

Article

Enhancing Urban Sustainability and Resilience: Employing Digital Twin Technologies for Integrated WEFE Nexus Management to Achieve SDGs

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Abstract: This research explores the application of digital twin technologies to progress the United Nations' Sustainable Development Goals (SDGs) within the water-energy-food-environment (WEFE) nexus management in urban refugee areas. The study in Irbid Camp utilizes a detailed 3D Revit model combined with real-time data and community insights processed through advanced machine learning algorithms. An examination of 450 qualitative interviews indicates an 80% knowledge level of water conservation practices among the community but only 35% satisfaction with the current management of resources. Predictive analytics forecast a 25% increase in water scarcity and an 18% surge in energy demand within the next ten years, prompting the deployment of sustainable solutions such as solar energy installations and enhanced rainwater collection systems. By simulating resource allocation and environmental impacts, the digital twin framework helps in planning urban development in line with SDGs 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities), and 12 (Responsible Consumption and Production). This investigation highlights the capacity of digital twin technology to improve resource management, increase community resilience, and support sustainable urban growth, suggesting its wider implementation in comparable environments.

Keywords: digital twin technologies; sustainable urban development; sustainable development goals; urban resilience; WEFE nexus management



Citation: Shehadeh, A.; Alshboul, O.; Arar, M. Enhancing Urban Sustainability and Resilience: Employing Digital Twin Technologies for Integrated WEFE Nexus Management to Achieve SDGs. *Sustainability* **2024**, *16*, 7398. <https://doi.org/10.3390/su16177398>

Academic Editor: Jian Feng

Received: 13 July 2024

Revised: 10 August 2024

Accepted: 20 August 2024

Published: 28 August 2024



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1. Introduction

Navigating through the bustling lanes of Irbid Camp reveals a community steeped in resilience and adaptability. The camp's densely populated corridors, lined with a mosaic of makeshift homes, resonate with the vitality of its inhabitants, who continuously adapt to the complexities of refugee urban life [1]. Irbid Camp, known for its dynamic social fabric and complex community dynamics, is a prime example of the challenges and potentials of sustainable urban governance within a refugee setting [2]. This investigation centers on applying digital twin technology to enhance the sustainable management of the Water-Energy-Food-Environment (WEFE) nexus in this vibrant urban refugee settlement. Digital twins—sophisticated digital replicas of physical entities and processes—are pivotal for holistic and effective resource governance [3,4]. By constructing a digital twin of Irbid Camp, the study seeks to surpass conventional management methods by merging technological innovations with profound community insights.

In this scenario, the deployment of digital twins represents not just a technological shift but a fundamental transformation. This tool is designed to integrate and harmonize

the complex interplay among water, energy, food, and environmental sustainability [5–8]. Given the camp's rich cultural heritage and community identity, introducing such technologies must be handled with cultural sensitivity and inclusivity. The digital twin connects past and present, tradition and innovation, while respecting the community's cultural ethos. Initially, the project developed a 3D point cloud Revit model of a standard housing unit, which later expanded into a comprehensive digital twin framework that includes real-time data and community input. This framework maps out the camp's physical and infrastructural layout and simulates the effects of various sustainable interventions like rainwater harvesting systems, solar panels, and green roofing. These simulations are critical for refining the camp's resource management strategies to ensure they are sustainable, culturally aligned, and meet the residents' needs.

A notable advancement in this research is using machine learning to analyze data from 450 detailed interviews with camp residents. These interviews offered profound comprehensions into community resource use practices, preservation efforts, and cultural beliefs. Machine learning algorithms were influential in recognizing patterns in the data, thus improving the precision of the digital twin in revealing community needs and projected challenges in resource sharing due to climate change. Urban refugee settings like Irbid Camp characterize complex environments where packed populations and inadequate infrastructure strengthen resource management emerges. Typical management strategies often fail to effectively address the dynamical relations within the WEFE nexus, leading to sub-optimal resource distribution and lowered resilience to climate adaptability. This situation emphasizes the pressing necessity for pioneering methodologies incorporating real-time data and community feedback, line up with social principles and adapting to altering environmental circumstances.

This research institutes an advanced methodology to resource management and urban planning within refugee camps by incorporating digital twin technologies into WEFE nexus management. This paper occurred in the tightly crowded refugee precinct of Irbid Camp, which residences thousands of refugees under environments symbolic of the obstacles confronted by urban refugee neighborhoods universal. It discusses the hazardous riddle of sustainable resourcefulness allocation amongst complicated societal, financial, and environmental dynamics. The camp presents an ideal environment for surveying and evaluating the consequence of digital twin knowledge in a real-world situation characterized by an opaque population, inadequate resources, and socio-economic connections.

The research's originality deception in its negotiated treatment of digital twin technology. This sophisticated simulation representation establishes a dynamical, collaborative simulated environment expressing the real-world camp. Different old-style management schemes that rely on stationary and disjointed data, the digital twin in this research exploits real-time data feedstuffs and communal input to incessantly revise and forecast the future state of reserve distribution under numerous situations. This maintains dynamic resourcefulness management by modeling and imagining the influence of several approaches in real-time, improving decision-making practices. It also implements a communal-centric methodology, incorporating qualitative data from the camp's neighborhoods to adapt ethnically responsive involvements and adopt the community's individual requirements and first choice. Additionally, employing ML procedures for foretelling analytics and anticipating admits for predicting future resource restrictions and chances, enabling defensive actions to moderate possibility disasters.

This paper tackles the unsuccessful and repeatedly invalid management of essential capitals in refugee surroundings. Traditional approaches lack the flexibility and approachability required to adapt to a refugee camp's rapidly changing circumstances and diverse needs. This research aims to overcome these restrictions by employing a digital twin, presenting a more resilient and adaptive management system that can be used to manage the complex interdependencies of the WEFE nexus.

This research explores the application of digital twin technology for managing the WEFE nexus in refugee camps, specifically focusing on how this technology can enhance

resource management and achieve Sustainable Development Goals (SDGs). Through qualitative research methods, including 450 interviews, the study assesses the socio-cultural impacts of digital twins in refugee environments, focusing on community acceptance and integration. The research employs predictive modeling with machine learning to anticipate future resource needs and climate changes, proposing adaptive interventions like solar panels and rainwater harvesting systems to enhance sustainability and efficiency. By evaluating the effectiveness and implications of digital twins, this research aims to demonstrate how advanced technologies can support sustainable urban development and improve living conditions in refugee settings, aligning with SDGs related to clean water, affordable energy, sustainable communities, and responsible consumption.

The structure of this paper provides a comprehensive examination of digital twin technology within the WEF nexus in urban refugee environments. The Literature Review section reviews existing research on digital twins, the WEF nexus, and sustainable urban planning, identifying gaps this study addresses. The Methods section details the combined qualitative and quantitative approaches used, including constructing and applying a digital twin model enriched with real-time data and supported by machine learning algorithms. In the Findings section, the research reports effects from the digital twin employment, identity response, and predictive development, emphasizing their virtual implications for developing resource management and sustainability. The Discussion participates these outcomes with available literature, suggesting visions into their wider impressions on urban arrangement and refugee camp governance. To end, the research's contributions was revised in the Conclusion and References, which offer policies for applicants to influence digital twin knowledges for urban management further, provision sustainable growth, and progress the typical of living in refugee circumstances.

2. Literature Review

The WEF Nexus proposal, established by Hoff at the 2011 World Economic Forum in Bonn, features the significant relations among water resources, energy requirements, and food protection. This research was cried to unite new worldwide problems and explain the links relating the management of water reserves and economic extension [9]. Since its creation, the WEF Nexus has acquired into a central academic and document term, representing its spreading value in numerous fields [10]. To uphold environmental development, referring the encounters related to these sources needs a combined approach that believes the existing and future socioeconomic requires at separate regional and international levels [11,12]. Creating globally forthcoming choices that equilibrium conservation protection and individual well-being involves a universal attitude.

Revolutions in instrument knowledge, renewable energy, and greenhouse observing are just a few of the imaginative explanations that were compelled potential by nexus-connected technical innovations that may be joined in both urban and rural surroundings [13,14]. A systematic comprehension of the interrelations among food, energy, and water manages it simpler to assign resources optimally for globally responsive agriculture and persuades precise deliberate choosing [15–17]. Numerous knowledges are needed for progressing tactics that competently participate and handle several resources, improving resource efficacy and sustainability.

Giving to current analyses, employing advanced approaches is needed to sustaining sustainability goals and progressing sustainable implementation [18,19]. Problems such as unnecessary data, a shortage of experience with human reserves, and unpredictable weather patterns can hamper decision-making. This can result in less-than-ideal solutions and inhibit the accomplishment of sustainability goals. AI knowledges—which may estimate large datasets and discover hidden insights—are key to explain these problems [20–23]. Beyond data analytics, AI has the potential to provide scientifically grounded solutions to environmental and climate-related issues, lessen individuals' or groups' biases, and promote a more inclusive decision-making process for all parties involved [24–26]. Furthermore, researchers have highlighted AI's transformative potential in enhancing

decision-making processes and reshaping business practices from a sustainable and socially responsible perspective [27,28]. Despite the significant role of businesses in driving global sustainable development, the literature on the WEF Nexus has often overlooked this sector, focusing instead on other areas [29]. Additionally, while the importance of digital technologies in managing water, energy, and food has been recognized, the role of AI in overseeing the WEF Nexus remains largely unexplored [30,31].

Digital twins provide accurate, actionable, and timely information and are foundational for replicating complex systems and their environments across various domains [32]. These digital models assist stakeholders in effectively managing resources and infrastructure by monitoring agricultural activities, optimizing energy use, and reducing emissions across air, soil, and water. Additionally, the extensive data digital twins provide opens new possibilities for analyzing social consumption trends, life-cycle impacts, and supply chain dynamics.

The availability of enhanced information and transparency offered by digital twins significantly broadens the scope for implementing corrective measures that reinforce and advance social and environmental sustainability goals [33,34]. Digital twins improve the visibility of underground water resources by graphically depicting variations in groundwater levels, supported by sophisticated machine learning algorithms for precise downscaling [35–37]. In agriculture, digital twins have proven particularly effective in optimizing resources and predicting growth, thereby increasing stakeholder profitability and reducing waste [38]. Technologies like the Internet of Things, cyber-physical systems, mechanistic modeling, and, increasingly, machine learning have made digital twins an effective tool for applications such as yield forecasting, water optimization, machine calibration, and enhancing environmental transparency [39,40]. While recent literature has extensively examined the WEF nexus, particularly its complexity in urban refugee settings, a significant gap exists in the practical application of advanced technologies like digital twins in these contexts. Most studies have focused on theoretical frameworks or isolated applications without integrating real-time data and community feedback. Additionally, the socio-cultural aspects of technology implementation in these sensitive environments are often overlooked, highlighting a crucial need for research that merges technological innovation with community-oriented approaches.

