

Smart integrated system for optimal resource utilisation

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ABSTRACT

One of the main obstacles to agriculture development and sustainability is the improper use of such natural resources as water, fertilizer, and energy. In this paper, the concept of smart integrated system for optimal resource utilization (SISORU) will be presented. The idea of the project consists of the development of the web application based on ICT, machine learning (ML), and visualizing technology on behalf of the executive process in agriculture. SISORU differs from existing agricultural solutions by combining the recommendations on crop choice, cost estimation, and resource shortages detection in one solution.

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1. INTRODUCTION

The world is still plagued by poor management of natural resources, which results in inefficiencies and destruction of the environment. ICTs such as machine learning (ML), prediction models, and decision support through the use of the Web can solve the problems in natural resource management. In India, for example, agricultural over-exploitation of groundwater in states such as Punjab, and wasteful energy consumption in urban areas, have highlighted the compelling requirement for intelligent, adaptive resource management systems. This need is even more compelling due to climatic change, population pressures, and dwindling ecological buffers. There are needed new generations of smart, data-driven solutions to inform sustainable use of critical resources such as water, energy, and agricultural inputs.

Even though scientific investigations might have developed tremendously in all domains, there has been coherence. ML has been critical in elevating smart farming to unprecedented levels [1]–[3]. Crop recommendation systems [4] and IoT-ML advisory models [5] show promise, though neither extends to full resource optimization. Precision agriculture has at least established its value for food security [6]. Although the SmartAgro system [7] successfully estimated crop yield without fertilizer prediction, the fertilizer prediction approaches [8], [9] did not consider the effect of environmental variables since they were considered to be fixed. Despite significant progress in IoT in agriculture in the framework of Agriculture 4.0 [10] and deep learning methods for remote sensing data [11], the challenges of cost-effectiveness and user-friendliness were not overcome yet. Smart irrigation systems [12] showed water savings of up to 15% but remained too costly for small farmers. Intelligent irrigation work [13] ignored market dynamics. Even though the optimization model of fertilization achieved very high accuracy [14],

water management was not considered within its framework. Based on survey and systems integration study outcomes [15]–[18], the need for scalability and holistic systems is still not met.

The following three limitations may apply commonly:

- Absence of holistic approach: The issue is that despite the presence of such aspects as crop yield [7], irrigation water supply [12] and fertilization rate [17] in the proposed solution, the decision-making aspect is not considered [19].
- Static input: Historical data application causes the input to become static and inflexible [14], [16], [20].
- High costs: Incorporating IoT devices along with ML techniques might prove to be expensive [21].

The discussed problems can be solved through the use of smart integrated system for optimal resource utilization (SISORU). SISORU refers to a decision-making platform supported by ICT technology [22]. The problem with the traditional IoT-powered one-purpose platforms is that they are not efficient and they are not integrated; however, SISORU incorporates ML and analytics for efficient resource utilization in agriculture.

2. METHOD

SISORU system is an advanced and scalable web-based system using ML algorithms for aiding the farmers in making decisions. The four modules in the SISORU web-based system include crop recommendation, cost calculation, shortage prediction, and visualization dashboard. The operation of the SISORU system involves a number of features such as soil type, past productivity, weather, and price trends. The overall building of SISORU is illustrated in Figure 1.

