainwater harvesting system in Mediterranean climate. Water Science and Technology: Water Supply, 16(6): 1614-1623.

Müftüoğlu TD., 2024. Evaluating rainwater harvesting potential of concrete and tile roofings for detached houses in Aydın, Türkiye. Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 7(3): 1096-1115.

Notaro V, Liuzzo L, Freni G., 2017. Evaluation of the optimal size of a rainwater harvesting system in Sicily. Journal of Hydroinformatics, 19(6): 853-864.

Okoye CO, Solyalı O, Akıntuğ B., 2015. Optimal sizing of storage tanks in domestic rainwater harvesting systems: A linear programming approach. Resources, Conservation and Recycling, 104: 131-140.

Ruso M., 2018. Rainwater harvesting analysis for Northern Cyprus. Middle East Technical University, Master's thesis, Türkiye.

Ruso M, Akıntuğ B, Kentel E., 2019. Optimum tank size for a rainwater harvesting system: Case study for Northern Cyprus. IOP Conference Series: Earth and Environmental Science, 297.

Ruso M, Akıntuğ B, Kentel E., 2024. Rainwater harvesting system analysis for semi-arid climate: A daily linear programming model. Turkish Journal of Civil Engineering, 35(5): 1-28.

Saplioglu K, Kucukerdem TS, Şenel FA., 2019. Determining rainwater harvesting storage capacity with particle swarm optimization. Water Resources Management, 33(14): 4749-4766.

Snir O, Friedler E, Laronne O., 2021. Dual benefit of rainwater harvesting—high temporal-resolution stochastic modelling. Water, 13(17): 2415.

Snir O, Friedler E, Ostfeld A., 2022. Optimizing the control of decentralized rainwater harvesting systems for reducing urban drainage flows. Water, 14(4): 571.

Soh YK, Roach M, Sadler JR, Ilic M., 2023. Robust optimisation of combined rainwater harvesting and flood mitigation systems. Water Research, 245: 120532.

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Farklı Tip Pülverizatörler ile Yapılan Pestisit Uygulamalarında Oluşan Operatör Maruziyetleri

Ali BOLAT[1*]

[1]Adıyaman Üniversitesi, Ziraat Fakültesi, Tarla Bitkileri Bölümü, Adıyaman, Türkiye

[1]http://orcid.org/0000-0002-1019-0069
*Sorumlu yazar: alibolat@adiyaman@edu.tr

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ÖZ

Bu derleme, farklı tip pülverizatörler kullanılarak yapılan pestisit uygulamalarında operatör maruziyetlerini incelemektedir. Pestisitler, tarımsal zararlılarla mücadelede kritik bir rol oynamakla birlikte, insan sağlığı ve çevre üzerinde olumsuz etkiler yaratabilir. Araştırmada, tarla pülverizatörleri, bağ ve bahçe pülverizatörleri, sırt pülverizatörleri ve insansız hava araçları (İHA) ile yapılan ilaç uygulamalarında operatör maruziyeti üzerindeki etkileri değerlendirilmiştir. Pülverizatör tasarımlarının, operatörlerin maruziyet seviyelerini etkileyen önemli bir unsur olduğu vurgulanmaktadır. Pülverizatörlerin kullanımı sırasında yaşanan zorluklar ve düzenlemelerin yetersizliği, operatörlerin sağlık risklerini artırmaktadır. Ayrıca, İHA'ların kullanımının maruziyet düzeylerini %90-99 oranında azaltabileceği gösterilmektedir. Sonuç olarak, pestisit uygulamalarının güvenliğini artırmak için kişisel koruyucu ekipman kullanımı, eğitim ve ekipman tasarımının önemi vurgulanmakta; sürdürülebilir tarım uygulamalarının geliştirilmesi gerektiği belirtilmektedir. Bu çalışma, tarımsal güvenlik ve operatör sağlığı açısından önemli bulgular sunmakta ve gelecekteki araştırmalara ışık tutmaktadır.

