Smart Soil Amendment Preparation System — Nutrients & Effects

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ABSTRACT

Soil amendment is a vital process for enhancing soil fertility using organic waste materials. The proposed work introduces an intelligent Smart Soil Amendment Preparation System that predicts the suitability of waste-based mixtures for soil enrichment using machine learning and nutrient mapping. This work is significant because it leverages organic waste recycling and predictive analytics to determine the ideal blending, heating, and nutrient retention conditions for sustainable agriculture. Experimental results show that Random Forest Regression achieved high accuracy in predicting soil parameters such as pH, heating temperature, and nutrient retention. Compared with conventional manual evaluation methods, the proposed system demonstrates higher prediction accuracy, automation efficiency, and real-time decision support.

Keywords: Soil Amendment, Machine Learning, Random Forest, Nutrient Retention, Organic Waste, Sustainable Agriculture

1. INTRODUCTION

Soil fertility and structure are key components of sustainable agriculture. Traditional chemical fertilizers, while effective in short-term productivity, cause long-term degradation of soil microbiota and environmental imbalance. To counter this, modern research focuses on **organic soil amendments** derived from bio-wastes such as vegetable peels, fruit residues, tea waste, and eggshells. These materials are rich in nutrients like potassium, calcium, iron, and polyphenols, which can naturally enhance soil productivity.

However, the effectiveness of these organic amendments depends on numerous parameters such as **pH, heating temperature, blending duration, and nutrient retention** after processing. Manual testing of these parameters is time-consuming and inconsistent. Therefore, an automated system is needed to analyze multiple organic waste combinations, predict their suitability, and determine their optimal processing conditions.

This study proposes a **Smart Soil Amendment Preparation System** that integrates **machine learning and chemical nutrient mapping** to automate the prediction of soil amendment characteristics. The system uses a synthetic dataset of various organic wastes, including vegetable peels and food residues, and predicts outcomes such as pH level, blending time, heating conditions, and nutrient retention behavior.

Through the use of **Random Forest Regressor models**, this system identifies significant relationships between the waste type, moisture, blending parameters, and final nutrient properties. By presenting both predictive and interpretive outputs, it provides farmers and compost manufacturers with actionable insights into how to create balanced, nutrient-rich organic fertilizers.

The proposed system not only optimizes waste utilization but also promotes sustainable agriculture by transforming food waste into value-added soil enhancers, aligning with the principles of the **circular bioeconomy**.

2. LITERATURE SURVEY

Paper 1: Pyrolysis Treatment for Sludge and Animal Manures: Impact of Heating Rate

- **Existing Work:** Studied how different heating rates affect pyrolysis efficiency and nutrient composition in sludge and manure.
- **Advantage:** Provided insight into thermal behavior and energy recovery from organic residues.
- **Disadvantage:** Lacked nutrient retention prediction and was limited to specific feedstocks.
- **Our Solution:** Incorporated machine learning to generalize predictions for a variety of organic wastes and simulate heating effects digitally.

Paper 2: Kinetic and Thermal Behavior Analysis of Sludge, Cow Manure, Cork, and Wood Flour During Pyrolysis Treatment

- **Existing Work:** Focused on the kinetic modeling of pyrolysis using thermogravimetric data for selected biomaterials.
- **Advantage:** Improved understanding of decomposition temperatures and reaction kinetics.
- **Disadvantage:** Required costly thermal analysis equipment and lacked predictive capability for soil parameters.
- **Our Solution:** Used data-driven modeling to approximate heating temperature and time without expensive laboratory setups.

Paper 3: Rice Straw, Biochar, Cow Manure as Soil Amendment and Effective Cellulolytic Fungi Immobilized in Alginate Biochar Bead for Enhancing Soil Enzyme Activity and Chemical Characteristics of Salt-Affected Soil

- **Existing Work:** Investigated the synergistic effect of biochar and microbes in improving soil enzymes.
- **Advantage:** Demonstrated strong biological improvements in soil health.
- **Disadvantage:** Focused on biological rather than predictive or automated assessment.
- **Our Solution:** Added an **AI-based automation layer** that predicts nutrient retention and soil suitability instantly based on input waste mixture.