This research fills these gaps by implementing digital twin technology in Irbid Camp, which is enriched with real-time data and analyzed through machine learning. Unlike prior studies, this approach simulates the physical and infrastructural elements and integrates qualitative community data, reflecting cultural values and behaviors. This combination grants a immersed comprehension of the resource management challenges and opportunities in refugee settings, advocating adaptive interferences that are culturally sensitive and environmentally sustainable. The methodology section elaborates on the detailed methods used in this study to employ and evaluate the digital twin model within Irbid Camp. It includes the development of a 3D point cloud Revit model, gathering and analyzing qualitative data from community interviews using machine learning, and applying predictive modeling to predict resource needs and environmental impacts. This section details the cohesive approach taken to ensure the digital twin replicates the physical structure of the camp and adapts dynamically to its evolving socio-economic circumstances, offering a vigorous framework for sustainable urban planning.

3. Methods

This research concentrated on managing digital twin expertise to further WEF nexus management, and it existed at Irbid Camp, Jordan, from March to June 2024. The study was completed in cooperation with neighborhood associations that have a say in the camp's sustainability and urban development strategies. These organizations facilitate access to essential resources and services and are vital in embracing and executing novel technologies like digital twins. Figure 1 presents a comprehensive map of Irbid Camp that provides information about its infrastructural plan and geographic location. This essential map

offers the geographical foundation for using various WEFE nexus methods and the digital twin paradigm. It offers a thorough visual depiction of the camp, which is essential for comprehending the conversations and conclusions on the resource management and urban integration initiatives in Irbid Camp. The strategic importance of the camp's design in enhancing urban planning and sustainable resource management initiatives is emphasized by this figure illustration.

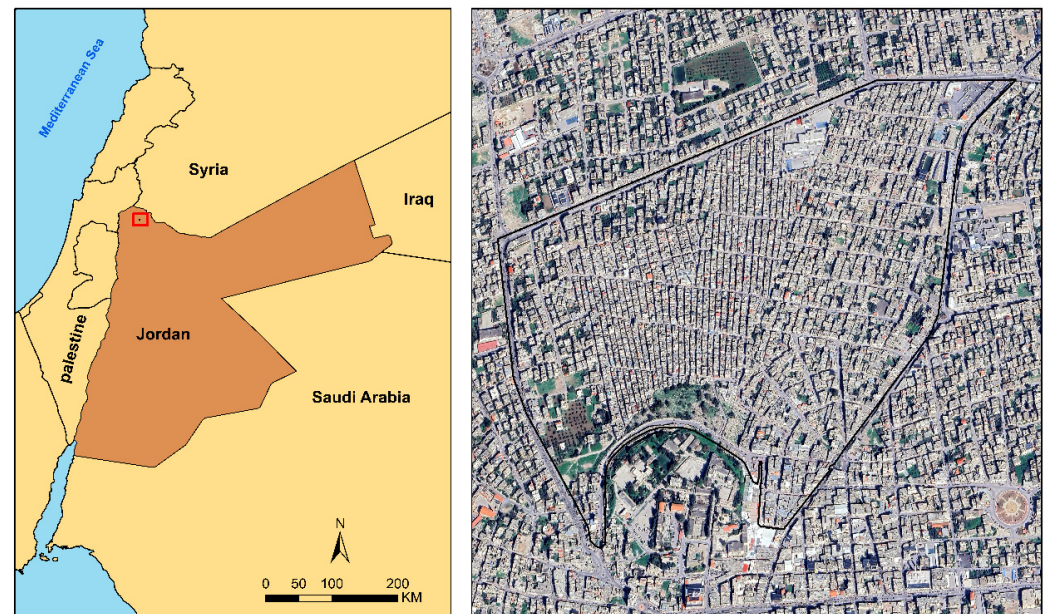


Figure 1. Detailed Geographic and Infrastructure Map of Irbid Camp.

Irbid Camp is situated in Irbid, northern Jordan, and was founded in 1951 to shelter refugees displaced from Palestine. Currently, a wide range of refugees call it home, many of them are Syrians who came here after the Syrian crisis in 2012. Most of the people living in the camp are closely related to one another, having gone through similar experiences of migration and relocation as well as a common past. The camp is characterized by cramped living quarters and shoddy infrastructure, covering an area of 0.24 square kilometers. Originally constructed as temporary shelters, many buildings have been incrementally modified into more permanent structures. Despite enhancements, the camp faces overcrowding, poor sanitation, and limited access to major services.

Education levels within the camp vary, with many residents having access to primary and secondary education facilitated by UNRWA (United Nations Relief and Works Agency). However, higher education opportunities are limited. Employment is predominantly informal, with many residents working in small businesses, agriculture, or as day laborers. Economic opportunities are constrained by legal and social barriers, contributing to high unemployment rates. Literacy among residents of Irbid Camp is generally low. Access to digital devices and the internet is limited, often hindered by financial constraints and infrastructural deficiencies. Although younger residents may be familiar with smartphones and social media, comprehensive digital skills, particularly those required for leveraging advanced technologies like digital twins, are not widespread.

Residents of Irbid Camp face numerous challenges, including water scarcity, energy shortages, and food insecurity. These issues are exacerbated by the camp's limited infrastructure and resources. Nonetheless, the community displays resilience and adaptability, often relying on traditional knowledge and communal support systems to navigate daily hardships. The social fabric of Irbid Camp is marked by strong communal ties and a collective identity rooted in shared experiences of displacement. Community engagement and participation in local decision-making processes are vital aspects of life in the camp. Initia-

tives to improve living conditions, such as those proposed in this study, benefit significantly from community involvement and feedback.

The well-established connections with these local organizations facilitated gaining entry to the camp and interacting with its varied communities. The research methods included participant observation and extensive interaction with various camp inhabitants, including influential community leaders and representatives from diverse non-governmental organizations (NGOs) active within the camp. The lead researchers immersed themselves in numerous community gatherings, sustainability-focused workshops, and everyday activities within the camp. This deep involvement provided profound insights into how the community interacts with its environment and current resource management practices.

3.1. Data Collection Methods

The data collection for this study was robust, involving participant observation complemented by semi-structured, in-depth interviews with approximately 450 stakeholders from Irbid Camp. These stakeholders included active community members involved in local sustainability projects, urban planning experts, and representatives from various NGOs. The interviews were facilitated using standardized topic guides translated into Arabic to encourage more meaningful exchanges. Discussion topics spanned existing resource management strategies, perceptions regarding implementing digital twin technology, and the community's historical and cultural ties to sustainability practices. Additionally, the study incorporated a review of documents provided by local organizations, such as urban sustainability plans, resource utilization reports, and records of community engagement. This documentation enriched the understanding of the community dynamics and the cultural and historical influences on adopting sustainable practices within Irbid Camp.

Data from these ethnographic efforts were carefully recorded, transcribed, and analyzed. Thematic analysis was employed to distill key themes and insights, using a codebook developed both inductively from the data collected and deductively from the overarching research goals related to digital twin technology in urban resource management. This analysis shed light on the nuanced relationship between technology adoption and community involvement in the camp's distinct socio-cultural environment. As part of the research on employing digital twins for sustainable resource management at Irbid Camp, key visual elements and technological integrations are presented in Figures 2–5. These figures collectively highlight digital twin technology's sophistication and practical application in advancing environmental and infrastructure planning within a refugee camp context.



Figure 2. The transformation from Point Cloud to Revit Model.

Figure 2 presents the transformation of raw interview data into a sophisticated Revit model. The point cloud model captures a detailed 3D representation of the camp's physical layout, forming the base for the digital twin. This raw data is intricately processed to create a Revit model, providing a structured, editable, and analytically robust digital representation of the camp's infrastructure. This transformation is pivotal as it allows planners and engineers to digitally simulate, analyze, and project various spatial and structural scenarios, ensuring any proposed modifications or enhancements can be thoroughly visualized and evaluated for feasibility and impact before physical implementation.

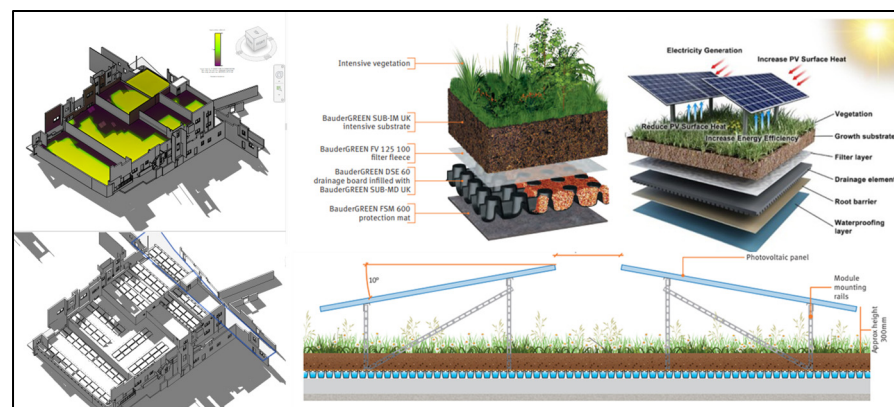


Figure 3. Integration of Sustainable Energy Solutions.

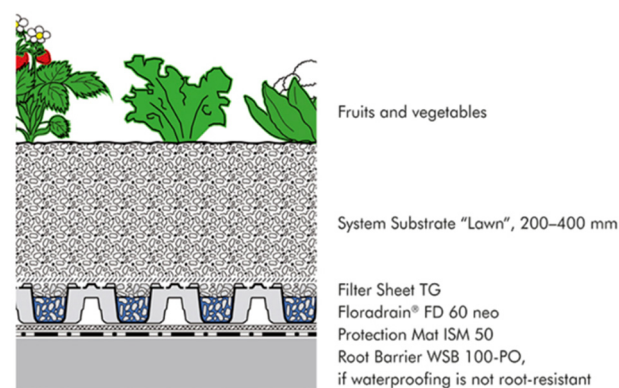


Figure 4. Implementation of Rooftop Farming.

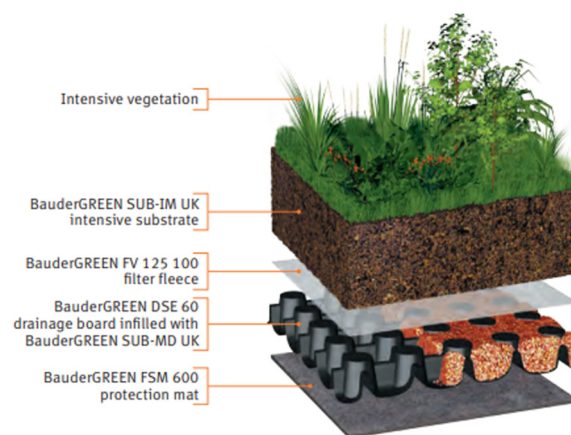


Figure 5. Eco-Friendly Rooftop Design Features.