Operator Exposures in Pesticide Applications Using Different Types of Sprayers

Review Article

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ABSTRACT

This review investigates operator exposure to pesticides during applications using various types of sprayers. Pesticides play a crucial role in managing agricultural pests; however, they can pose significant risks to human health and the environment. The research evaluates the effects of field sprayers, vineyard and orchard sprayers, backpack sprayers, and unmanned aerial vehicles (UAVs) on operator exposure levels. The study emphasizes that the design of sprayers is a critical factor influencing operator exposure. Challenges encountered during the use of sprayers, along with inadequate regulations, contribute to increased health risks for operators. Furthermore, the findings indicate that the use of UAVs can reduce exposure levels by approximately 90-99%. In conclusion, the study underscores the importance of implementing personal protective equipment (PPE), providing training, and improving equipment design to enhance the safety of pesticide applications. It also highlights the need for the development of sustainable agricultural practices. This research offers significant insights into agricultural safety and operator health, paving the way for future investigations in this field.

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Introduction

Pesticides are essential for managing harmful or destructive pest species in crops, such as weeds, insects, and disease-causing organisms (Karunamoorthi et al., 2012). Pesticide application is currently a crucial control management tactic to guarantee food supply and distribution globally (Oliveira Pasiani et al., 2012). However, reports indicate that some pesticides are extremely hazardous to the environment and human health (Soko, 2018). According to various studies, the rate of poisoning, disability, and mortality due to pesticide exposure may increase with the inappropriate use of pesticides (Kangavari et al., 2024). Pesticide poisoning is the leading cause of death and harmful health effects globally. However, the true prevalence of pesticide poisoning among farmers in less developed countries is difficult to determine. Thus, farmers now face greater health hazards as a result of pesticide use (Houbraken et al., 2016; Kangavari et al., 2024).

Protective measures that can reduce the severity of the effects of pesticides on farmers' health include avoiding associated health risks, adopting protective behaviors, using personal protective equipment, and using pesticides appropriately during handling, transport, mixing, and spraying (Fan et al., 2015). Most farmers do not consider using safety measures that can reduce the likelihood of pesticide poisoning. Therefore, it is very important to identify the features that farmers find successful when it comes to preventive measures for pesticide use (Sharifzadeh et al., 2019). Analysis of previous safety research reveals that several variables can influence farmers' preventive practices in case of pesticide poisoning (Rezaei et al., 2019). When farmers use pesticides, they implement preventive measures based on several factors such as age, education level, farming experience (Isin and Yildirim, 2007). Perceived risk, awareness, attitudinal and belief variables, perceived barriers, facilitators, health expectations, social norms, emotions, physiological arousal and intention (Afshari et al., 2019).

The terms ‘toxicity’ and ‘risk’ have different meanings regarding pesticide safety. The term ‘toxicity’ describes the innate capacity of a substance to be poisonous (Garud et al., 2024). The risk (hazard) of a particular pesticide is determined by the toxicity of the substance in question and the type and amount of exposure. Risk (hazard) should be determined from information on exposure and toxicity. In general, highly toxic pesticides have a higher potential for adverse human effects than less toxic ones (Daraban et al., 2023). However, other factors that significantly affect the risk of poisoning include the concentration of pesticides in the formulation, the duration of exposure, the point of entry of the pesticide into the human body, and the technical features of the sprayers types (Tudi et al., 2022). The design of sprayers poses significant challenges that hinder users' ability to perform their tasks efficiently. A notable example is the difficulty associated with opening the tank cap, which can result in users being exposed to hazardous chemicals. Furthermore, operators are often in direct contact with the sprayer during the spraying process, leading to both direct and indirect exposure to pesticides. Such exposure can result in various health issues. Additionally, the regulations governing the design of sprayers frequently overlook the actual working conditions faced by users. Albert et al (2025) in the study indicates that a four-level analysis of pesticide exposure situations. The first level examines the challenges faced by farmers during sprayer use and how these challenges increase exposure risks. The second level emphasizes that the design of sprayers often overlooks the real needs of farmers, thereby heightening health risks. The third level indicates that legal regulations typically only meet minimum requirements, complicating the work of designers. The fourth level highlights that the interests of farmers are not adequately represented in regulatory processes, leading to neglect of health and safety issues. Overall, these four levels underscore the complexity of pesticide exposure issues and the necessity for a multi-level approach to address them.