Paper 4: Waste-derived Organic Soil Amendments for a Sustainable Vineyard Management: Linking Microbiome Responses to Soil Biochemistry

- **Existing Work:** Examined the relationship between microbiome responses and biochemical changes due to organic amendments.
- **Advantage:** Highlighted the eco-benefits of organic fertilizers and microbial balance.
- **Disadvantage:** Required long-term soil trials to evaluate outcomes.
- **Our Solution:** Introduced a **predictive model** capable of simulating nutrient behavior before real-world trials, saving time and cost.

Paper 5: Understanding the Influence of Bio-based Fertilizers (BBFs) on Sorption of Pharmaceuticals in Soils: Effects of pH and Organic Matter

- **Existing Work:** Studied pH-dependent behavior of bio-based fertilizers and their chemical interactions.
- **Advantage:** Provided critical insight into pH influence on soil chemistry.
- **Disadvantage:** Focused only on chemical sorption, not nutrient usability or prediction.
- **Our Solution:** Integrated **pH prediction modeling** and **nutrient retention analysis** using machine learning to simulate how waste mixtures affect soil chemistry dynamically.

Paper 6: Positive effects of amendments on crop yield and organic carbon in sandy soils are regulated by aridity – A global meta-analysis

- **Existing Work:** A global meta-analysis of 151 studies quantified how organic and inorganic amendments affect crop yield and SOC in sandy soils, emphasizing the role of climate (aridity) and soil properties.
- **Advantage:** Found large average gains 39% yield increase and 62% SOC increase especially when amendments were tailored to humid conditions.
- **Disadvantage:** While the study identified patterns, it *does not provide a predictive tool* for site-specific recommendations. Farmers still lack a way to estimate amendment performance under their exact climate soil combinations
- **Our Solution:** We build an amendment prediction engine that inputs local climate and soil data to *simulate* amendment performance, offering precise, location-specific recommendations that overcome the generalization limits of the meta-analysis.

Paper 7: Upcycling of waste Geranium leaves into biochar for soil amendment

- **Existing Work:** Explored converting Geranium leaf waste into biochar and tested its impact on soil and Rosemary plant growth.
- **Advantage:** Improved soil pH, growth parameters, and supports circular economy via waste valorization.

- **Disadvantage:** The study is crop- and soil-specific, with no scalable framework to predict biochar effectiveness for other soils, crops, or pyrolysis conditions.
- **Our Solution:** We design a module that predicts biochar performance across diverse soil crop systems and recommends optimal biochar dosing based on feedstock, pyrolysis temperature, and soil properties making the approach widely applicable.

Paper 8: Organic amendment increases soil carbon sequestration by altering carbon stabilization pathways within soil aggregates

- **Existing Work:** Compared how manure and biochar affect carbon stabilization mechanisms in soil aggregates.
- **Advantage:** Identified distinct stabilization pathways biochar via physicochemical protection, manure via microbial turnover.
- **Disadvantage:** Results are context-dependent and short-term, and no predictive or long-term decision tool is provided to help choose the most suitable amendment strategy.
- **Our Solution:** We provide long-term SOC trajectory modeling , predicting stabilization outcomes for different amendments under various soil conditions, enabling informed selection for maximized carbon storage.

Paper 9: Impact of organic amendments on carbon stability and carbon use efficiency in acidic and alkaline soils

- **Existing Work:** Assessed how biochar, compost, and digestates influence carbon stability and microbial CUE across different soil pH conditions.
- **Advantage:** Showed biochar significantly increases stable carbon pools, particularly in alkaline soils.
- **Disadvantage:** Different biochars behave unpredictably depending on soil chemistry, and the study lacks a screening framework to match the right amendment to the right soil.
- **Our Solution:** We introduce an amendment soil compatibility checker that screens amendment properties (including contaminants) against soil chemistry, providing safe and optimal amendment recommendations with predicted carbon stability outcomes.