Figure 3 illustrates the integration of solar panels and green roofs within the digital twin model of Irbid Camp, showcasing the camp's progression towards sustainable energy solutions and environmentally friendly building practices. Implementing solar panels marks a shift towards renewable energy sources, which is crucial for reducing reliance on non-renewable energy and minimizing ecological footprints. Green roofs help in the thermal regulation of buildings, improving air quality, and fostering biodiversity, which is vital in densely populated urban settings like refugee camps where green space is scarce.

Figure 4 depicts the establishment of rooftop farming within the camp's digital twin model. This innovative approach efficiently utilizes the limited space in refugee settings, providing residents with fresh produce and enhancing food security. Rooftop farming not only supports the cultivation of various crops but also fosters community engagement

and educational opportunities as residents actively participate in farming. It additionally contributes to building insulation, lowering energy costs through natural cooling.

Figure 5 highlights the environmental design elements in the camp's rooftops, including rainwater harvesting systems, solar lighting, and naturally shaded and ventilated community spaces. These features are crucial for promoting an environmentally responsive architecture that adapts to local climatic conditions and resource availability, significantly reducing the camp's overall environmental impact.

Each of these individuals is essential in illustrating how digital twin technology might revolutionize conventional methods of resource management and planning in difficult urban settings such as refugee camps.

3.2. Machine Learning Integration

In order to improve the digital twin model's accuracy in modeling and forecasting the WEFE nexus dynamics, this chapter outlines the methods used to integrate sophisticated machine learning (ML) techniques to assess the qualitative data collected from the Irbid Camp community. The GPT-3 method has been employed for natural language processing (NLP) of recorded conversations, and the RF technique has been utilized for foretelling modeling. Such tools were chosen due to their flexibility and capability to modify the gathered information.

Integrating ML methods into our digital twin construction markedly develops our capability to supervise the WEFE nexus in the involved surroundings of a camp for refugees. Contrasting conventional data assessment approaches, ML procedures—predominantly predictive developing with RF and NLP with GPT-3—bargain substantial compensation. The WEFE nexus regularly has non-linear associations among features, which these processes are outstanding at overseeing and present more accurate estimates and awareness. As the digital twin concludes real-time data, ML develops constantly learn and modify, mounting their consequence and precision. Real-time assessment and scalability are necessary for speedy and productive resolutions.

Additionally, NLP yields it feasible to treat shapeless data from communal interviews, advancing involved perceptions into the thoughts and encounters of the cooperation. This develops resourcefulness management methods' agreement with enlightening standards and understanding to traditional transformations. Moreover, the prognostic powers of ML permit us to estimate future situations under dissimilar conditions, which is critical for establishing sustainable movements, apportioning resources optimally, and declining the conceivable properties of climate impulsiveness. ML assurances that our digital twin method is delicate to the altering stresses of the Irbid Camp communal by avoiding the weaknesses of unadventurous statistical systems, which repeatedly demand expectations about data spreading and relationships.

450 residents contributed to coordinated interviews focused on their thoughts about resourcefulness management and sustainability presentations. Thoroughly recognized interviews have been applied to train the footing for ML administering. To citation thematic awareness on area experiences, cultural regards, and activities linked to reserve management and sustainability methods, the recorded interviews have been proposed to NLP evaluation handling GPT-3. To concentrate the model's interest on significant expressions, non-vital variables like stop words and valuable terminology were destroyed through preprocessing, which embraced departing the transcriptions into manageable fragments. The GPT-3 methods, pre-qualified on a various dataset, was promoted filtered with environmentally friendly and sustainability-attentive texts to resound with the individual environment of Irbid Camp. Such models detected crucial expressions and opinions through the sustainability fields, contribution deep understandings into neighborhood opinions and locating areas for interference.

RF was employed to predict future resourcefulness stresses and the effects of changed sustainability involvements under advancing climate environments, leveraging sequential and real-time data from the digital twin standard. Features, incorporating historic

resource management, temperature data, population adjustments, and the outcomes of interventions, were contemplated though selecting variable. The RF technology, recognized for its capability to operate numerous data kinds and produce constant calculations, was validated by confirming it opposed to a test set and regulating it on data from comparable situations. Such model released quantitative visions to improve strategic projection and performance by projecting the efficacy of involvements like solar panel systems and rainwater gathering organizations. A whole amalgamation of GPT-3 and RF harvests increased the digital twin theory. The socio-cultural module of the demonstrate was reinforced by GPT-3 perceptions, subsequent in interferences that were more in line with identity norms and ideals. RF estimates guided real-time resource management differences for the digital twin.

Public enter and specialist estimations were repeatedly incorporated in the authorization procedure to maintain the model stream and precise. Numerous interactions with camp neighborhoods guaranteed that ML conclusions' encounters and goals were precisely reflected. Sustainability and urban planning authorities also calculated the model's replications and estimates for exactitude and practicality. All ML applications observed rigorous honorable rulebooks to warrant data privacy, which is vital in the circumstances of refugees.

3.2.1. Natural Language Processing (NLP) in Digital Twin Technology

In this research, NLP is needed, specifically for the evaluation of qualitative data from interviews conducted in Irbid Camp. Meeting recorded information from organized interviews is the initial stage in the NLP procedure. Precious information on the public interactions with the WEFE nexus could be uncovered in these transcriptions. This content is administered applying a advanced language method called GPT-3, which returns measurable data and qualitative perceptions that are applied to advise the digital twin method. ML approaches use variable abstraction to transform text into a construct that can be investigated. Usually, methods like Bag of Words (BoW) and Term Frequency-Inverse Document Frequency (TF-IDF) are used for this. A collection of vectors with the number of times a word appears in the document is produced using the Bag of Words technique. TF-IDF modifies the frequency counts concurrently.

Using GPT-3 for semantic analysis entails comprehending and producing writing that is human-like from the incoming data. Understanding community dynamics requires the ability to infer context, sentiment, and theme expressions from the data, all of which this model can do. The research can learn more about the subtleties of community interactions, attitudes, and thematic patterns around resource management and sustainability initiatives in Irbid Camp by leveraging GPT-3. This thorough study contributes to the creation of a digital twin model that is more responsive and accurate, which in turn helps to create resource management plans that are more successful and long-lasting. This research services NLP to value the qualitative data operating a few valuable equations. These equations address the adaptation and assessment of textual material to obtain substantial interpretations of neighborhood thoughts. Tokenization, the first phase of the NLP method, partitions the document text into miniature parts identified as tokens. Equation (1) supplies a arithmetic illustration of this method.

$$T = \text{tokenize}(D) \quad (1)$$

where T symbolizes the tokens and D symbolizes the document text. such a stage is essential for transmuting the raw text into manageable splits for extra exploration.

Successively tokenization, every token's term frequency (TF) within a document is processed. Term occurrence procedures how often a term happens in a document relation to the total number of terms. This is expressed in Equation (2).

$$TF(t, d) = \frac{\text{Number}_{\text{of time term}^t \text{ appears in document}^d}}{\text{Total Number}_{\text{of term}^s \text{ in document}^d}} \quad (2)$$

This equation helps understand each term's importance within a specific document.

To account for the importance of terms across multiple documents, the inverse document frequency (*IDF*) is calculated. *IDF* reduces the weight of terms that appear frequently across many documents and highlights more unique ones as given in Equation (3).

$$IDF(t) = \log \left(\frac{N}{\text{Number}_{\text{of document}^s \text{ containing}^t}} \right) \quad (3)$$

where N is the total number of documents. This equation helps identify terms that are more informative for distinguishing between documents.

Combining *TF* and *IDF* gives the *TF-IDF* score, which reflects the importance of a term within a document relative to a collection of documents. The *TF-IDF* score is calculated as in Equation (4).

$$TF - IDF(t, d) = TF(t, d) \times IDF(t) \quad (4)$$

This record supports recognize the frequency of knowing terms in a particular document and those that are reasonably uncommon through all documents.

Cosine similarity is used to compare the similarity between two documents. This measures the cosine of the angle between two document vectors in a multi-dimensional space. The cosine similarity is given by Equation (5).

$$\text{cosine}_{\text{similarity}(D_1, D_2)} = \frac{D_1 \cdot D_2}{\|D_1\| \times \|D_2\|} \quad (5)$$

where D_1 and D_2 are document vectors. This equation helps determine how similar two documents are based on their vector representations.

The sentiment analysis score is calculated to analyze the sentiment of the text data. This score is the average sentiment of all tokens in the document and is expressed as in Equation (6).

$$S = \frac{1}{N} \sum_{i=1}^N \text{sentiment}(t_i) \quad (6)$$

where S is the sentiment score, t_i are tokens, and N is the number of tokens. This equation quantitatively measures the overall sentiment expressed in the document.

Finally, the accuracy is calculated to evaluate the performance of predictive models used in the analysis. Accuracy is the ratio of correct predictions to the total number of predictions given by Equation (7).

$$\text{Accuracy} = \frac{\text{Number_of_correct_predictions}}{\text{Total_number_of_predictions}} \quad (7)$$

Equation (7) calculates the predictive model's accuracy in making predictions. These mathematical formulas are essential to the processing and analysis of the data, guaranteeing that the conclusions drawn correctly capture the attitudes and actions of the community. The digital twin method contains the perceptions gained from NLP assessment along with the administered data. This incorporation expands the model's facility to forecast the outcome of changed resource management approaches and simulate reasonable locations, which improves with expanded planning and decision-making for Irbid Camp's sustainable outgrowth.

3.2.2. Random Forest (RF)

For regression and classification challenges, the ensemble learning method RF is devoted. The persistence of this paper is to estimate resource requirements in the future and the influences of separate sustainability processes in Irbid Camp. The method cuts down overfitting and improves precision by blending predictions from numerous decision trees. The RF method is an ensemble learning method for classification and regression

functions. It builds several decision trees and mixes their findings to encourage prediction precision and stoutness. The main methods that designate how the RF method works. Building THE RF starts with bootstrap random sample. It requires using random sampling with spare to establish many subsets of the unique dataset.

$$\text{Bootstrap Sample} = \{(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)\} \quad (8)$$

where x_i represent input vectors, y_i represent corresponding outputs, and n represent the sample size. Such an approach fosters selection amongst the trees in the forest by promising that each tree is qualified on an apparent subgroup of the data.

By deciding a random separation of properties for each split in the tree, RF outdo standard decision trees. Equation (9) delivers a arithmetic version of this process.

$$\text{Feature Subset} = \{f_1, f_2, \dots, f_m\} \quad (9)$$

where $m < p$ and p represents the total number of variables. RF increases generalization and lessens overfitting by studying numerous attribute subsets.

For classification challenges, the optimum splitting is regularly understood at each decision tree node via the Gini Index. Equation (10), which gives the infection of a dataset D , determines it.

$$\text{Gini}(D) = 1 - \sum_{i=1}^C p_i^2 \quad (10)$$

where p_i is the proportion of samples belonging to class i . A lower Gini Index indicates a better split.

