Optimization of Wheat Straw and Distiller's Grains Fertilizer Via Life Cycle Assessment and Genetic Algorithm

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Abstract. This study optimizes wheat straw and distiller's grains bio-fertilizers for improving various soil types (sandy, clay, loam). A multi-objective model integrating Life Cycle Assessment (LCA) and Genetic Algorithm is proposed to maximize soil fertility, crop growth, and environmental benefits. A dynamic soil-fertilizer-crop model is developed to assess the effects of fertilizer application on soil nutrients, pH, and microbial activity. Simulations examine long-term impacts of fertilizer combinations and application methods, with optimization via GA. Results show that the fertilizer improves soil fertility and crop growth, but strategies must consider soil type differences. Loam and clay soils absorb fertilizer better, while sandy soils risk nutrient loss. Sensitivity analysis and model validation confirm accuracy and stability, providing a scientific basis for green agriculture. This study supports optimal fertilization strategies and validates the environmental benefits of wheat straw and distiller's grains fertilizers for sustainable agricultural waste recycling.

Keywords: Wheat Straw, Distiller's Grains, Life Cycle Assessment, Genetic Algorithm, Crop Growth.

1. Introduction

As concern over agriculture's environmental impact grows [1], enhancing crop yield while minimizing negative effects is crucial. Traditional fertilizers improve soil fertility but cause degradation [2], nutrient loss, and water pollution, highlighting the need for sustainable alternatives. Wheat straw and distiller's grains, by-products of beer and liquor production [3], show potential as fertilizers due to their nutrients and organic matter. While studies suggest they improve soil and crop growth with minimal environmental impact, factors like application rate [4], method, and soil type affect their effectiveness, requiring optimized strategies [5].

Existing research has predominantly focused on the individual effects of these fertilizers on soil or crops [6]. However, these studies often overlook the complex feedback mechanisms between soil, fertilizer, and crop growth [7], and fail to consider the impact of varying soil types. Additionally, while LCA and GA have been applied in certain contexts, they are rarely integrated into a multi-objective model that simultaneously accounts for soil fertility [8], crop growth, and environmental sustainability [9]. Moreover, the role of soil type in optimizing fertilizer effectiveness has not been adequately addressed [10], leaving a gap in the understanding of how soil properties interact with organic fertilizers [11].

This study addresses these gaps by proposing an innovative LCA-GA-based optimization model. This model integrates the feedback between soil, fertilizer, and crop growth while accounting for different soil types. By optimizing fertilizer application through GA, the model aims to improve soil fertility, enhance crop growth, and reduce environmental impacts, providing a more comprehensive and sustainable approach to fertilizer use. This research not only offers a scientifically grounded methodology for optimizing agricultural practices but also contributes to the development of sustainable fertilization strategies in the context of agricultural waste recycling.

2. Soil-Fertilizer-Crop Feedback Model

2.1. Soil Dynamic Model and Impact Analysis

To achieve the research objectives, a dynamic soil-fertilizer-crop feedback model is developed to study the effects of wheat straw and distiller's grains fertilizer ratios and application methods on soil properties and crop growth across different soil types (sandy, clay, loam). The following assumptions are made for model operability:

(1) Soil fertility change is linearly related to fertilizer type and amount.
(2) Fertilizer effectiveness remains stable in the short term.
(3) Soil pH changes post-fertilization are driven by microbial activity.
(4) Crop growth is assessed through root, leaf, and plant height.
(5) Fertilizer dissolution is immediate and complete.
(6) Fertilizer absorption is constant across soil types.
(7) Crop growth duration lasts 10 years.

The model describes changes in nitrogen (N), phosphorus (P), and potassium (K) concentrations, soil pH, and microbial activity affecting crop growth, captured through differential equations.

Soil fertility changes with time due to fertilizer application and crop absorption. The absorption rates for N, P, and K are 0.1, 0.05, and 0.05, respectively:

$$\frac{dN}{dt} = N_{add} - 0.1 \cdot N \tag{1}$$

$$\frac{dP}{dt} = P_{add} - 0.1 \cdot P \tag{2}$$

$$\frac{dK}{dt} = K_{add} - 0.05 \cdot K \tag{3}$$

Soil pH (pH) is influenced by fertilizer and microbial activity (MA), with a faster pH drop due to stronger microbial activity. The differential equation describing the pH change is as follows:

$$\frac{dpH}{dt} = -0.02 \cdot MA \tag{4}$$

Where:

pH= Soil pH, MA = Microbial activity.