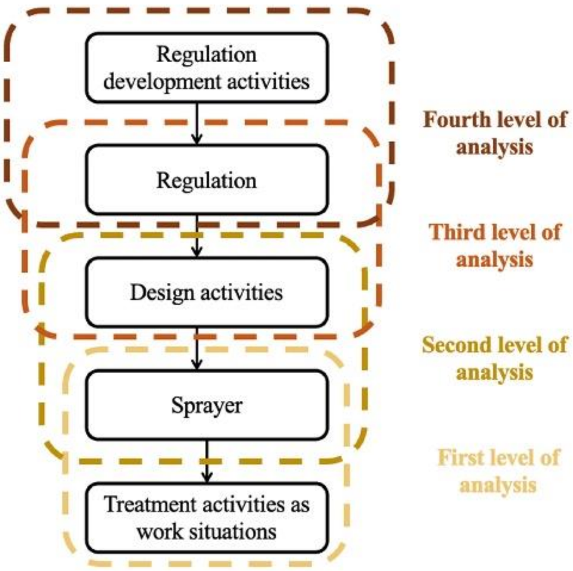

Figure 1. Processes affecting levels pesticide exposure (Albert et al., 2025)

The aim of this study is to comprehensively investigate operator exposure to pesticides during applications utilizing various types of sprayers, while also evaluating the associated health impacts of such exposure. Furthermore, this research endeavors to develop and recommend safe application methodologies and robust protective measures designed to mitigate pesticide use and enhance operator safety in agricultural practices.

Materials and Methods

This review study utilized databases such as Web of Science, ScienceDirect, Google Scholar, and ResearchGate to gather publications up to December 20, 2025. The keywords used for the search were pesticide exposure, operator safety, spraying application techniques, personal protective equipment (PPE). The topics examined in the review utilize a narrative-based approach.

Effects of Pesticide Exposure on Operators During Pesticide Application Using Field Sprayers

Pest management is an essential aspect of modern agriculture, yet it poses significant risks to operators during pesticide application, particularly when using field sprayers. Several factors contribute to the extent of pesticide exposure among agricultural workers, including the properties of the pesticide compounds, agronomic factors such as crop height and application techniques, and environmental conditions like wind speed and direction (Boonupara et al., 2023; Fattahi et al., 2025).

Operators often face challenges in accurately estimating their exposure levels during routine activities, as direct measurement is complicated by various factors, including climatic conditions and the diversity of application methods (Colosio et al., 2012). Consequently, exposure levels are frequently predicted using models designed for this purpose. Notable models include the Bystanders, Residents, Operators, and Workers Exposure models (BROWSE), the German Operator Exposure Model, the UK Predicted Operator Exposure Model (UK POEM), and the European Predicted Operator Exposure Model (EUROPOEM) (Lammoglia et al., 2017; Wong et al., 2018).

A study conducted by Lebailly et al. (2009) utilized a whole-body approach, where operators wore coveralls and cotton gloves during a one-day application of the herbicide is oproturon on winter wheat and barley. This study measured contamination across twelve body parts, revealing that hands and forearms were the most contaminated, with a staggering 64% of exposure occurring during the mixing and loading phases. This indicates that the type of spraying equipment used significantly impacts exposure levels, with rear-mounted sprayers associated with higher contamination rates. Notably, two-thirds of the total daily exposure occurred during the mixing-loading process, underscoring it as the most hazardous activity in outdoor pesticide application. Furthermore, the study highlighted that conventional pesticide-related criteria, such as field area and application time, did not correlate positively with exposure levels. In the study by Ramwell et al. (2004), it was stated that the outer surface of the field sprayer was also exposed to pesticides during application, which increased the operator's exposure. Residue measurements were conducted on the field sprayer and the attached tractor (Table 1). The delivery system recorded the highest number of pesticide detections, and for all sprayers, pesticides were found on both the boom and the nozzle. For this reason, most producers reduce the spray height and pressure during spraying to minimise drift (Seyfioğlu et al., 2023). Overall, the number of detections on the mudguards was at least double that of the rest of the tractor's body, including the door, rear window, and windscreen.

Table 1. Pesticide expose in tractor and field sprayer sample points

Sample	Number of positive detections of all pesticides per sprayer (n = 26)	Number of zero detections per sprayer	Mean pesticide dose (mg m−2)
Boom	42	0	41
Nozzle Spray tank	236	0	149
Spray tank	169	0	7.2
Mudguard (n = 25)	119	3	7.2
Door	61	4	0.5
Rear window (n = 24)	50	7	0.6
Windscreen	31	11	0.3

This finding suggests that relying solely on these criteria may not adequately account for the complexities of operator exposure during pesticide application (Lebailly et al., 2009).

In conclusion, understanding the multifaceted factors influencing pesticide exposure is crucial for developing effective risk mitigation strategies. Continuous research and targeted training for operators can enhance safety measures and reduce the health risks associated with pesticide application in agricultural settings.