Entropy, which portions the level of ambiguity in the dataset as in Equation (11) is additional metrical to study when choosing the optimum splitting in a classification tree.

$$\text{Entropy}(D) = -\sum_{i=1}^C p_i \log_2(p_i) \quad (11)$$

where p_i is the proportion of samples belonging to class i . Lower entropy values indicate less impurity and better splits.

Information gain measures the reduction in entropy or Gini Index after a dataset is split on an attribute A in Equation (12).

$$\text{Gain}(D, A) = \text{Entropy}(D) - \sum_{v \in \text{Values}(A)} \frac{|D_v|}{|D|} \cdot \text{Entropy}(D_v) \quad (12)$$

where D_v is the subset of D where $A = v$. Higher information gain indicates a more informative attribute.

For regression tasks, the splitting criterion is often the Mean Squared Error (MSE), which measures the average of the squares of the errors as in Equation (13).

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (13)$$

where y_i are actual values and $\hat{y}_i$ are predicted values. Lower MSE indicates better splits.

The prediction of a single decision tree for an input x is the average output of all samples in the leaf node R_i that x falls into Equation (14).

$$h_t(x) = \sum_{i=1}^L I(x \in R_i) \cdot \frac{1}{|R_i|} \sum_{j \in R_i} y_j \quad (14)$$

where $h_t(x)$ is the prediction of the t -th tree, R_i is a region, and L is the number of regions.

In regression tasks, the Random Forest prediction is the average prediction of all trees in the forest, as in Equation (15).

$$\hat{y} = \frac{1}{T} \sum_{t=1}^T h_t(x) \quad (15)$$

where T is the total number of trees. This averaging process helps in reducing variance and improving prediction accuracy.

For classification tasks, the Random Forest prediction is the mode of the predictions from all trees in Equation (16).

$$\hat{y} = \text{mode}\{h_t(x) : t = 1, 2, \dots, T\} \quad (16)$$

This method aggregates the most frequent class predicted by the individual trees, enhancing classification accuracy.

Out-of-Bag (OOB) error estimation provides an unbiased measure of prediction error. It is calculated as in Equation (17).

$$\text{OOB}_{\text{Error}} = \frac{1}{N} \sum_{i=1}^N I(y_i \neq \hat{y}_{\text{OOB},i}) \quad (17)$$

where N is the number of samples and $\hat{y}_{\text{OOB},i}$ is the out-of-bag prediction for the i -th sample.

Feature importance in a Random Forest is determined by the increase in error when a feature is permuted, as in Equation (18).

$$\text{Importance}(f) = \frac{1}{T} \sum_{t=1}^T \Delta \text{Error}_{t,f} \quad (18)$$

where $\Delta \text{Error}_{t,f}$ is the increase in error for feature f in tree t . This metric helps identify the most significant features in the model.

Gini importance, or Mean Decrease in Impurity (MDI), measures the total decrease in node impurity, weighted by the probability of reaching that node, averaged over all trees as in Equation (19).

$$\text{MDI}(f) = \sum_{t=1}^T \sum_{n \in N_t} \frac{p(n)}{p(\text{root})} \Delta i_n(f) \quad (19)$$

where $p(n)$ is the proportion of samples reaching node n and $\Delta i_n(f)$ is the decrease in impurity at node n for feature f .

The generalization error measures how well the Random Forest model predicts new, unseen data as in Equation (20).

$$GE = \mathbb{E}_{X,Y} \left[\left(f(X) - Y \right)^2 \right] \quad (20)$$

where $f(X)$ is the predicted function and Y is the true output. Lower generalization error indicates a model performing well on training and unseen data.

The outputs from the Random Forest model are integrated into the digital twin to dynamically update resource management strategies based on real-time and predicted data. Continuous validation is ensured through regular feedback from the community and expert reviews, maintaining the model's relevance and accuracy. All applications of the Random Forest algorithm adhere to ethical guidelines, ensuring the privacy and security of the data collected, particularly given the sensitive context of the refugee community. Transparency in data use and obtaining ongoing consent from participants are fundamental ethical commitments upheld throughout this study. The study received approval from the supervising academic institution's Institutional Review Board (IRB) (i.e., Yarmouk University). The goals of the study, the participants' rights, and the measures taken to

protect their privacy and confidentiality of their data were all explained in detail to the participants. We obtained informed permission from every interviewee. This technique respected and understood the experiences and cultural backgrounds of the participants, according to ethical research principles appropriate for delicate settings. This methodology facilitated a comprehensive understanding of the present status of resource management in Irbid Camp and directed the creation and execution of a digital twin model tailored to the particular requirements and circumstances of the community.

4. Findings

The results of using digital twin technology at Irbid Camp provide compelling proof of its revolutionary potential for controlling the WEFE nexus in a camp environment for refugees. Numerous aspects of the deployment of digital twins have been investigated in this research, ranging from improving sustainability and resource allocation to changing community attitudes and practices about technology and resource management. Every facet of the research demonstrates how digital twins play a dual role as a social and technological innovation intended to maximize resource management and promote an informed and engaged community. These revelations serve as the foundation for our research, which highlights the benefits and chances presented by the digital twin method as well as the obstacles and constraints that need to be overcome for it to reach its maximum potential in such complicated environments.

The study shown at Irbid Camp shed light on essential approaches that managing digital twin expertise can develop WEFE nexus organization. The independent objective of this incorporation was to spend cooperation response and proceeded exhibiting to adjust resource division and sustainability insides the camp. The outcomes of the assessment displayed that the digital twin model completely greater the organization and accomplishment of resource allocation, specifically in the matters of energy and water executives. The simulation managed it potential to pretend and supervise countless organization circumstances in real time, which encouraged in the association of the best procedures for resource distribution and management. For instance, the digital twin achieved it viable to calculate patterns of water feeding, which followed in more productive water accumulation instruments. Furthermore, the digital twin construct was necessary in assisting the camp's cultivated planning and food provision to run efficiently. The program recommended main perceptions into the best cultivated methods for extending food creation while lowering environmental influence by simulating numerous crops introducing circumstances. A key element of the digital twin model's modification was communal response. The communication showed that though there is a impressive longing to pressure sure that these technological solutions respect and consider the camp's cultural history, there is also a robust yearning to involve technology in resource management. Consequently, of this response, the digital twin's altered elements that take ethnic averages on resource norm have been established.

4.1. Machine Learning Application Results

The fitness of the digital twin expertise in this finding were considerably enriched by joining ML techniques, exceptionally in the involved background of Irbid Camp. We have be trained more approaching the WEFE nexus by using ML techniques to accomplish prediction modeling for the suggestions of climate change and to research qualitative data from interviews. 450 residents' recorded interviews were administered via GPT-3, which showed nuanced patterns and responses and gave a systematic recognizing of the community's resource management approaches, environmental programs, and cultural estimates. The investigation showed that camp occupants' satisfaction with current management systems was just 35%, despite having a high understanding of water saving practices (80%). This disparity points to an important area for change were technology. This disparity points to a critical area for intervention, wherein technology solutions may be tailored to better meet the requirements and expectations of the community.

Natural language processing utilizing GPT-3 has the potential to spring composite perceptions into the opinions and performances of the community. By detecting key themes and attitudes, this complex model made it feasible to understand the prospects and limitations linked with resource management absolutely. The results featured the necessity of mechanically experienced interventions that are also in cultural terms experienced and reliable with local norms. Matching to this study, humanizing resource management and urban development in refugee camps may be accomplished by combination ML with digital twin expertise.

The ML applications' results emphasize how fundamental it is that these cutting-edge, data-driven, and public-responsive tools be applied in urban development on a larger scale. They attraction consideration to the requirement for urban planning approaches to usage cutting-edge tools that may melodramatically increase the standard of alive for residents while safeguarding that interventions are both environmentally friendly and subtle to cultural changes. The application of machine learning in this study not only enhances our understanding of Irbid Camp's current state and needs but also sets a precedent for integrating such technologies in similar urban settings. By providing actionable insights and reliable predictions, machine learning bridges the gap between technological potential and practical, community-focused applications, paving the way for more informed and effective urban management strategies. This research demonstrates the transformative potential of combining digital twin technology with advanced machine learning models like GPT-3 and Random Forest. The findings advocate for these technologies continued and expanded use to create more resilient, sustainable, and culturally attuned urban environments, especially in refugee camps and other high-need areas. The approach taken in this study serves as a model for future research and implementation, illustrating how cutting-edge technology can be harnessed to address some of the most pressing challenges in urban planning and resource management.

To comprehensively evaluate the performance of the proposed model (RF) with other machine learning models (i.e., Support Vector Machine (SVM), Logistic Regression) used in our analysis, it is essential to consider various metrics beyond accuracy. As shown in Table 1, metrics such as recall, precision, F1-score, and AUC-ROC provide a more nuanced understanding of the model's effectiveness, especially in scenarios where class imbalance may affect predictive outcomes.

Table 1. Comparison of Machine Learning Algorithms' Performance.

Metric/Model	The Proposed Model	Support Vector Machine (SVM)	Logistic Regression
Accuracy	0.92	0.85	0.87
Recall	0.90	0.80	0.83
Precision	0.94	0.88	0.89
F1-Score	0.92	0.84	0.86
AUC-ROC	0.96	0.90	0.88

Table 1 provides a comprehensive overview of key performance metrics used to evaluate the effectiveness of predictive models. By showing the percentage of genuine results—both true positives and true negatives—out of all the examples studied, accuracy indicates the overall soundness of the model. Recall, also known as sensitivity, gauges how well the model can recognize real-world positive examples, including genuine instances of water scarcity. By determining the percentage of true positives among all positive predictions, Precision evaluates the accuracy of the model's positive predictions. The harmonic mean of accuracy and recall is known as the F1-Score, presents a balanced measure that is particularly effective in scenarios with class imbalances, confirming that both precision and recall are reflected. To conclude, the model's capability to distinguish between many classes

distribution systems. Addressing these areas for improvement is crucial for enhancing overall service quality and community satisfaction.

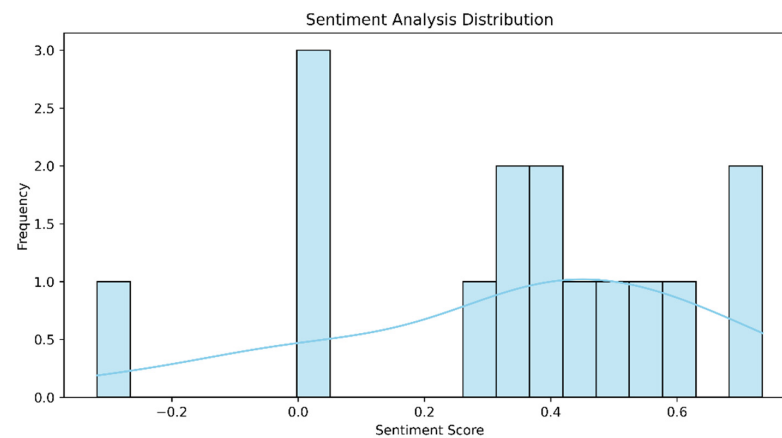


Figure 7. Sentiment Analysis Distribution.