Microbial activity (MA) is influenced by nutrient concentrations and pH. It correlates with nitrogen (N), phosphorus (P), and potassium (K), and its rate of change is inversely proportional to the current activity. The differential equation for microbial activity is:

$$\frac{dpH}{dt} = 0.1 \cdot (N + P + K) \cdot (1 - MA) - 0.05MA \tag{5}$$

2.2. Dynamic Model of Crop Growth and Fertilization Strategy

Crop growth is influenced by soil fertility, microbial activity, and fertilizer application, which affect root growth, leaf development, and plant height. The growth rates are modeled by the following differential equations:

$$\text{Root Growth:} \quad \frac{dRG}{dt} = r_{RG} \cdot (N + P + K) \cdot (1 - RG) \tag{6}$$

$$\text{Leaf Growth:} \quad \frac{dLG}{dt} = r_{LG} \cdot (N + P + K) \cdot (1 - LG) \tag{7}$$

$$\text{Plant Height:} \quad \frac{dPH}{dt} = r_{PH} \cdot LG \cdot (1 - PH) \tag{8}$$

Where RG, LG, and PH are root growth, leaf growth, and plant height, respectively. The model assumes known annual fertilization rates for nitrogen, phosphorus, and potassium, with initial conditions for soil fertility, pH, and microbial activity. It is solved using numerical methods like $odeint$ in SciPy.

The model simulates changes in soil fertility, pH, microbial activity, and crop growth over time, offering insights into optimal fertilization strategies for different soil types and application methods.

2.3. Model Solution and Result Analysis

A soil-fertilizer-crop feedback model is developed and solved numerically to examine the dynamic relationships between soil improvement and crop growth. After setting initial conditions changes in soil fertility, pH, microbial activity, and crop growth over 10 years are obtained. The relationship between soil fertility and crop yield is shown, highlighting the impact of fertilization and soil fertility changes on yield. Figure 1 demonstrates this relationship.

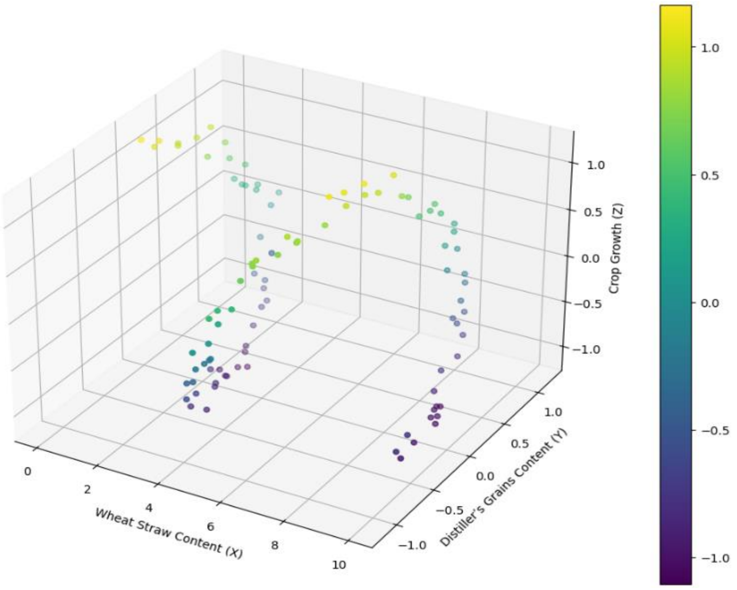

Figure 1. Soil Fertility-Crop Yield 3D Scatter Plot

(1) Initial Conditions and Fertilization Amounts

Based on experimental data, the initial soil conditions and fertilization amounts are set as shown in Table 1:

Table. 1. Soil Fertility-Crop Yield 3D Scatter Plot

Parameter	Value
Initial Nitrogen Fertilizer (N_0)	2.0 g/kg
Initial Phosphorus Fertilizer (P_0)	0.5 g/kg
Initial Potassium Fertilizer (K_0)	1.5 g/kg
Initial pH (pH_0)	6.5
Initial Microbial Activity (microbial activity$_0$)	1.0
Root Growth Rate (root growth rate)	0.1
Leaf Growth Rate (leaf growth rate)	(8) 0.15
Plant Height Growth Rate (plant height growth rate)	0.05
Nitrogen Fertilizer Application (N_addition)	0.5 g/kg
Phosphorus Fertilizer Application (P_addition)	0.2 g/kg
Potassium Fertilizer Application (K_addition)	0.3 g/kg

(2) Differential Equations and Solution

The differential equation system based on experimental data is as follows: Changes in nitrogen, phosphorus, and potassium concentrations are modeled by substituting the fertilization amounts into equations (1)– (3).

As shown in Figure 2, microbial activity lowers soil pH annually.

Microbial Activity Change:

$$\frac{dMA}{dt} = 0.1 \cdot (N + P + K) \cdot (1 - MA) - 0.5 \cdot MA \tag{9}$$

Microbial activity is influenced by soil fertility and also undergoes self-decline.