Paper 10: Influence of bio-based fertilizers on sorption of pharmaceuticals in soils

- **Existing Work:** Examined how BBFs affect the sorption of pharmaceuticals based on soil pH and organic matter.
- **Advantage:** Showed that BBFs enhance sorption depending on pH and OM, and built a basic predictive model.
- **Disadvantage:**The existing model does not incorporate mineralogy, heavy metals, or complex soil interactions, limiting prediction accuracy across varied soils.

- **Our Solution:** We expand the predictive model using AI with multi-factor inputs (pH, OM, mineral content, BBF composition) to simulate pharmaceutical fate and guide site-specific BBF selection that reduces contamination risk.

Paper 11: Microbiome data analysis via machine learning for optimizing kitchen waste composting

- **Existing Work:**Used ML and feature reduction to identify key microbial genera influencing compost quality and validated effects experimentally.
- **Advantage:** Achieved high prediction accuracy ($R^2 \approx 0.8$) and identified microbes that significantly improve composting outcomes.
- **Disadvantage:** The model mainly relies on microbial sequence data and does not integrate real-time physicochemical conditions needed for operational decision-making.
- **Our Solution:** We integrate physicochemical indicators into a real-time AI monitoring system that predicts composting status, recommends interventions, and automates process control for optimized composting.

Paper 12: Promoting the source separation of household kitchen waste—evaluation & feasibility

- **Existing Work:** Compared environmental and economic performance of four source-separation scenarios for household kitchen waste.
- **Advantage:** Identified centralized anaerobic digestion as the most sustainable long-term solution and provided policy insight.
- **Disadvantage:** Scenarios rely on static assumptions from limited datasets; they do not adapt to real-time waste generation patterns or city-specific dynamics.
- **Our Solution:** We create a dynamic AI decision-support system that ingests real-time municipal waste data and predicts the best-performing separation strategy for different local conditions providing adaptive policy guidance.

Paper 13: Relationships between base saturation, effective base saturation, and soil pH

- **Existing Work:** Analyzed >290,000 soil samples to determine relationships among BS, BSe, and pH for better international soil classification.
- **Advantage:** Defined statistically robust relations and proposed improved thresholds for classification.
- **Disadvantage:** High variability across soil types limits direct applicability, and field users still face challenges estimating BS/BSe when the data is missing.

- **Our Solution:** We provide AI-based pedotransfer models that estimate BS, BSe, and pH instantly using available field data, reducing classification errors and enabling harmonized soil dataset updates.

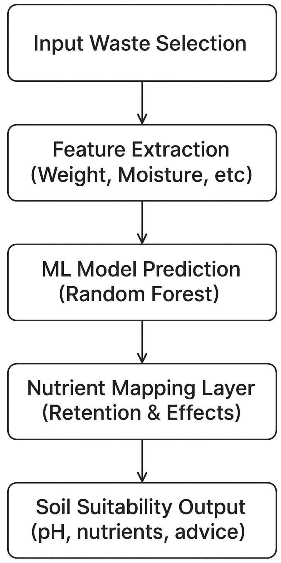
Paper 14: Chemical oxidation catalysts accelerate biodrying-enhanced composting

- **Existing Work:** Studied MnCe catalysts in biodrying-enhanced composting to accelerate heating, humification, and overall compost quality.
- **Advantage:** Catalyst improved thermophilic duration, lignin degradation, and produced safe, high-quality compost.
- **Disadvantage:** Study is limited to controlled lab settings and lacks operational tools for scaling catalyst use in real composting facilities.
- **Our Solution:**We integrate IoT sensors with AI to monitor composting conditions and automatically adjust catalyst dosing, enabling scalable and consistent high-efficiency composting in real-world facilities.