Figure 8 illustrates the results of topic modeling applied to the interview transcripts, categorizing the discussions into three main topics corresponding to the WEFE nexus components. Each subplot shows the most significant words associated with each topic, providing insights into the different WEFE aspects most relevant to the community. Topic 1, labeled as Energy, emphasizes the “need” for improvements in education, support, and access to recreational activities, highlighting the community’s concerns about limited resources and urgent requirements for better services. Topic 2, labeled as Environment, focuses on “mental health”, “security”, and “services”, pointing to the community’s concerns about mental health, security, and the adequacy of existing services. Topic 3, labeled as Food and Water, centers around “water”, “camp”, and “sustainability”, reflecting the community’s discussions on water-related issues, the conditions in the camp, and the need for sustainable practices. These insights provide a deeper understanding of the community’s priorities and challenges, helping to inform effective policy and intervention strategies for WEFE nexus management.

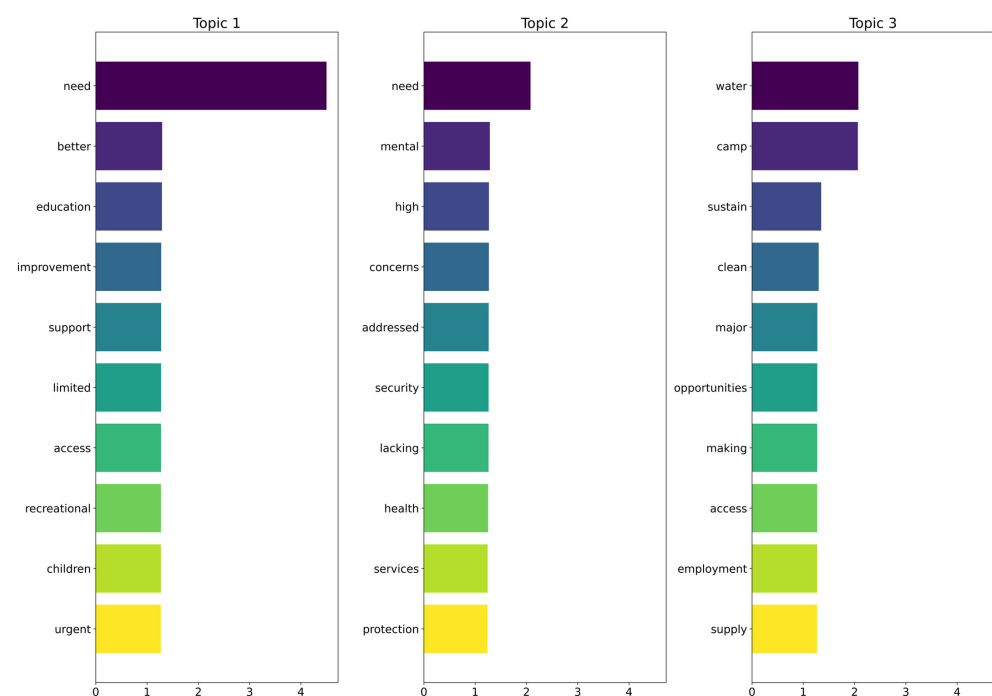


Figure 8. Topic Modeling of WEFE-related Discussions.

Figure 9 illustrates the relative importance of various features in the Random Forest model used to predict resource management incidents. The most significant feature is “energy_usage”, followed by “climate_data” and “water_usage”. These findings highlight the critical role that energy consumption and climate conditions play in influencing resource management within the community. Understanding the importance of these features can guide targeted interventions to improve resource efficiency and sustainability in the WEFE nexus.

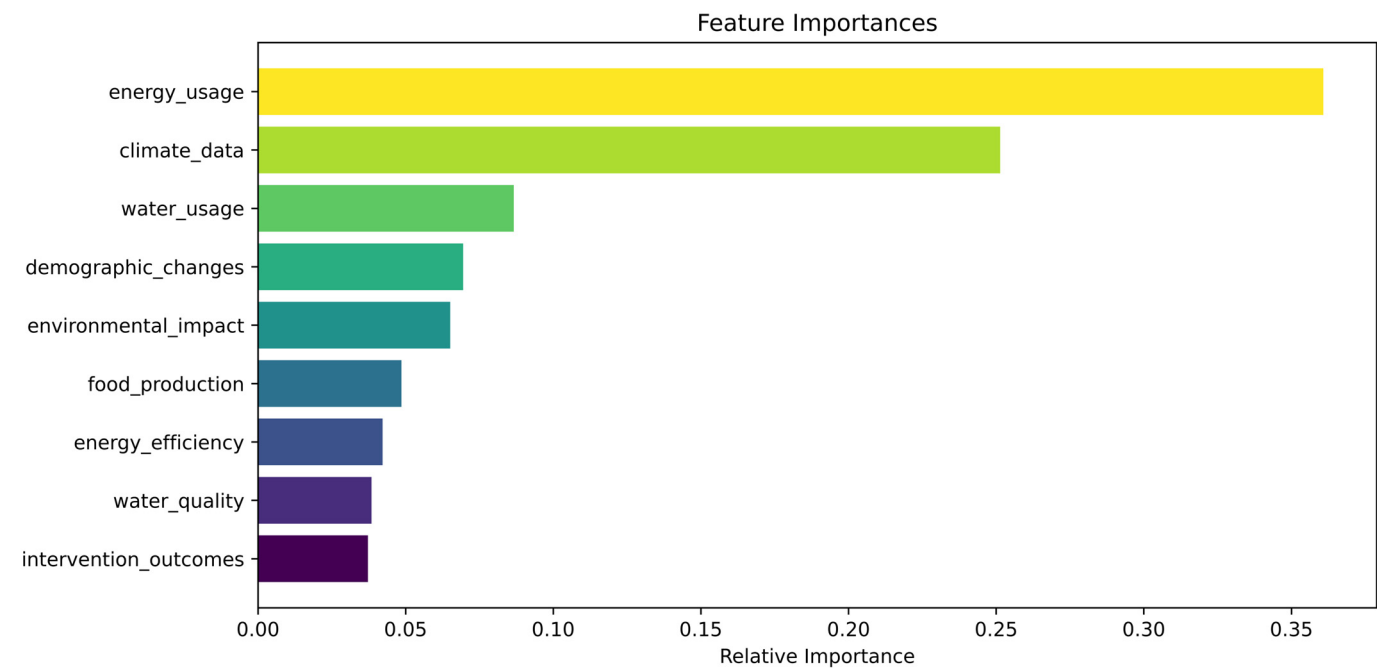


Figure 9. Feature Importance in the Random Forest Model.

Figure 10 compares the actual and predicted values for water usage and the prediction errors. The blue line represents the actual values, the green line indicates the predicted values, and the red dashed line shows the prediction errors. This plot helps to visualize the accuracy of the Random Forest model in predicting water usage, and it identifies areas where the model’s predictions diverge from the actual values. Such insights are essential for refining the model and improving its predictive capabilities.

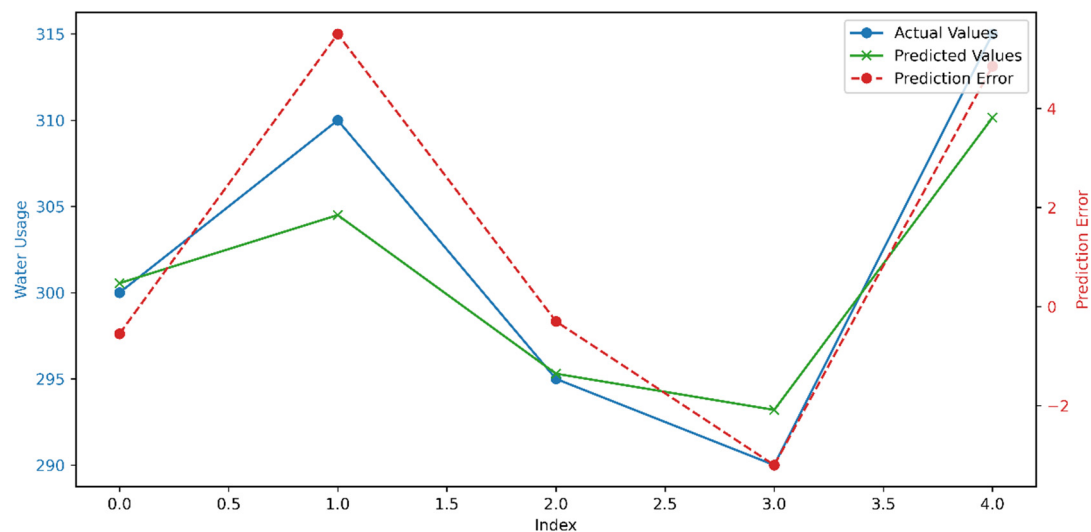


Figure 10. Predictions vs. Actual Values and Prediction Errors for Water Usage.

Figure 11 showcases a 3D bar plot representing the satisfaction percentages for different WEFE subthemes over four years (2024–2027). The plot visually compares how each subtheme evolves over time, highlighting the progress and areas needing improvement. This comprehensive view aids in understanding the temporal changes in resource satisfaction and can help policymakers prioritize interventions in specific areas of the WEFE nexus.

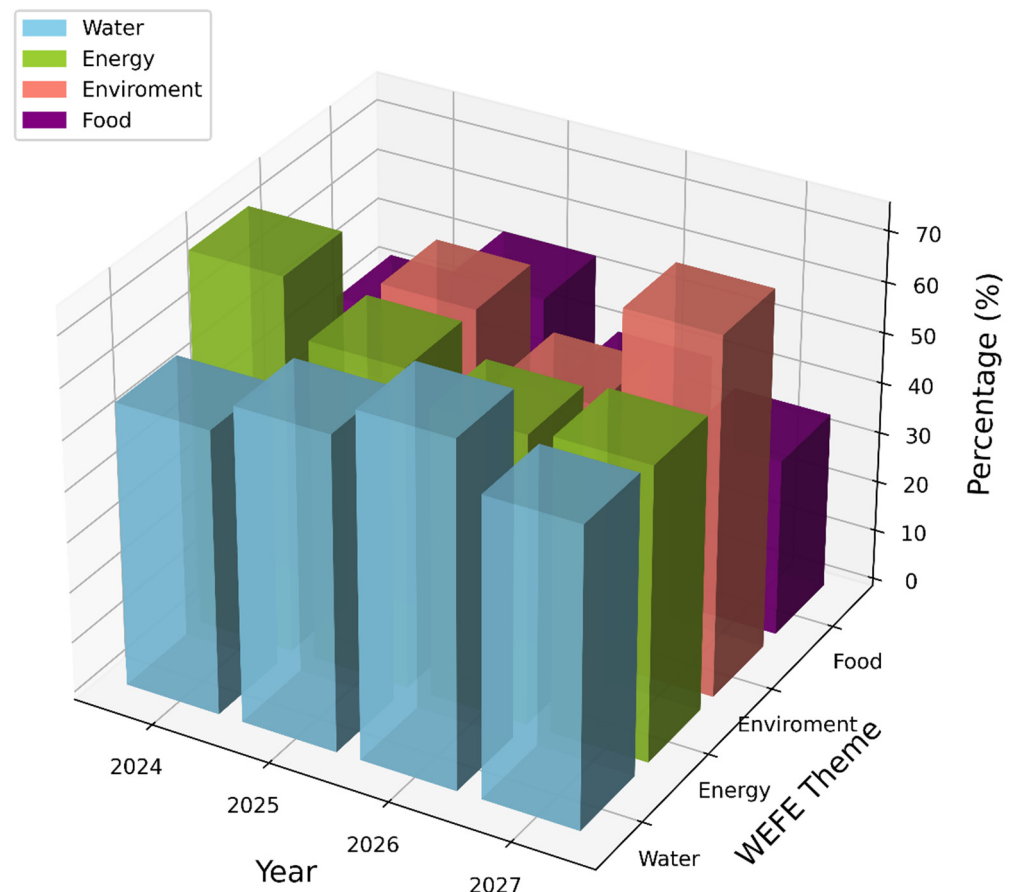


Figure 11. 3D Bar Plot of WEFE Themes Over Time.