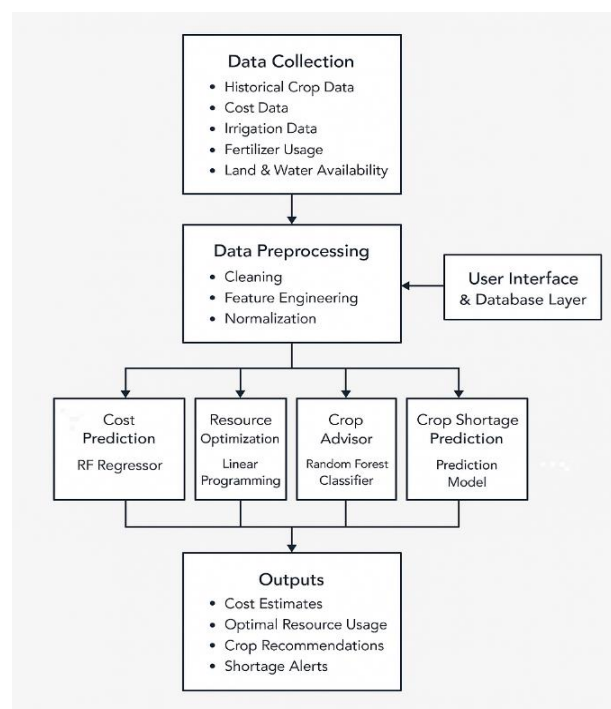


Figure 1. SISORU architecture

2.1. Crop advisor module

The crop advisor module offers suggestions for crops depending on the characteristics of soil and climate, along with trend analysis of yields. Random forest (RF) classifier is preferred due to its reliability, scalability, and capacity to reveal nonlinear associations between variables from different datasets. This approach belongs to ensemble algorithms and thus prevents overfitting and helps detect important features. Other algorithms are also employed in this project like support vector machine (SVM) and naive bayes (NB). The model generates a ranked list of crops recommendations for a specific area, which helps the decision maker to choose what to plant. Figure 2 displays the evolution of the RF model and how it uses the features to make predictions, combining the output of the trees.

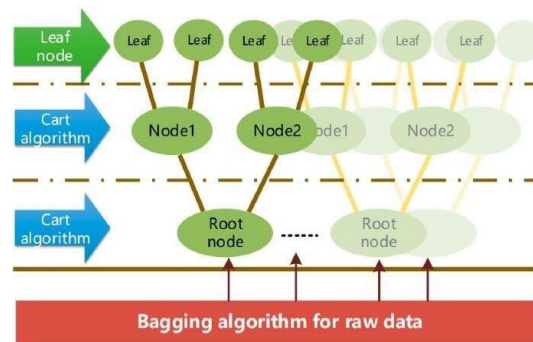


Figure 2. RF workflow [23]

2.2. Cost prediction engine

Using the historical data collected in the previous few years, the RF regression model can be used to estimate the cost of agriculture activities. This includes the expense associated with water usage, energy use, labor force, seed and fertilizers. The model captures the seasonality and market influences on costs and calculates the cost for each acre and each crop; this is valuable for budgeting and loan calculation.

2.3. Shortage analysis engine

This module predicts water, fertilizer and electricity shortages for critical agricultural needs. Then, the data are gathered on the crop grown in the particular area and the amount of irrigation needed. If the crop's irrigation requirement falls below ten units, then there is a shortage of resources. Such crops are then shortlisted as possible alternate crops, enabling real-time risk assessment for farmers and planners.

2.4. Dashboard and visualization interface

The dashboard was developed using flask and plotly to provide interactive agricultural visualizations. In regard to trends of cost of fertilizers, they are represented by the ten-year average cost of fertilizers, namely nitrogen, phosphate, and potash, per hectare. However, when one has to analyze crop yields between different Indian states, then it becomes necessary for one to utilize the crop yield comparison tool. Irrigation shortage analysis plots percentage shortfalls per crop against historical averages using horizontal bar charts.

2.5. Integration of the system and database management

Development of the SISORU application has taken place using the Flask framework which serves as the base for developing web applications. Various elements involved in the making of the SISORU application have been developed using the use of blueprints such as cost estimation, shortages, farm advise, and optimization among others. SQLite provides the database layer for user authentication and data management, with a users table containing a unique ID, username, email, and hashed password. In the process of initialization, the SISORU application tests for the existence of the table that holds the hashes of the passwords and also unique emails for each user.

At this juncture, it is possible to use the module through the 'dashboard' URL, where all the options needed to create the charts would be used to generate the HTML charts. It is possible for the server to execute the application on a specified port as well as allow debugging to take place. The modular architecture makes the system scalable and portable, allowing multiple users to access the platform. The flask-based system architecture and request-response flow are illustrated in Figure 3.

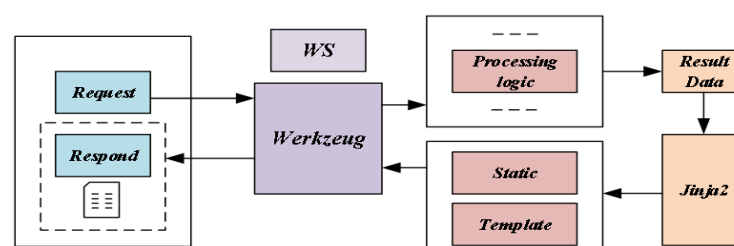


Figure 3. Flask request-response workflow [24]

2.6. Experimental setup and evaluation

The SISORU system applies district-wise agriculture data, including soil, yield, climate, and market information. The absent values in the continuous variables were assigned and then normalized before feeding the model. The data set was split into training and test set in an 80:20 proportion. Accuracy measure was applied for the assessment of crop advisor model. The RF classifier was tuned with respect to the number of trees, maximum tree depth, splitting criterion, feature-selection strategy, and class-weight configuration.

3. RESULTS AND DISCUSSION

Earlier studies have addressed crop recommendations, cost estimation, and resource allocation separately, whereas SISORU mixes these functions into a unified decision-support system. SISORU is the new research connecting these three different areas. The results produced by building and implementing this model are discussed in relation to the successful use of agricultural resources.