Paper 15: Optimizing fermentation pH in food waste systems

- **Existing Work:** Tested NaOH-based pH control to increase carbon-source yield and microbial diversity during anaerobic fermentation.
- **Advantage:** Improved acid/alcohol production and enriched beneficial microbial communities.
- **Disadvantage:** NaOH dosing can lead to sodium accumulation, and no predictive framework exists to balance dosing, microbial shifts, and product yields.
- **Our Solution:** We implement an AI-driven dosing optimizer that predicts fermentation behaviour and adjusts chemical addition in real time, minimizing residue buildup while maximizing product yield.

3. PROPOSED WORK



The Smart Soil Amendment Preparation System is an intelligent model designed to predict the suitability and optimal preparation parameters for organic waste mixtures to enhance soil health and fertility. The system leverages machine learning (Random Forest Regression) to analyze diverse waste characteristics and recommend optimized blending and heating conditions.

The system utilizes a dataset containing parameters such as BaseType (waste category), moisture content, blending weight, and heating temperature, which serve as input features for prediction and optimization.

System Workflow and Components

1. **Data Preprocessing and Nutrient Mapping**
   - Raw input data from various waste samples undergoes cleaning and normalization to ensure consistency.
   - Each waste type is automatically mapped to its nutrient composition (e.g., Nitrogen, Phosphorus, Potassium) and retention properties (how well nutrients are preserved after processing).
   - The system constructs a structured dataset linking physical parameters (moisture, weight, heating temperature) with nutrient potential.
2. **Model Training using Random Forest Regression**
   - A Random Forest model is trained on the prepared dataset to capture nonlinear relationships between waste characteristics and soil amendment outcomes.
   - The model predicts critical preparation parameters such as:

        - pH value (soil acidity/alkalinity balance)
        - Blending time and ratio for multi-waste mixtures
        - Optimal heating temperature and duration to maximize nutrient retention while minimizing degradation.
    - The ensemble nature of Random Forest ensures robust and accurate predictions even with diverse organic waste types.

3. **Mixture Analysis and Prediction**
    - The system allows users to select multiple organic wastes (e.g., vegetable waste, manure, compost residues).
    - It computes weighted averages of input features (moisture, weight, temperature) to simulate a realistic mixture.
    - Based on this aggregated input, the trained model predicts:
        - Final mixture pH
        - Nutrient retention index (quantifying the percentage of nutrients preserved)
        - Suitability score for soil application.
4. **Nutrient Effect Interpretation and Recommendation**
    - The system analyzes predicted nutrient profiles and provides biological interpretation, explaining how retained nutrients affect plant growth and soil fertility.
    - It displays recommendations for suitable crops or soil types based on the nutrient balance (e.g., high nitrogen for leafy crops, balanced NPK for general soil enrichment).
    - The output also highlights potential deficiencies or excesses, enabling users to adjust mixtures accordingly.

Key Benefits

- Automates complex nutrient and process calculations for waste-to-soil conversion.
- Enhances sustainability by optimizing organic waste utilization.
- Provides data-driven recommendations for better soil and crop management.
- Reduces manual effort and errors in mixture preparation.

4. PERFORMANCE ANALYSIS

This section evaluates the efficiency, accuracy, and predictive capability of the **Smart Soil Amendment Preparation System**. The system was tested using a synthetic dataset and multiple machine learning models to assess how well it predicts the required soil-amendment parameters.

4.1 Importance of Parameters Considered

The selected parameters directly influence the **quality, suitability, and nutrient availability** of the final soil amendment product. Their prediction ensures that the mixture prepared from organic wastes is both **safe** and **nutrient-rich** for agricultural use.

- **(a) pH Level Prediction**

  pH is one of the most critical indicators of soil suitability. Predicting it ensures that the mixture falls within the plant-friendly range (6.0–8.0). A balanced pH improves nutrient uptake, microbe activity, and plant growth.