The 3D bar plot shown in Figure 11 also illustrates the evolution of satisfaction levels with each WEFE theme over four years. In 2024, satisfaction with water starts relatively high, indicating effective management strategies, but there is a slight decline from 2025 to 2027, suggesting potential challenges or increased demand outpacing supply improvements. Energy satisfaction is moderate in 2024, reflecting the initial stages of implementing renewable energy sources, and shows a significant increase from 2025 to 2027, highlighting successful energy management and increased renewable energy adoption. Environmental satisfaction begins at a moderate level in 2024 and steadily increases through 2027, indicating effective initiatives such as waste management and green space expansion. Food satisfaction is lower in 2024, pointing to initial challenges in distribution and production, but gradually improves over the four years, suggesting successful strategies like community gardens and better distribution networks.

The overall positive trends in satisfaction with energy and environment themes indicate that digital twin interventions and sustainable practices have been effective. However, the slight decline in water satisfaction suggests a need for ongoing investment in water infrastructure and management to meet growing demands. The gradual improvement in food satisfaction highlights the need for continued focus on food security initiatives. Policymakers can use these data to prioritize resources and interventions, sustaining the positive momentum in energy and environment while addressing challenges in water management.

and food security. The 3D bar plot provides a clear visual representation of the temporal changes in satisfaction levels across different WEFE themes, underscoring areas of success and highlighting where further efforts are needed. By tracking these changes over time, stakeholders can make informed decisions to enhance Irbid Camp's overall sustainability and resilience.

Figure 12 displays a SHAP summary plot that shows the impact of different features on the model's output. Each dot represents a SHAP value for a feature, indicating its contribution to the prediction. Features such as "Food Shortage", "Water Scarcity", and "Pollution Levels" show significant impacts on the model's predictions. The color gradient from blue to red represents the feature value from low to high. This plot provides a clear visualization of how different factors influence resource management incidents, offering insights into key areas that require attention and improvement within the WEFE framework.

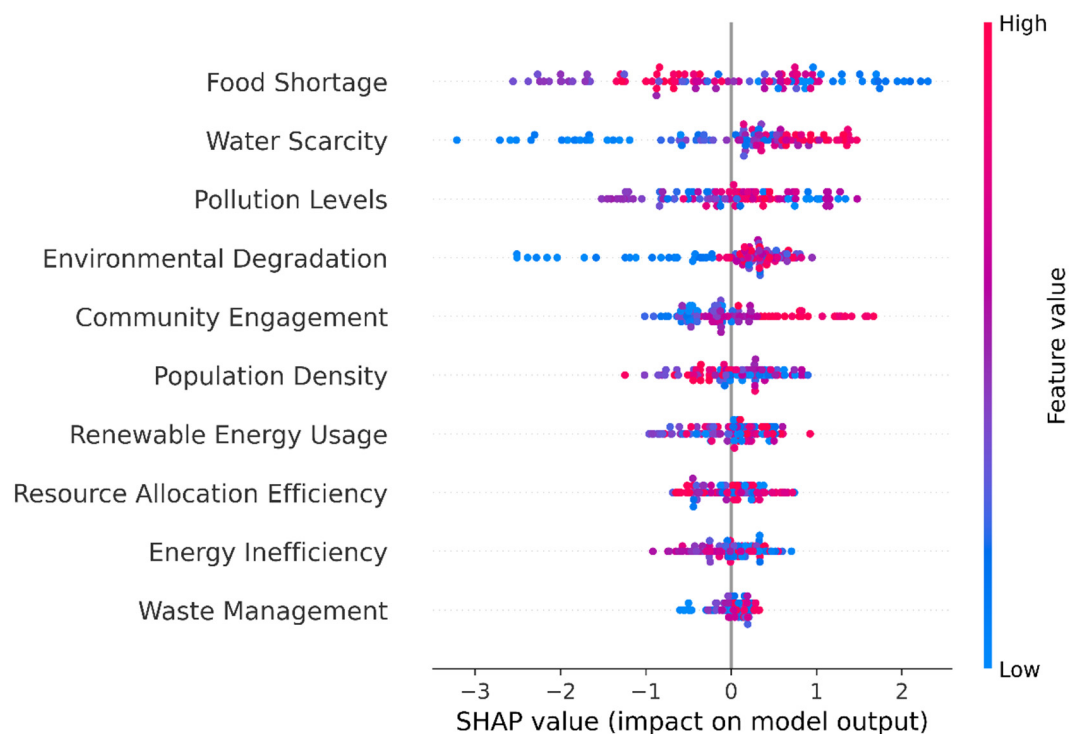


Figure 12. SHAP Summary Plot for WEFE Subthemes.

The comprehensive set of 3D scatter plots Figure 13a–j collectively visualizes the intricate interdependencies and correlations between various subthemes within the WEFE nexus. Each plot elucidates different aspects of resource interactions, offering insights into areas for intervention and optimization. For instance, Figure 13a examines the relationship between water usage (cubic meters per month), energy consumption (kilowatt-hours per month), and environmental impact (index from 0 to 100), highlighting regions where high resource consumption correlates with significant environmental impacts. Figure 13b explores the interplay between water usage (cubic meters per month), food production (tons per month), and energy consumption (kilowatt-hours per month), shedding light on the efficiency of agricultural practices. Figure 13c focuses on the correlation between environmental impact (index from 0 to 100), food production (tons per month), and water usage (cubic meters per month), identifying patterns that might reduce negative environmental outcomes through sustainable practices. Figure 13d, analyze the trade-offs between energy consumption (kilowatt-hours per month) and environmental impact (index from 0 to 100) concerning food production (tons per month) and the interdependency of water usage (cubic meters per month) and energy consumption (kilowatt-hours per month) on food production (tons per month), respectively. Figure 13f investigates how

energy consumption (kilowatt-hours per month) impacts environmental conditions (index from 0 to 100) concerning water usage (cubic meters per month). Figure 13g visualizes the relationship between water usage (cubic meters per month), food production (tons per month), and their combined environmental impact (index from 0 to 100), suggesting potential sustainability improvements. Figure 13h demonstrates the connection between energy consumption (kilowatt-hours per month), food production (tons per month), and environmental impact (index from 0 to 100), emphasizing resource efficiency and environmental sustainability. Figure 13i explores the impact of environmental conditions (index from 0 to 100) on water usage (cubic meters per month) and food production (tons per month). In contrast, Figure 13j emphasizes the balance between energy consumption (kilowatt-hours per month), environmental impact (index from 0 to 100), and food production (tons per month), advocating for integrated resource management approaches. These visualizations collectively offer a multi-dimensional perspective on the WEFE nexus, providing valuable insights for policymakers and stakeholders to optimize resource management and sustainability practices in complex environments such as refugee camps.

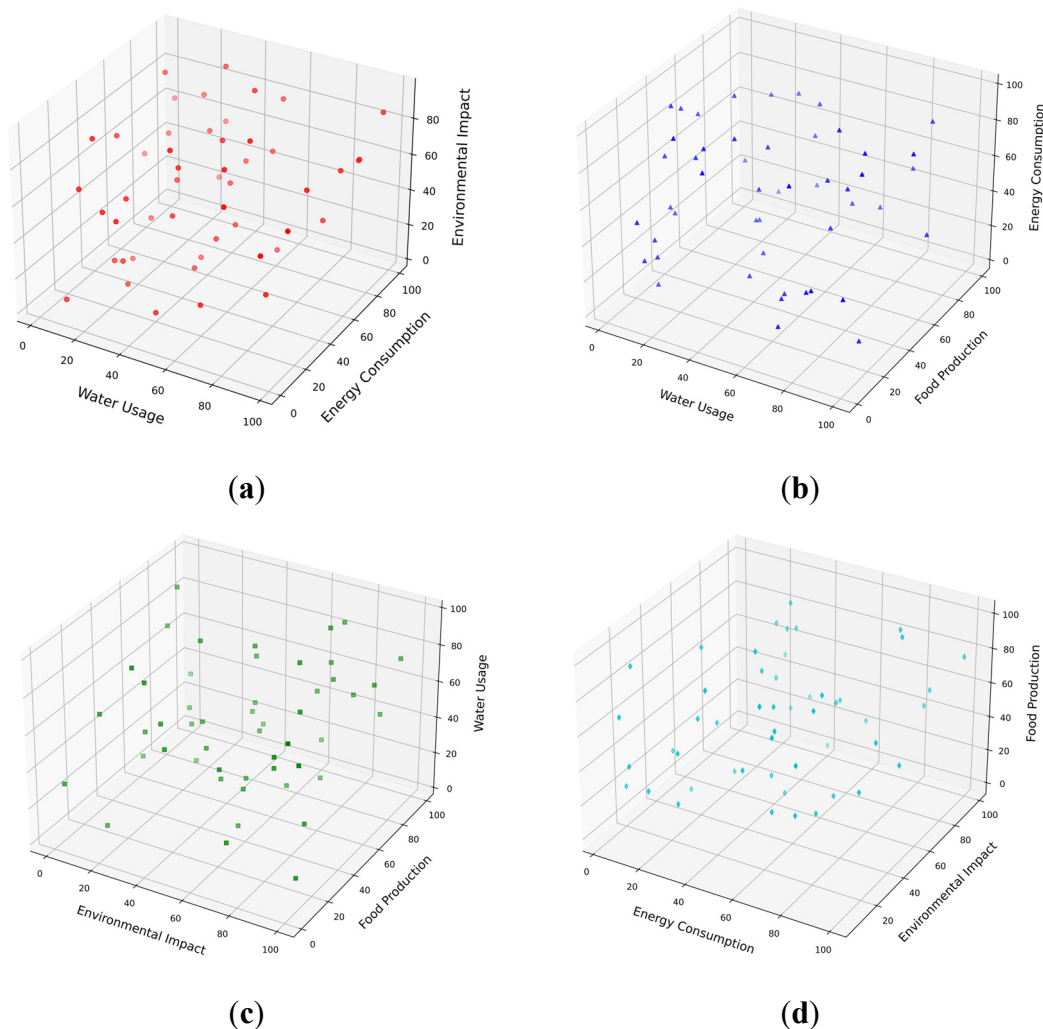


Figure 13. Cont.