3.1. Performance of ML models and their implications

Table 1 précises the presentation of ML techniques used as building blocks across SISORU's modules. Although decision trees performed better than the SVM with 83.7% compared to 85.2%, the RF classifier showed highest accuracy of 91.5%, consistent with the results of previous works which showed that ensemble classifiers are superior in crop advisory systems [1]. As the ensemble structure of RF is composed of multiple decision trees, it proved to be better in this context due to its ability to handle agricultural data that is nonlinear and heterogeneous, as used in SISORU [25]. This helps the model to better describe the relationship of soils, climatic, and historical crop characteristics. RF was used for together organization and regression problems because it can handle the nonlinear data.

Table 1. Performance metrics of ML models

Module	Algorithm	R ² Score	RMSE	F1-Score
Crop Advisor	RF Classifier	91.5%	-	0.89
Cost Prediction	RF Regressor	0.87	152.4	-
Shortage Analysis	Support Vector Machine	88.4%	-	0.86
Irrigation Optimization	Linear Programming	93.2%	124.8	-

Our model, using RF, performed better in terms of classification accuracy than the other models, which is 6.5% higher than the 85% accuracy obtained by NB in [1]. The improvement is due to large amounts of feature extraction, such as the soil parameters and previous crop yields, as well as the ensemble design of the RF model. The choice of algorithms and feature selection are important considerations for sustainability and efficiency of the agricultural prediction models in processing large, noisy data sets, as presented in [26]. However, the performance of the models might differ based on the geographical region due to availability of data and regional characteristics. This would be complemented by cross-region validation to better test the model robustness.

3.2. Resource optimization impact and comparative advantage

The impact of the SISORU recommendations was assessed through comparing the resource-use results with the traditional farming practices reported. The figures of the percentage decrease in the consumption of the resources in relation to the recommendations given by SISORU and the traditional farming method are shown in Figure 4.

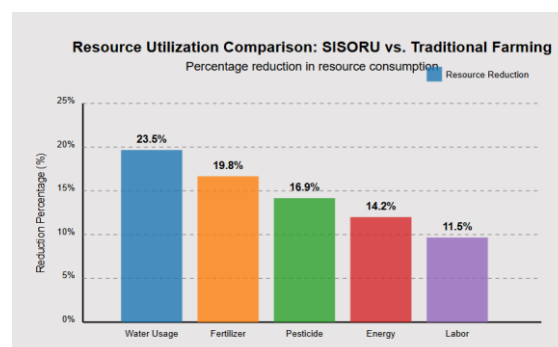


Figure 4. Resource utilisation of Sisoru versus traditional farming

The SISO RU used 23.5% less water and 19.8% less fertilizer compared to earlier systems but had a similar or higher yield. The success with the use of water is greater than the 15% reduction reported by Soussi *et al.* [12] for precision agriculture, and the reduction in fertilizer demonstrates the advantage of using all resources as one.

Unlike existing approaches [7], [12], [17] that address individual components of agricultural decision-making, SISO RU consolidates crop recommendation, cost calculation, shortage prediction, and resource optimization into a single platform. This software architecture results in better agricultural decision-making using ICTs due to the integration of predictive analysis, resource management, and web visualization within the same system and forms the backbone for the future cloud-based smart farming system referred to in [27].

3.3. Crop recommendation accuracy and real-time adaptability

The crop advisor module was assessed on past data from three agricultural years in different parts of the geographical area. The model had a weighted F1 score of 0.89, especially well performing in areas with more extensive datasets. The confusion matrix obtained is presented in Figure 5.

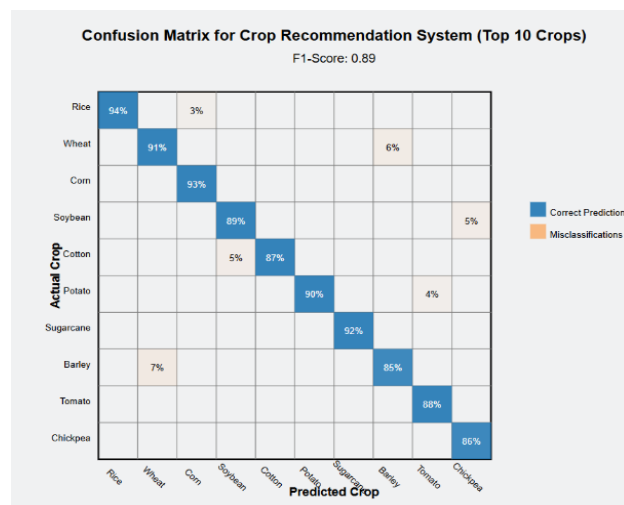


Figure 5. Confusion matrix for crop recommendation system (Top 10 crops)