Substituting data into equations (6)– (8) yields the changes in root growth, leaf growth, and plant height:

$$\frac{dRG}{dt} = 0.1 \cdot (N + P + K) \cdot (1 - RG) \tag{10}$$

$$\frac{dLG}{dt} = 0.15 \cdot (N + P + K) \cdot (1 - LG) \tag{11}$$

$$\frac{dPH}{dt} = 0.05 \cdot LG \cdot (1 - PH) \tag{12}$$

(3) Numerical Solution and Results

The differential equations are solved using the odeint method to simulate changes in soil fertility, pH, microbial activity, and crop growth over 10 years with 100-time steps. Key trends include:

a) Soil Fertility: Fertilization increases nitrogen, phosphorus, and potassium concentrations, as shown in Table 2.

b) pH Change: Microbial activity reduces pH to 6.2, as shown in Table 3.

c) Crop Growth: Root, leaf, and plant height increase, with plant height reaching 30 cm after 10 years, as shown in Table 4.

Table. 2. Soil Fertility Change

Year	Nitrogen (g/kg)	Phosphorus (g/kg)	Potassium (g/kg)
0	2.0	0.5	1.5
1	2.5	0.6	1.8
2	3.0	0.7	2.0
...	...	...	...
10	5.0	1.0	2.5

Table. 3. pH Change

Year	pH Value
0	6.5
1	6.45
2	6.4
...	...
10	6.2

Table. 4. Crop Growth

Year	Plant Height (cm)	Leaf Growth (cm)	Root Growth (cm)
0	0	0	0
1	2	3	1
2	5	6	2
...	...	...	...
10	30	25	15

The differential equations are solved using the odeint method to simulate variations in soil fertility, pH, microbial activity, and crop growth (root, leaf, and plant height) over 10 years with 100-time steps. Fertilization leads to an increase in nitrogen, phosphorus, and potassium concentrations, confirming the effectiveness of the fertilizer. Additionally, microbial activity results in a reduction of soil pH to 6.2 over time, reflecting the impact of microbial dynamics. Crop growth also improves, with root, leaf, and plant height all increasing, and plant height reaching 30 cm after 10 years.

This study introduces a dynamic feedback model that integrates soil fertility, microbial activity, and crop growth. Unlike previous studies, this model links microbial activity, pH changes, and nutrient cycling to crop growth, offering a more comprehensive approach. The model also adapts fertilization strategies based on different soil types, optimizing nutrient retention. By combining LCA with GA, the model enhances both environmental and agricultural outcomes, making it a more integrated and sustainable solution.

Previous models typically treated soil, fertilizer, and crop growth as independent factors. In contrast, this study's integrated approach provides a more accurate and holistic model, highlighting the importance of feedback loops between these elements. The consideration of soil types further differentiates this work, offering more tailored and effective fertilization strategies.

2.4. Optimization of Wheat Straw and Distiller's Grains Fertilizer via Life Cycle Assessment and Genetic Algorithm

The model results reveal patterns in fertilizer ratios and application methods, as shown in Figure 2.