Effects of Pesticide Exposure on Operators During Pesticide Application Using Vineyards and Orchards Sprayers

The use of pesticides in vineyards and orchards is a common agricultural practice aimed at protecting crops from pests, diseases, and weeds. However, these applications pose significant health and environmental risks due to the physical characteristics of the areas, application methods, and frequency of use. Factors such as protective measures, climatic conditions, and user awareness also substantially influence pesticide exposure levels (Bureau et al., 2022). In vineyards and orchards, the vertical arrangement of trees and the need to penetrate the foliage often necessitate the use of equipment like air-assisted sprayers (Figure 2).

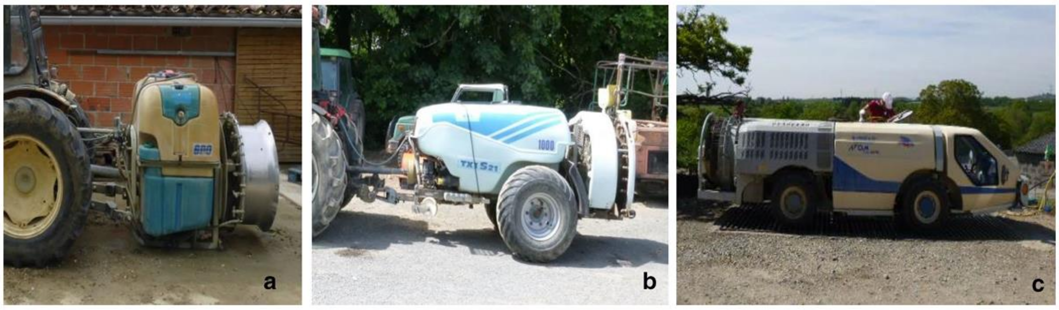

Figure 2. Types of sprayers commonly used in vineyard and orchard agriculture: (a) Rear-mounted sprayer. (b) Trailed sprayer. (c) Self-propelled sprayer (Bureau et al., 2022)

This increases the potential for pesticide drift. research indicates that up to 30% of applied pesticides may drift to non-target areas, contaminating water sources and residential zones (Dubuis et al., 2023). Workers are exposed to pesticides primarily through inhalation and dermal contact during mixing, loading, and spraying operations (Tsakirakis et al., 2014). A study by Lebailly et al. (2009) found significant pesticide residues on workers' hands, arms, and torsos, often due to inadequate use of personal protective equipment (PPE). Chronic pesticide exposure in vineyards has been linked to respiratory illnesses, neurological disorders, and cancer (González-Alzaga et al., 2014; Ahrens et al., 2024). Additionally, pesticide accumulation in soil, leaching into groundwater, and adverse effects on non-target species, especially pollinators, represent critical environmental concerns (Wang et al., 2020). The adoption of drift-reducing technologies and the establishment of buffer zones are essential for mitigating these risks. In orchards, pesticide use is often carried out by non-professionals and is frequently unregulated. A lack of training and improper use leads to over-application and unintended exposures (Morgan, 2012). Gardeners often lack access to PPE and fail to comply with safety guidelines. Residues from pesticides used in orchards can also spread through air and water, affecting surrounding areas (Afandi and Irfan, 2024). In urban ecosystems, pesticide exposure has been associated with significant declines in insect populations. Sánchez-Bayo and Wyckhuys (2019) highlighted the role of pesticide use in gardens in contributing to these declines, emphasizing the need for more environmentally friendly alternatives.

Key factors influencing pesticide exposure in vineyards and orchards include application techniques, PPE use, climatic conditions, and user awareness. For instance, applications conducted at low wind speeds and moderate temperatures reduce drift and operator exposure (Nuyttens et al., 2011). Educational programs and community-based awareness campaigns can promote safe use practices, thereby reducing risks (Fan et al., 2015). Various measures are recommended to reduce pesticide exposure and associated risks. The adoption of precision agriculture technologies can optimize pesticide use and minimize drift. Integrated Pest Management (IPM) strategies, which combine biological controls with pesticide use, offer a sustainable alternative (Kogan, 1998). Furthermore, regulatory measures for pesticide use, particularly in residential and urban areas, should be strengthened (Rezaei et al., 2019).

Addressing the health and environmental impacts of pesticide use in vineyards and orchards requires a multifaceted approach. Enhancing protective measures, adopting safer application techniques, and promoting sustainable pest management practices are crucial for safeguarding human health and protecting the environment. Future research should focus on developing innovative solutions and policies to further reduce these risks and ensure the sustainability of agricultural and gardening practices.