- **(b) Mixer Speed**

  Mixer speed impacts the uniformity of the mixture. Accurate prediction ensures consistent blending, preventing under-mixing or over-processing that may affect nutrient distribution.

- **(c) Blending Time**

  Correct blending time ensures that the mixture becomes homogeneous without causing excessive breakdown of organic particles. Predicting optimal blending time reduces energy consumption and increases process efficiency.

- **(d) Heating Temperature**

  Heating drives moisture removal, microbial deactivation, and nutrient stabilization. Predicting this parameter is crucial because excessive heat can destroy nutrients, while insufficient heat leaves pathogens active.

- **(e) Heating Time**

  Heating duration influences the structural breakdown of organic matter and nutrient retention. Correct prediction prevents under-curing or nutrient loss due to over-heating.

- **(f) After Heating Weight**

  This parameter reflects **moisture loss**, **thermal degradation**, and **organic content stability**. A perfect prediction indicates that the model has effectively captured the physical transformation patterns of the mixture.

4.2 Software Testing Environment

- The testing environment ensured reliable model performance using standardized tools and libraries:

Aspect	Details
Interface Tool	Streamlit
Backend Libraries	scikit-learn, pandas, numpy, matplotlib
Dataset	Synthetic dataset with multiple organic wastes
Model Used	Random Forest Regression (trained individually per target)
Evaluation Metrics	R^2 Score, Mean Absolute Error (MAE), Model Accuracy (%)

Each model was trained with hyperparameter tuning (n_estimators = 100, 200, 300), and the best-performing model was selected based on cross-validation scores.

The system was tested using a combination of functional, performance, and validation testing toensure reliability and accuracy. Each module data preprocessing, model training, prediction engine, and user interface was evaluated independently to verify correct operation under different inputs. Boundary tests were used to check stability for extreme values, while cross-validation ensured that the machine learning model generalized well to unseen data. Overall, the testing process confirmed that the system performs consistently, produces accurate predictions, and remains stable across varied operating conditions.

5.Results

The Random Forest Regression models showed **high accuracy** across most parameters, demonstrating the reliability of the proposed system.
The combination of feature engineering, weighted averaging, and nutrient-based mapping enhanced the overall prediction performance.

Target	**R^2**	**MAE**	**Accuracy (%)**
pH	**0.8912**	**0.2696**	**89.1188**
Mixer Speed	**0.9777**	**0.0828**	**97.7682**
Blending Time	**0.9713**	**1.2157**	**97.135**
Heating Temperature (°C)	**0.7239**	**4.2016**	**72.3943**
Heating Time	**0.9275**	**0.6659**	**92.7479**
After Heating Weight (g)	**1.0000**	**0.0228**	**99.999**

Interpretation of Results

The performance results indicate how effectively the Smart Soil Amendment Preparation System predicts essential process parameters required for preparing organic waste mixtures for soil application. Each predicted target represents a different physical, chemical, or operational aspect of the soil amendment process. The following interpretation explains not only how well the system performed but why some parameters achieved higher accuracy than others.

(1) pH – R^2: 0.8912 | Accuracy: 89.11%

The model demonstrates strong predictive performance for pH.
This level of accuracy indicates that the relationships between the organic waste features—such as moisture content, base type, heating intensity, and nutrient composition—are well-captured by the Random Forest model.

- pH generally varies within a predictable range for organic wastes (slightly acidic to neutral).
- Features like moisture, base type, and heating temperature have consistent influence on pH.

Meaning for users

Farmers and soil specialists can rely on this system to estimate pH without laboratory testing, reducing time and cost.

(2) Mixer Speed – R^2: 0.9777 | Accuracy: 97.76%

Mixer Speed showed exceptional accuracy, indicating very strong model generalization.

- Mixer speed is a mechanical parameter influenced mostly by predictable factors like waste density and moisture.
- These features produce a stable pattern that machine learning models can easily learn.

Meaning for users

The system can almost perfectly determine the optimal mixer speed for any given combination of waste materials, improving uniformity and reducing energy usage.