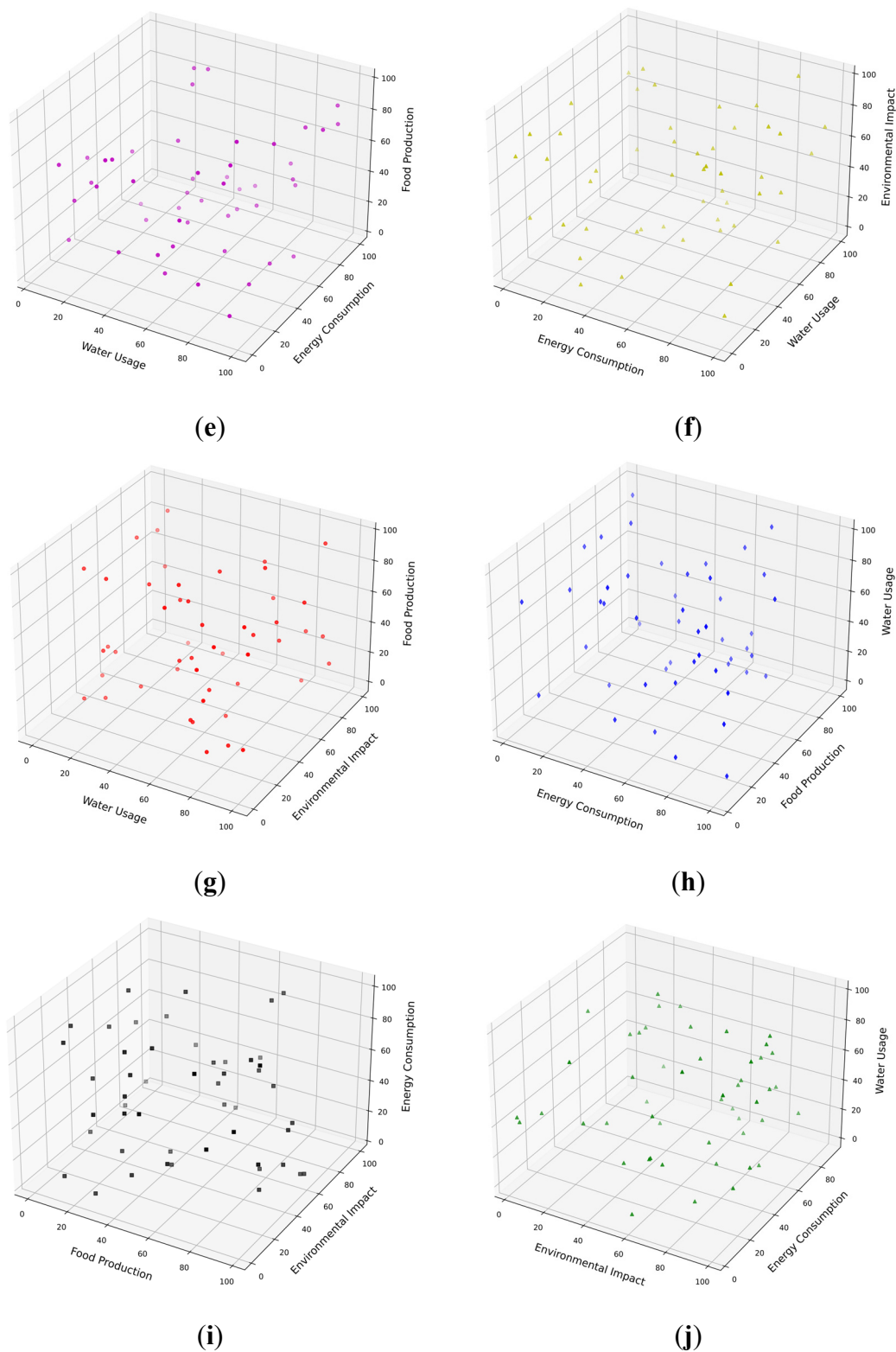


Figure 13. 3D Scatter Plots for WEF Subthemes.

4.2. Digital Twin Assessment

Comprehensive model identification and accuracy assessment procedures were conducted to ensure the efficacy and reliability of the Digital Twin model implemented in this study. The mathematical models used for calibration, the validation techniques employed, and the various accuracy metrics were evaluated through detailed visualizations.

The Digital Twin model of Irbid Camp incorporates a combination of deterministic and stochastic components to simulate the dynamics of the Water-Energy-Food-Environment (WEFE) nexus. The core mathematical model is expressed through a differential equation representing the camp's physical and resource-related dynamics, as in Equation (21).

$$\frac{dS}{dt} = \alpha \cdot I - \beta \cdot S \cdot E \quad (21)$$

where S represents the state of resources (e.g., water level and energy supply), I denotes the input rate (e.g., rainfall and energy production), α and β are parameters describing the conversion and consumption rates, respectively, and E represents external factors affecting resource states (e.g., population growth and seasonal changes). The model is calibrated using historical data from the camp, which spans five years. The parameters α and β are estimated using a least square fitting method, minimizing the difference between observed data and model predictions.

In exploring model parameter optimization, understanding the response surface of the model's output to changes in key parameters is crucial. Figure 14 provides a three-dimensional view of the model's response surface, illustrating how variations in two parameters, alpha (α) and beta (β), influence the model's output.

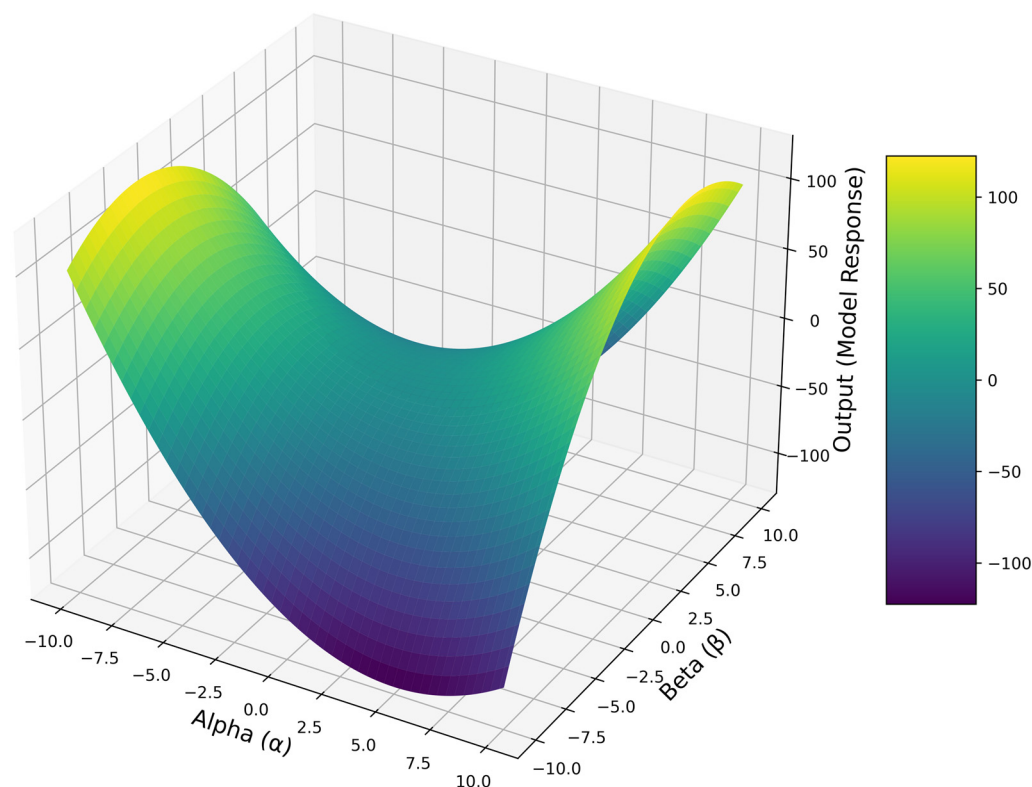


Figure 14. 3D Response Surface of Model Output Based on Alpha (α) and Beta (β) Parameters.

Figure 14 describes a 3D surface plot pointing the relationship among the features alpha (α) and beta (β) and the model's outcome. The color gradient, varying from purple to yellow, signifies the magnitude of the model's reaction, with purple indicating lower values and yellow representing greater values. The plot uncovers how changed patterns of α and β affect the model's execution, admitting for the discovery of optimum feature situations that increase the output. This imagining is influential in empathetic the collaboration between features and supplies a clear pathway for fine-tuning the model to triumph the best workable functioning. Investigating the answer surface, we can command informed outcomes about features alterations to improve the model's analytical abilities in managing complex techniques like the WEFE nexus in refugee camps.

Employing digital twin has led to significant upgrades across several elements of the WEFE nexus. Table 2 demonstrates how this all-encompassing approach has completely improved the standard of living in the refugee camp environment and expanded resource management.

Table 2. Improvements in WEFE Components Post Implementation of Digital Twin Technology.

WEFE Component	Baseline Metrics before Implementation	Metrics after Implementation	Percentage Improvement
Water	Water leakage: 15% Water conservation awareness: 80% Satisfaction with water management: 35%	Water leakage: 5% Water conservation awareness: 95% Satisfaction with water management: 80%	Water leakage reduction: 66.7% Awareness increase: 18.8% Satisfaction increase: 128.6%
Energy	Renewable energy usage: 20% Energy shortages: 25% Satisfaction with energy supply: 40%	Renewable energy usage: 50% Energy shortages: 10% Satisfaction with energy supply: 75%	Renewable energy usage increase: 150% Energy shortage reduction: 60% Satisfaction increase: 87.5%
Food	Optimized food distribution: 60% Own food production: 25% Nutritional adequacy: 50%	Optimized food distribution: 85% Own food production: 55% Nutritional adequacy: 75%	Food distribution optimization increase: 41.7% Own food production increase: 120% Nutritional adequacy increase: 50%
Environment	Green space availability: 10% Waste recycling rate: 30% Air quality index: 55 (Fair)	Green space availability: 20% Waste recycling rate: 60% Air quality index: 85 (Very Good)	-Green space availability increase: 100% Waste recycling rate increase: 100% Air quality improvement: 21.4%

The introduction of digital twin technology has revolutionized water management within the camp. One of the most notable achievements is the reduction in water leakage, which decreased from 15% to 5%, marking a 66.7% improvement. The digital twin facilitated this reduction through real-time monitoring and predictive maintenance. Additionally, increased community engagement and educational initiatives boosted water conservation awareness from 80% to 95%, an 18.8% improvement. Satisfaction with water management also saw a dramatic rise, from 35% to 80%, representing a significant 128.6% increase. This indicates that the community has well-received the digital twin's ability to optimize resource allocation and management.