Effects of Pesticide Exposure on Operators During Pesticide Application Using Backpack Sprayers

Backpack sprayers are widely utilized in agricultural settings, particularly in developing countries, due to their convenience and effectiveness in applying pesticides. However, the health risks associated with pesticide exposure during the application process are significant and warrant thorough investigation. Studies have demonstrated that operators using backpack sprayers are at risk of both dermal and inhalation exposure to harmful chemicals (Liu et al., 2019). Research conducted in various regions has highlighted the correlation between the type of sprayer used and the level of exposure experienced by operators. For instance, a study in Egypt found that pesticide applicators using knapsack sprayers exhibited higher levels of contamination on their bodies compared to those using conventional motor sprayers (Elhalwagy et al., 2010). This finding underscores the need for improved safety measures and protective equipment for operators who regularly handle these devices.

Moreover, a recent analysis of glyphosate exposure among backpack sprayer users in Thailand revealed that urinary biomarkers indicated low levels of health risk; however, the study emphasized the importance of PPE to mitigate exposure (Chaiklieng et al., 2024). The findings suggest that while the immediate health risks may appear manageable, continuous exposure without adequate protection could lead to long-term health issues. In France, a study assessing herbicide exposure among gardeners and municipal workers using backpack sprayers found that dermal exposure was the predominant route of pesticide entry into the body (Boulanger et al., 2023). The research indicated that the levels of contamination approached those observed in agricultural workers, raising concerns about the occupational safety of non-agricultural users of these sprayers.

In conclusion, while backpack sprayers are an essential tool in modern agriculture, the associated risks of pesticide exposure to operators cannot be overlooked. Enhanced training on the use of PPE, along with ongoing monitoring of exposure levels, is crucial to safeguard the health of those involved in pesticide application.

Effects of Pesticide Exposure on Operators During Pesticide Application Using Unmanned Aerial Vehicles (UAVs)

In recent years, the use of UAVs in agricultural applications has been on the rise. UAVs are noted for their efficiency and flexibility in pesticide application. However, the health effects of this new technology, particularly concerning pesticide exposure among operators, pose significant concerns. Research has been conducted to examine the levels of operator exposure during UAV-based pesticide applications and to compare these levels with those associated with conventional application methods (Yan et al., 2023). One study evaluated operator exposure during the mixing and loading phases of UAV-based pesticide application. The findings revealed that mixing concentrated products resulted in the highest levels of exposure, whereas transferring diluted mixtures to the UAV tank led to significantly lower exposure figures (Felkers et al., 2024). Additionally, the use of PPE was shown to substantially mitigate potential exposure during these phases. Another study indicated that operator exposure levels during UAV applications were reduced by 90-99% compared to traditional handheld sprayers (Figure 3).

	Potential Exposure (mg/person/kg applied/day)		Actual Exposure (mg/person/kg applied/day)		Actual Exposure with gloves (mg/person/kg applied/day)	
Drone Study 75th centile, pilot	0.67		0.40		0.03	
	Potential Exposure (mg/person/kg applied/day)	Exposure reduction (drone vs handheld)	Actual Exposure (mg/person/kg applied/day)	Exposure reduction (drone vs handheld)	Actual Exposure with gloves (mg/person/kg applied/day)	Exposure reduction (drone vs handheld)
Bayer Safety standard, handheld normal crop, application only	159.7	99.6%	10.9	96.3%	3.5	99.3%
Bayer Safety standard, Handheld dense crop	324.6	99.8%	50.3	99.2%	42.9	99.9%
AOEM, 75th centile, backpack, downwards	99.3	99.3%	10.5	96.1%	8.9	99.7%
AOEM, 75th centile, backpack, upwards	65.4	99.0%	3.9	89.7%	1.2	97.8%
CLI - Handheld backpack	N/A	N/A	29.4	98.6%	25.0	99.9%

Figure 3. Comparison of operator exposure between UAVs and backpack ssprayers (Kuster et al., 2023).

These findings highlight the potential of UAVs to decrease exposure risk, particularly during mixing and loading operations. However, it was noted that specific job steps unique to UAV operations require further investigation to fully understand their implications for operator exposure (Bonds et al., 2024). In conclusion, while UAV-assisted pesticide applications offer the potential to reduce operator exposure levels, further research is necessary to ensure the safe use of this emerging technology. It is crucial to promote the use of appropriate protective clothing and equipment among operators and to raise awareness regarding exposure risks.