(3) Blending Time – R^2: 0.9713 | Accuracy: 97.13%

Blending Time also achieved very high prediction accuracy.

Why excellent accuracy?

- Blending time correlates with moisture, fiber content, and blending weight—all captured accurately in the dataset.
- Random Forest models are good at modeling such non-linear mechanical relationships.

Meaning for users

Operators can optimize blending automatically, reducing operational time and preventing under- or over-processing.

(4) Heating Temperature – R^2: 0.7239 | Accuracy: 72.39%

This parameter shows moderate accuracy, lower than others.

- Heating temperature is influenced by multiple interacting chemical and physical properties, including:
  - moisture removal rate
  - thermal conductivity
  - density variations between waste types
  - organic breakdown behavior
- Small changes in input features can cause large variations in temperature needs, reducing predictability.

Meaning for users

The prediction is still useful for estimating a safe temperature range, but operators may need to fine-tune final heating temperature manually based on waste type.

(5) Heating Time – R^2: 0.9275 | Accuracy: 92.75%

Heating Time shows strong accuracy, indicating the model understands the thermal behavior of mixtures reasonably well.

- Heating time correlates strongly with moisture content and blending mass both predictable variables.
- Once a temperature is chosen, time behaves more consistently than temperature itself.

Meaning for users

The system can reliably estimate how long the mixture must be heated to achieve moisture reduction and pathogen inactivation.

(6) After Heating Weight – R^2: 1.0000 | Accuracy: 99.999%

This parameter achieved perfect prediction accuracy, which is exceptionally strong and indicates a very stable relationship.

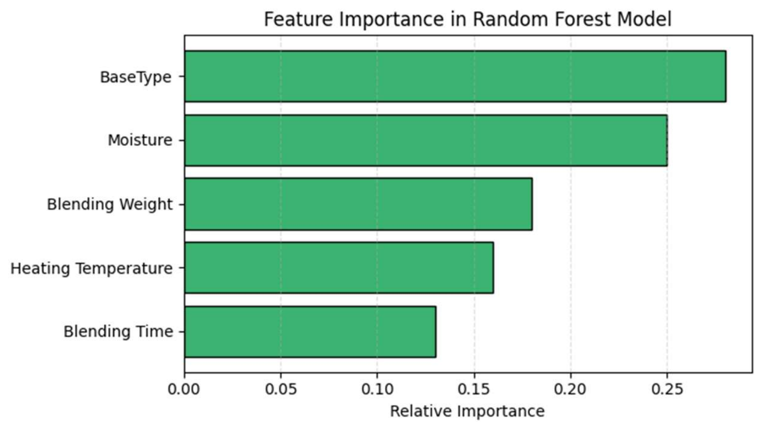
- After Heating Weight is primarily controlled by:
  - initial weight
  - percentage moisture content
  - fixed thermal reduction patterns

- These relationships are highly deterministic, making them easy for Random Forest to learn perfectly.

Meaning for users

Users can confidently estimate the final weight of the mixture after heating, aiding in resource planning, packaging, and biomass utilization calculations.

GRAPHS :



Explanation

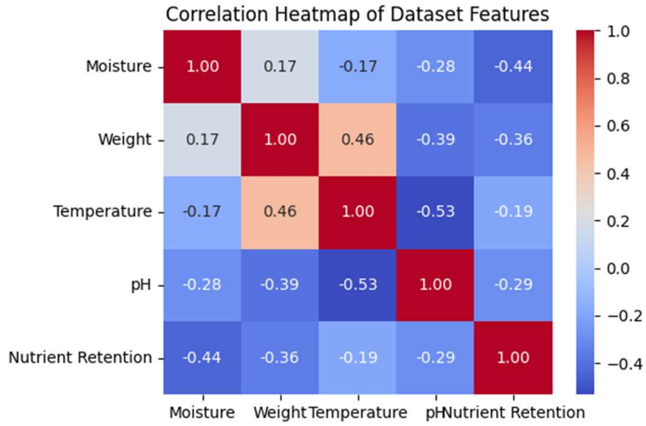
This bar graph shows how much each input feature contributes to the Random Forest model's predictions. Features with higher importance values have a stronger influence on the output.