The most common misclassifications happened between crops with similar growth needs, even when the top suggestions were not the same, the proposed options were still deemed to be agriculturally appropriate [9]. SISO RU is: Adaptive: it integrates real-time data and generates adaptive recommendations, as opposed to traditional mode which relies on historical data only. The cost prediction engine was tested against the actual agricultural input costs during 2022-2024 (Figure 6). The R^2 for the RF regressor is 0.87 with a mean absolute percentage error (MAPE) of 8.3%, which is better than the error rates of 12–15% in [8], [14]. The highest performance was for fertilizer costs ($R^2 = 0.92$) and irrigation expenses ($R^2 = 0.89$) while the least was for labor costs ($R^2 = 0.81$) due to the variability of the market in different regions.

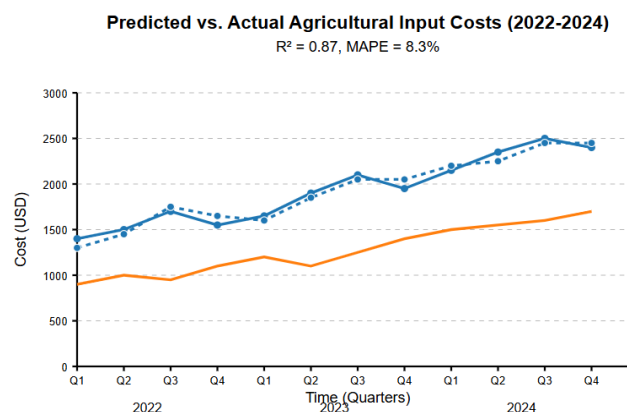


Figure 6. Predicted versus actual agricultural input costs (2022–2024)

The software-based solution of SISORU is cost effective and scalable, which is aligned with the recommendations in [18] which were hardware-based architectures described in [10] and [12]. The use of data that is publicly available and a simple web front-end makes SISORU more accessible than some alternatives that require specialized equipment or technical expertise.

3.4. Limitations and future directions

Although these results were obtained, there are still some limitations:

- Granularity of data: A future plan might be to include remote sensing methods to allow more localized recommendations, as proposed by Li *et al.* [11].
- Market volatility: During periods of market volatility and disruption, cost forecasts may not be as accurate. The use of additional economic parameters and sensitivity analysis may be helpful to look at the effect of uncertainty in cost forecasts on the entire system.
- Time resolution: Current shortage predictions are based on monthly time steps and might not be adequate for time-sensitive decisions [4]. Future studies are needed for weekly or daily predictions.
- Crop coverage: The model is currently available for high value and long-cultivated crops. Basically, if they expanded to a wider variety of crop types, they would make future iterations stronger.

These weaknesses will be corrected in future research by the following changes:

- Increased temporal accuracy of shortage forecasts - data made more frequently.
- Reinforcement learning techniques used to repeatedly update suggestions based upon feedback of results.

In addition to this, studies on federated learning and adaptive learning will be done in order to support privacy-preserving data sharing and dynamic recommendation based on federated agriculture systems. Fast decision making can be achieved by edge computing [17], [28]. To conclude, the SISORU system proved to be effective in various aspects such as crop recommendation, resource optimization, and cost estimation, which represented the combination of different functions in one system and had no limitation.

4. CONCLUSION

The summary of the manuscript not only summarizes the manuscript but also emphasizes the academic and practical significance of SISORU as a technique. The concept of multi-functional agricultural systems was further enhanced by the introduction of SISORU as a comprehensive and integrated decision support system, consisting of crop recommendation, cost analysis, shortage identification and visualization tools.

From a practical standpoint, SISORU provides a light, open-source, and user-friendly platform to support both farmers as well as decision makers with useful insights in a timely and data driven manner. While the current solution is based on data that is district-level and uses agriculture ICT solutions in the cloud, in the future, it will be helpful to include satellite data along with federated learning. Overall, SISORU demonstrates the potential of integrated ICT based decision support for sustainable agricultural resource management.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : Conceptualization	I : Investigation	Vi : Visualization
M : Methodology	R : Resources	Su : Supervision
So : Software	D : Data Curation	P : Project administration
Va : Validation	O : Writing - Original Draft	Fu : Funding acquisition
Fo : Formal analysis	E : Writing - Review & Editing	

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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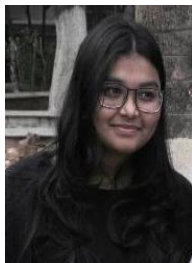
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