Conclusion

This study emphasizes the critical importance of understanding operator exposure to pesticides during agricultural applications involving various types of sprayers, including field sprayers, vineyard and orchard sprayers, backpack sprayers, and Unmanned Aerial Vehicles (UAVs). The findings indicate that while field sprayers are effective for large-scale pesticide applications, vineyard and orchard sprayers provide precision in targeting specific areas, thus reducing unnecessary exposure. Backpack sprayers, on the other hand, offer maneuverability in confined spaces but may increase operator exposure due to their design and usage patterns.

The integration of UAV technology in pesticide application has demonstrated a significant potential to reduce operator exposure by approximately 90-99%, while also minimizing chemical usage. However, challenges remain in ensuring the safety and effectiveness of these advanced methods. This research underscores the necessity for comprehensive safety measures, including the consistent use of personal protective equipment

(PPE) and thorough training programs for operators to mitigate health risks associated with pesticide exposure.

Furthermore, the study highlights the need for ongoing research to develop innovative strategies and technologies that further minimize health risks linked to pesticide applications. The combination of field sprayers, vineyard and orchard sprayers, backpack sprayers, and UAVs represents a multifaceted approach to achieving safer agricultural practices. Ultimately, fostering a safer agricultural environment through these initiatives is essential for enhancing operator health and promoting environmental sustainability.

Conflict of Interest Statement

The author of the article declares that there is no conflict of interest.

Contribution Statement Summary

The author declares sole responsibility for the entirety of the article.

References

Afandi GE, Irfan M., 2024. Pesticides risk assessment review: Status, modeling approaches, and future perspectives. Agronomy, 14(10): 2299. https://doi.org/10.3390/agronomy14102299

Afshari M, Poorolajal J, Rezapur-Shahkolai F, Assari MJ, Karimi-Shahanjarini A., 2019. Which factors influence farmers' use of protective measures during pesticides exposure? Workplace Healty Safety, 67(7): 338-349. https://doi.org/10.1177/2165079919827042

Ahrens K, Röver M, Molnar G, Martin S, Peter E, Schäckermann JN, Wegener JK., 2024. Novel field data for exposure of bystanders and residents towards spray drift during application of plant protection products in orchards. Journal of Consumer Protection and Food Safety, 19(2): 131-142. https://doi.org/10.1007/s00003-023-01468-3

Albert M, Galey L, Judon N, Charbonneau A, Garrigou A., 2025. Design and regulation as a chain of determinants in the emergence of pesticide exposure situations during the use of sprayers. Ergonomics, 68(11): 1813-1828. https://doi.org/10.1080/00140139.2024.2439923

Boonupara T, Udomkun P, Khan E, Kajitvichyanukul P., 2023. Airborne pesticides from agricultural practices: A critical review of pathways, Influencing factors, and human health ımplications. Toxics, 11(10): 858. https://doi.org/10.3390/toxics11100858

Boulanger M, de Graaf L, Pons R, Bouchart V, Bureau M, Lecluse Y, Lebailly P., 2023. Herbicide exposure during occupational knapsack spraying in French gardeners and municipal workers. Annals of Work Exposures and Health, 67(8): 965-978. https://doi.org/10.1093/annweh/wxad045

Bureau M, Béziat B, Duporté G, Bouchart V, Lecluse Y, Barron E, Baldi I., 2022. Pesticide exposure of workers in apple growing in France. International Archives of Occupational and Environmental Health, 95(4): 811-823. https://doi.org/10.1007/s00420-021-01810-y

Chaiklieng S, Uengchuen K, Gissawong N, Srijaranai S, Autrup H., 2024. Biological monitoring of glyphosate exposure among knapsack sprayers in Khon Kaen, Thailand. Toxics, 12: 337. https://doi.org/10.3390/toxics12050337

Colosio C, Rubino FM, Alegakis A, Ariano E, Brambilla G, Mandic-Rajcevic S, Vellere F., 2012. Integration of biological monitoring, environmental monitoring and computational modelling into the interpretation of pesticide exposure data: Introduction to a proposed approach. Toxicology Letters, 213(1): 49-56. https://doi.org/10.1016/j.toxlet.2011.08.018

Daraban GM, Hlihor RM, Suteu D., 2023. Pesticides vs. Biopesticides: from pest management to toxicity and ımpacts on the environment and human health. Toxics, 11(12): 983. https://doi.org/10.3390/toxics11120983

Dubuis PH, Droz M, Melgar A, Zürcher UA, Zarn JA, Gindro K, König SL., 2023. Environmental, bystander and resident exposure from orchard applications using an agricultural unmanned aerial spraying system. Science of The Total Environment, 881: 163371.