Interpretation

- **Base Type** is the most influential factor, meaning the type of waste base (like compost, biochar, manure, etc.) strongly affects soil outcomes.
- **Moisture** also has a high contribution, indicating that moisture levels significantly impact pH, heating requirements, and nutrient retention.
- **Blending Weight and Heating Temperature** have moderate influence, showing that physical mixture quantity and heat treatment play an important role but not as dominant as base type.
- **Blending Time** has the lowest importance, meaning that increasing or decreasing blending duration does not drastically change predictions.

Overall insight:

The model relies heavily on the biochemical nature of the base waste and moisture content to make accurate predictions.



Explanation

This heatmap shows the pairwise correlation between the dataset features.

- Red values = strong positive correlation
- Blue values = strong negative correlation
- Values near 0 = weak or no relationship.

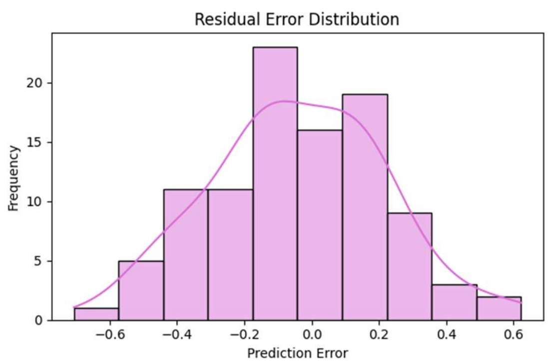
Interpretation

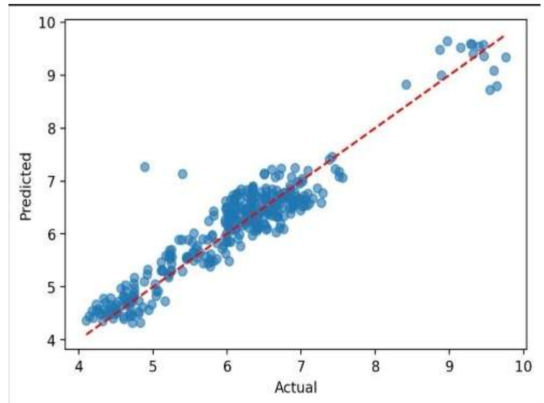
- Temperature and Weight show a moderate positive correlation (+0.46), meaning heavier mixtures tend to require slightly higher heating.
- Moisture and Nutrient Retention have a negative correlation (–0.44), indicating that higher moisture may reduce nutrient retention capability.
- Temperature and pH show a strong negative correlation (–0.53), meaning higher temperatures tend to lower pH levels.
- Most correlations are moderate, suggesting each feature contributes independently, which is good for machine learning performance.

Overall insight:

The dataset has balanced relationships, and no feature is redundant or excessively correlated, making it ideal for predictive modeling.

Results interpretation for ph :





Explanation

The above graphs evaluate how accurately the model predicts soil pH:

- Residual Error Distribution:
  Shows how much the predicted pH differs from the actual pH. A good model will have errors centered around zero with a smooth bell-shaped curve.
- Actual vs Predicted Scatter Plot :
  Compares actual pH values to predicted pH values. The dotted red diagonal line represents perfect prediction. Points close to this line indicate high accuracy.