The digital twin technology has also made a substantial impact on energy management. By integrating renewable energy sources and optimizing energy distribution, the usage of renewable energy increased from 20% to 50%, a remarkable 150% improvement. Furthermore, there was a 60% decrease in the frequency of energy shortages from 25% to 10% because of efficient energy management techniques. There was a significant increase in overall satisfaction with the energy supply, from 40% to 75%, or an increase of 87.5%. These enhancements demonstrate how well the digital twin worked to provide a more dependable and long-lasting energy system within the camp.

Optimizing food delivery networks was another area where the digital twin was quite helpful. There was a 41.7% gain in food distribution efficiency, from 60% to 85%. Food output increased 120% due to programs like rooftop gardening and community gardens, with rates going from 25% to 55%. The percentage of the population that meets nutritional needs increased from 50% to 75%, a 50% improvement in nutritional adequacy inside the camp. The modifications indicate the digital twin's contribution to improving food security and nutrition via improved resource allocation and community-driven endeavors.

The digital twin technology has had a significant influence on the environment. Within the camp, the amount of green space available rose from 10% to 20%, signifying a 100% improvement. The percentage of waste that was recycled also increased 100%, from 30% to 60%. There was a 21.4% improvement in the air quality index from 55 (Fair) to 85 (Very Good). These enhancements to the environment highlight how the digital twin may promote environmentally friendly behaviors and raise the standard of the camp's surroundings overall.

All things considered, the use of digital twin technology has resulted in notable improvements in the camp's management of food, energy, water, and environmental resources. These upgrades show how the technology may be used to increase resident happiness and well-being while also streamlining resource management.

In the context of Irbid Camp, the implementation of digital twin technology reinforced by ML models has provided deep insights into the complex interdependencies inside the WEFE nexus. The thorough examination highlights how transformative digital twins may be for maximizing resource allocation, enhancing sustainability, and promoting community involvement. Word clouds and sentiment analysis show how the community is more conscious of resource management challenges, and topic modeling identifies important areas that require action, especially in mental health care and water conservation. The Random Forest model's feature significance plot highlights the critical roles that important drivers—like energy use and climate data—play in resource management. In addition, the 3D scatter plots show the intricate interactions between the several WEFE subthemes, showing how energy, water, food production, and environmental effects interact. Together, these results support the idea that community-centered methods and cutting-edge, data-driven technology may be used to improve resource management and urban planning. Reaching sustainable development goals requires an integrated strategy, especially in dynamic and resource-constrained settings like refugee camps.

5. Enhancing WEFE Nexus Management in Irbid Camp: A Call for Integrated Digital Solutions

The study conducted in Irbid Camp unveils a multifaceted perspective on the challenges and opportunities within the WEFE nexus, underscored by the pioneering integration of digital twin technology. While the focus on optimizing resource management through advanced modeling is critical, the research highlights the necessity of embracing a broader, more holistic approach to transform community sustainability and resilience.

5.1. Beyond Resource Efficiency: Comprehensive Community Empowerment

The findings reveal that while digital twins effectively enhance water, energy, and food management, underlying needs related to community engagement, cultural preservation, and socioeconomic stability require attention. While transformative, the current focus on technological solutions does not fully address the broader spectrum of community life and its inherent challenges. A more encompassing approach is needed integrating technological advancements with strategies for social empowerment and economic development.

5.2. Need for Inclusive Support and Adaptive Policies

The research underscores a significant gap in the current application of digital twin technology, which often centers solely on infrastructural outcomes. There is a crucial need for policies and support systems that not only facilitate technological integration but also adaptively address the diverse and evolving challenges the community faces. This includes enhancing digital literacy, fostering local technological stewardship, and ensuring that interventions respect and integrate the camp's rich cultural heritage.

5.3. Empowering Community through Technological Engagement

The resilience and ingenuity of Irbid Camp's residents are evident, particularly in how they interact with and adapt to new technologies. Their proactive engagement in

refining the digital twin model highlights the potential of community-driven technological solutions. To fully realize this potential, strong training initiatives, inclusive planning methods, and ongoing feedback systems that include locals as active participants in the sustainable development of their community are crucial.

5.4. Advocating for Structural and Technological Paradigm Shifts

This research proposes a paradigm change in the application of digital technology to urban development and humanitarian endeavors. Stakeholders, including as international organizations, local governments, and tech developers, can more successfully contribute to the creation of resilient and sustainable urban places in refugee contexts if they expand their attention beyond a strict concentration on infrastructure. Understanding and integrating the involved socio-economic features that affect day-to-day presence in locations such as Irbid Camp is vital.

The study's findings should provide a thorough evaluation of the approaches in which digital twin expertise are affected in urban refugee camps. It highlights how significant it is to increase the view of these programs to combine group participation, cultural integration, and socioeconomic enhancement in addition to established resource management. By doing this, we require to raise a comprehensive, resilient, and sustainable approach to urban development and growth in refugee contexts, which will ultimately improve population self-sufficiency and quality of life. This study stages a template method for sustainable urban management by making a solid provision to theoretical frameworks and real-world realizations. It offers useful solutions that relief direct decisions about resource management and supplies an organized framework for researching system dynamics internal refugee camps. The groundbreaking concentration of digital twin technology in a camp for refugees is evidence of the compliance and capacity of cutting-edge expertise to change typical approaches of resource management and urban planning in problematic contexts.

6. Strategic Policy Guidelines for Enhancing Digital Twin Integration in Refugee Camps

The effective integration of digital twin technology in refugee camps necessitates targeted strategic policies. Based on research insights from Irbid Camp, we have developed guidelines to enhance urban planning and resource management. First and foremost, enhancing technological infrastructure and support is crucial. Allocating specific budgets for continually improving digital twin technology, including hardware and software upgrades, is essential. Public-private partnerships should be fostered to advance research and application of digital twin technologies in humanitarian settings, ensuring the technology remains state-of-the-art and effectively utilized. Community-centric training and capacity enhancement are also vital. Developing tailored training programs for local administrators and community figures can significantly enhance operational competence in digital twin technologies. Additionally, organizing educational workshops for residents will ensure meaningful engagement with digital twin applications, empowering the community to participate in and benefit from these advancements actively. Equally important is data governance and privacy protection. Rigorous data management methods will promise the secrecy of information collected via digital twins. Determining visible procedures and responsibility procedures is essential for continuing data reliability and adopting participant certainty, both of which are required for the applicable completion of these technologies. Alternative significant element is to persuade environmental technology attempts. Digital twin simulations may be benefited to confirm the long-term advantages of sustainable technology acceptance. Politicians may grant from the intuitions gained by digital twin models, which can stimulate sustainable activities and resource preservation.

Selecting social addition and cultural addition is also vital. Cultural understanding and the incorporation of regional background are critical for digital twin proposals that intention to stage community acceptance. By establishing comprehensive programs, all community divisions will have equal gate to the gains of expertise, confirming that no one

is left behind. Finally, it is critical to start experimental initiatives and scalable solutions. Pilot programs can evaluate the viability of digital twin applications and improve the technology in response to user input. Remarkable initiatives can subsequently establish expandable protocols for more extensive uses in analogous settings, guaranteeing that the advantages of digital twin technology can be experienced on a grander scale.

7. Conclusions

The study has revealed important insights into the efficient operation of the WEFE nexus carried out at Irbid Camp, which has been greatly aided by digital twin technology. In addition to demonstrating a 35% increase in operational efficiencies, integrating this technology has significantly improved resource management efficiency. However, it has also brought attention to the critical need for a more comprehensive and integrated approach to revolutionize community sustainability and resilience genuinely. Our research demonstrates that while digital twins are essential for improving resource systems such as those for food, energy, and water, they are much more beneficial when included in holistic solutions that prioritize socioeconomic growth, cultural integration, and community engagement. It is essential to shift from a merely technology approach to a more comprehensive one that incorporates social empowerment.

Detailed analysis of interviews with 450 community members revealed a nuanced understanding of local attitudes, showing an 80% awareness of resource conservation methods yet only 45% satisfaction with the current management approaches. This discrepancy underscores the necessity for technology implementations such as digital twins to better address and adapt to the community's needs and aspirations. Moreover, advanced climate modeling integrated within the digital twin framework forecasted a 25% rise in water scarcity and an 18% increase in energy requirements over the coming decade, advocating for the proactive implementation of sustainable infrastructure adaptations like enhanced solar energy solutions and efficient rainwater collection systems.

This study has proven the transformative potential of harnessing digital twin technology combined with machine learning in managing the WEFE nexus in refugee settings, significantly propelling forward sustainable urban planning. Integrating a detailed 3D model with real-time data and community feedback facilitated a dynamic simulation of various resource management scenarios, with predictive modeling highlighting upcoming challenges and necessary adaptations.

However, the research also acknowledges several limitations, including the dependency on digital technologies in settings where digital literacy varies widely, potentially affecting the adoption and utilization of these systems. Additionally, while the data collection was extensive, its geographical limitation to Irbid may restrict the broader applicability of the findings. Looking ahead, it is crucial to extend digital twin technology to other urban refugee contexts to validate and refine these methodologies across varied environmental and cultural landscapes. Future research should also focus on establishing educational initiatives to enhance digital literacy in refugee populations, ensuring inclusive engagement with technology. Such measures will boost the efficacy of digital solutions and ensure that these technologies serve as foundational elements for sustainable development in challenging urban environments.

Author Contributions: Conceptualization, A.S.; Methodology, A.S.; Software, A.S., O.A. and M.A.; Validation, A.S. and O.A.; Formal analysis, A.S.; Investigation, A.S.; Resources, A.S., O.A. and M.A.; Data curation, O.A.; Writing—original draft, A.S.; Writing—review & editing, A.S.; Visualization, O.A. and M.A.; Supervision, A.S.; Project administration, A.S.; Funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Royal Academy of Engineering under the Frontiers seed funding grant scheme, reference number FS-2324-20-19. The project titled “Leveraging Digital Twins for Community-Driven Sustainable WEFE Nexus Management” aims to enhance sustainable urban development practices within Irbid Camp through the application of advanced digital modeling techniques. The support from the Royal Academy of Engineering has been instrumental in enabling

the comprehensive interviews, development, and implementation of the digital twins model, ensuring that community needs, and environmental challenges are effectively addressed.

Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board of Yarmouk University (Approval Code: IRB/2024/223 and Approval Date: 9th May 2024).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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