Elhalwagy, ME, Farid HE, Gh FA, Ammar AE, Kotb GA., 2010. Risk assessment induced by knapsack or conventional motor sprayer on pesticides applicators and farm workers in cotton season. Environmental Toxicology and Pharmacology, 30(2): 110-115. https://doi.org/10.1016/j.etap.2010.04.004

Fan L, Niu H, Yang X, Qin W, Bento CP, Ritsema CJ, Geissen V., 2015. Factors affecting farmers' behaviour in pesticide use: Insights from a field study in northern China. Science of the Total Environment, 537: 360-368. https://doi.org/10.1016/j.scitotenv.2015.07.150

Fattahi SH, Abdollahpour S., 2025. Sensitivity analysis of variables affecting spray drift from pesticides for their environmental risk assessments on agricultural lands. Env. Developme and Sustainability, 27: 13023–13043. https://doi.org/10.1007/s10668-023-04452-x

Felkers E, Kuster CJ, Hamacher G, Anft T, Kohler M., 2025. Pesticide exposure of operators during mixing and loading a drone: towards a stratified exposure assessment. Pest Management Science. https://doi.org/10.1002/ps.8574

Garud A, Pawar S, Patil MS, Kale SR, Patil S., 2024. A scientific review of pesticides: Classification, toxicity, health effects, sustainability, and environmental impact. Cureus, 16(8). https://doi.org/10.7759/cureus.67945

González-Alzaga B, Lacasaña M, Aguilar-Garduño C, Rodríguez-Barranco M, Ballester F, Rebagliato M, Hernández AF., 2014. A systematic review of neurodevelopmental effects of prenatal and postnatal organophosphate pesticide exposure. Toxicology Letters, 230(2): 104–121. https://doi.org/10.1016/j.toxlet.2013.11.019

Houbraken M, Bauweraerts I, Fevery D, Van Labeke MC, Spanoghe P., 2016. Pesticide knowledge and practice among horticultural workers in the Lâm Đồng region, Vietnam: A case study of chrysanthemum and strawberries. Science of the Total Environment, 550: 1001-1009. https://doi.org/10.1016/j.scitotenv.2016.01.183

Isin S, Yildirim I., 2007. Fruit-growers' perceptions on the harmful effects of pesticides and their reflection on practices: The case of Kemalpasa, Turkey. Crop Protection, 26(7): 917-922. https://doi.org/10.1016/j.cropro.2006.08.006

Kangavari M, Sarvi M, Afshari M, Maleki S., 2024. Understanding determinants related to farmers' protective measures towards pesticide exposure: A systematic review. PLoS ONE, 19(2): e0298450. https://doi.org/10.1371/journal.pone.0298450

Kogan M, 1998. Integrated pest management: Historical perspectives and contemporary developments. Annual Review of Entomology, 43: 243-270. https://doi.org/10.1146/annurev.ento.43.1.243

Kuster CJ, Kohler M, Hovinga S, Timmermann C, Hamacher G, Buerling K, Anft T., 2023. Pesticide exposure of operators from drone application: A field study with comparative analysis to handheld data from exposure models. ACS Agricultural Science & Technology, 3(12): 1125-1130. https://doi.org/10.1021/acsagscitech.3c00253

Lammoglia SK, Kennedy MC, Barriuso E, Alletto L, Justes E, Munier-Jolain N, Mamy L., 2017. Assessing human health risks from pesticide use in conventional and innovative cropping systems with the Browse model. Environment International, 105: 66-78. https://doi.org/10.1016/j.envint.2017.04.012

Lebailly P, Bouchart V, Baldi I, Lecluse Y, Heutte N, Gislard A, Malas JP., 2009. Exposure to pesticides in open-field farming in France. Annals of Occupational Hygiene, 53(1): 69-81.

Lebailly P, Vigreux C, Lechevrel C, Ledemeney D, Godard T, Sichel F, Henry-Amar, M., 2009. DNA damage in mononuclear leukocytes of farmers measured using the alkaline comet assay: Modifications of DNA damage levels after a one-day field spraying period with selected pesticides. Int. Archives of Occupational and Environmental Health, 71(2): 85–93.