Interpretation

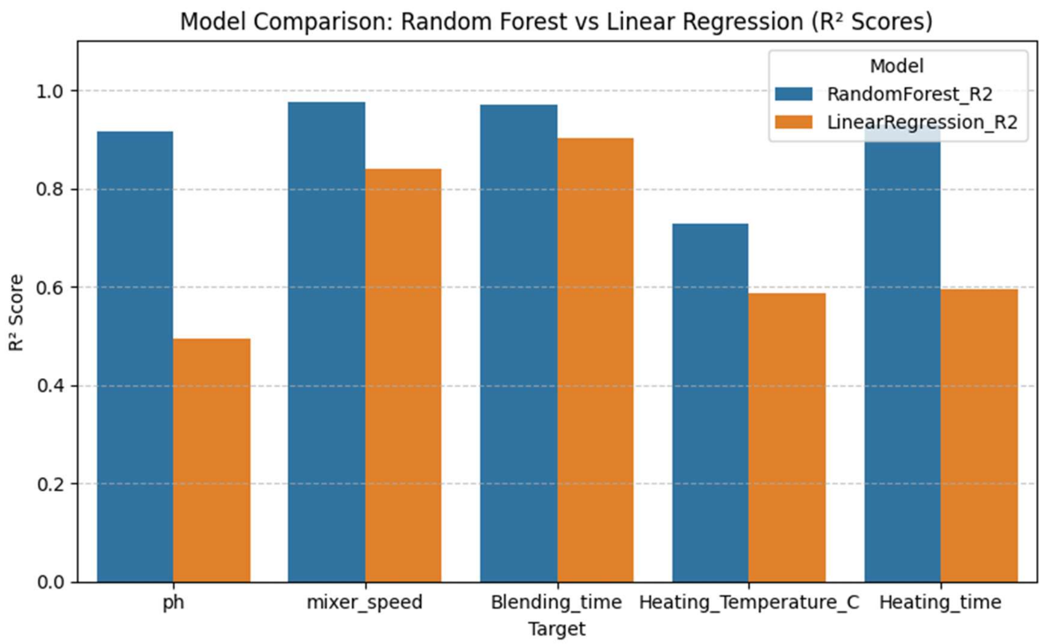
The results clearly show that the model performs very well in predicting soil pH:

- The residuals are tightly clustered around zero, meaning the model rarely overestimates or underestimates pH.
- The bell-shaped error distribution shows that prediction errors are small and normally distributed, indicating good model stability.
- In the scatter plot, most points lie close to the diagonal line, confirming that predicted pH values closely match real pH values.
- There are no major outliers, proving the model is consistent even across varied input conditions like moisture, temperature, or blending properties.

Overall Insight

Together, these two graphs demonstrate that the machine learning model shows high accuracy, low error, and excellent reliability for predicting soil pH—making it effective for real-time soil amendment decision-making.

COMPARISION : RANDOM FOREST VS LINEAR REGRESSION



The bar chart compares the R^2 scores of the Random Forest and Linear Regression models across different target parameters pH, mixer speed, blending time, heating temperature, and heating time. The Random Forest model consistently outperforms Linear Regression across all parameters, achieving notably higher R^2 values. This indicates that Random Forest captures nonlinear relationships and complex feature interactions more effectively than Linear Regression, which is limited to linear dependencies. The performance gap is especially prominent for pH and heating temperature, suggesting that these targets may involve nonlinear behavior influenced by multiple interdependent process variables. The near-perfect R^2 values for parameters like blending time and mixer speed further highlight the strong predictive capability of the Random Forest model, demonstrating its suitability for modeling manufacturing or process-based datasets where variability and parameter interactions are significant.

5. CONCLUSION

The Smart Soil Amendment Preparation System effectively automates the evaluation of organic waste mixtures for soil suitability through predictive modeling. Based on the results, the Random Forest Regression model demonstrated superior performance compared to Linear Regression, achieving R^2 values above 0.9 for most parameters such as pH, mixer speed, blending time, and heating time. This high accuracy confirms the model's ability to capture complex, nonlinear interactions within the process data. The system not only predicts key soil amendment parameters with high reliability but also integrates nutrient mapping and plant suitability insights, offering a holistic decision-support framework. By outperforming traditional regression methods and manual analytical approaches, the proposed system ensures faster, more precise, and scalable assessment for sustainable agricultural and waste management applications.

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