Liu W, Wu C, She D., 2019. Effect of spraying direction on the exposure to handlers with hand-pumped knapsack sprayer in maize field. Ecotoxicology and Environmental Safety, 170: 107-111. https://doi.org/10.1016/j.ecoenv.2018.11.121

Morgan MK., 2012. Children's exposures to pyrethroid insecticides at home: A review of data collected in published exposure measurement studies conducted in the United States. International Journal of Environmental Research and Public Health, 9(8): 2964-2985. https://doi.org/10.3390/ijerph9082964

Nuyttens D, De Schampheleire M, Baetens K, Sonck B., 2011. Effect of nozzle type, size and pressure on spray droplet characteristics. Biosystems Engineering, 99(3): 271–280. https://doi.org/10.1016/j.biosystemseng.2007.03.001

Ramwell CT, Johnson PD, Boxal BA, Rimmer DA., 2004. Pesticide residues on the external surfaces of field-crop sprayers: environmental impact. Pest Manag Sci 60: 795–802. https://doi.org/10.1002/ps.870

Rezaei R, Safa L, Ganjkhanloo MM., 2019. Understanding farmers' ecological conservation behavior regarding the use of integrated pest management: An application of the technology acceptance model. Global Ecology and Conservation, 17: e00555. https://doi.org/10.1016/j.gecco.2020.e00941

Rezaei R, Seidi M, Karbasioun M., 2019. Pesticide exposure reduction: Extending the theory of planned behavior to understand Iranian farmers’ intention to apply personal protective equipment. Safety Science, 120: 527-537. https://doi.org/10.1016/j.ssci.2019.07.044

Sánchez-Bayo F, Wyckhuys KAG., 2019. Worldwide decline of the entomofauna: A review of its drivers. Biological Conservation, 232: 8–27. https://doi.org/10.1016/j.biocon.2019.01.020

Sharifzadeh MS, Abdollahzadeh G, Damalas CA, Rezaei R, Ahmadyousefi M., 2019. Determinants of pesticide safety behavior among Iranian rice farmers. Science of the Total Environment, 651: 2953-2960. https://doi.org/10.1016/j.scitotenv.2018.10.179

Soko JJ., 2018. Agricultural pesticide use in Malawi. Journal of Health and Pollution, 8(20): 181201. https://doi.org/10.5696/2156-9614-8.20.181201

Tsakirakis AN, Kasiotis KM, Charistou AN, Arapaki N, Tsatsakis A, Tsakalof A, Machera K., 2014. Dermal & inhalation exposure of operators during fungicide application in vineyards: Evaluation of coverall performance. Science of the Total Environment, 470: 282-289. https://doi.org/10.1016/j.scitotenv.2013.09.021

Tudi M, Li H, Wang L, Lyu J, Yang L, Tong S, Yu QJ, Ruan HD, Atabila A, Phung DT, Sadler R, Connell D., 2022. Exposure routes and health risks associated with pesticide application. Toxics, 10(6): 335. https://doi.org/10.3390/toxics10060335

Oliveira Pasiani J, Torres P, Roniery Silva J, Zago Diniz B, Dutra Caldas E., 2012. Knowledge, attitudes, practices and biomonitoring of farmers and residents exposed to pesticides in Brazil. International Journal of Environmental Research And Public Health, 9(9): 3051-3068. https://doi.org/10.3390/ijerph9093051

Seyfioğlu B, Baran MF, Bolat A., 2023. Ankara ili tarım işletmelerinde ilaçlama makinelerinin seçimi ve kullanımına yönelik üretici değerlendirmeleri. ISPEC Journal of Agricultural Sciences, 7(2): 316-335. https://doi.org/10.5281/zenodo.8034703

Yan Y, Lan Y, Wang G, Hussain M, Wang H, Yu X, Song C., 2023. Evaluation of the deposition and distribution of spray droplets in citrus orchards by plant protection drones. Frontiers in Plant Science, 14: 1303669. https://doi.org/10.3389/fpls.2023.1303669

Wang Z, Meng Y, Mei X, Ning J, Ma X, She D., 2020. Assessment of handler exposure to pesticides from stretcher-type power sprayers in orchards. Applied Sciences, 10(23): 8684. https://doi.org/10.3390/app10238684

Wong HL, Garthwaite DG, Ramwell CT, Brown CD., 2018. Assessment of exposure of professional agricultural operators to pesticides. Science of the Total Environment, 619: 874-882.