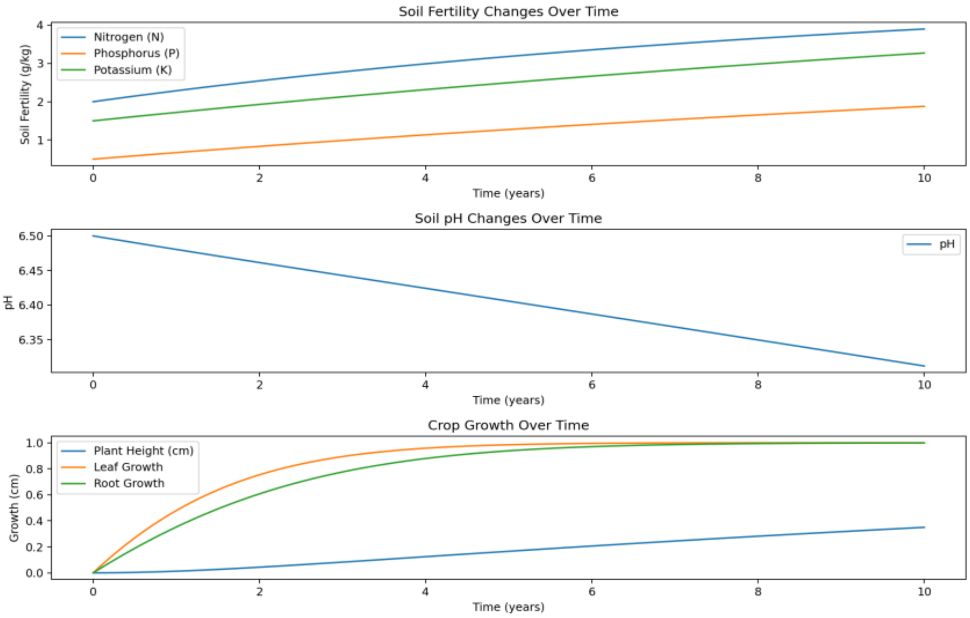

Figure 2. Fertilizer Ratios and Application Methods

(1) Impact on Soil Properties

Applying nitrogen (N), phosphorus (P), and potassium (K) alters soil fertility. According to the model, nitrogen is absorbed at a rate of 0.1, while phosphorus and potassium are absorbed at 0.05. This affects soil nutrient concentrations, leading to increases or decreases over time, as shown in Figure 3.

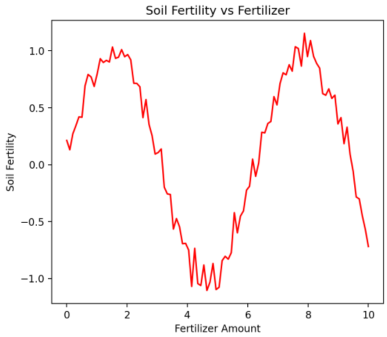

Figure 3. Soil Fertility vs. Fertilizer Amount

Soil types differ in fertilizer absorption and retention. Sandy soils lose nutrients quickly, resulting in short-term fertilization effects, while loam and clay soils retain nutrients better, improving fertility long-term, as shown in Figure 4.

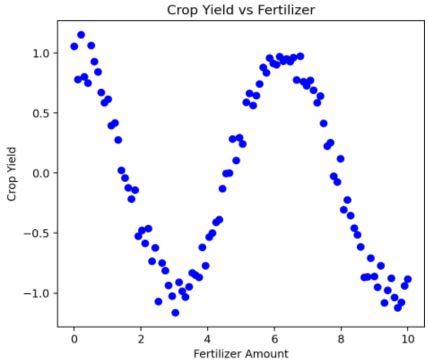

Figure 4. Crop Yield vs. Fertilizer Amount

Soil pH is affected by fertilizer and microbial activity, with organic fertilizers typically lowering pH by 0.02 units annually. Clay soils show higher acidity due to strong buffering, while sandy soils have less pH change but more nutrient loss.

Microbial activity correlates with soil nutrients. Fertilizers increase nitrogen, phosphorus, and potassium, promoting microbial growth. In sandy soils, fertilizers boost microbial activity but increase nutrient loss, while loam and clay stabilize microbial activity, enhancing soil fertility and crop nutrient efficiency, as shown in Figure 5.

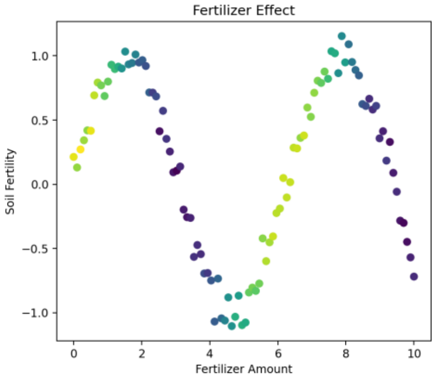

Figure 5. Fertilizer Effect

(2) Impact of Fertilizer on Crop Growth

Fertilizers enhance root growth, improving nutrient and water absorption. Loam and clay support better root expansion, while fertilizers boost leaf growth in these soils. Sandy soils lose nutrients quickly, resulting in poor leaf growth. Fertilization accelerates crop growth, particularly in loam and clay, where nitrogen availability enhances photosynthesis and stability.

(3) Soil Fertility, Microbial Activity, and pH Impact on Crop Growth

Nitrogen, phosphorus, and potassium are essential for crop growth. Fertilizers increase soil nutrients and promote growth. Microbial activity helps release nutrients and improves disease resistance. Soil pH affects nutrient availability, with extreme pH values limiting nutrient uptake and altering microbial communities, impacting growth.

(4) Summary and Fertilization Recommendations

Wheat straw and distiller's grains fertilizers improve fertility, pH, and microbial activity, promoting root and leaf growth. Fertilization strategies should account for soil type, as sandy soils have high nutrient loss, while loam and clay are more efficient. Proper fertilization contributes to sustainable agriculture.

3. Conclusions

This study introduces a novel model combining LCA and GA to optimize wheat straw and distiller's grains fertilization. The innovation lies in integrating environmental impacts with fertilization strategies, considering soil type variations and the dynamic feedback between soil, fertilizer, and crop growth.

Experimental results show significant improvements, especially in loam and clay soils, where better fertilizer retention enhances soil fertility and crop growth. Unlike previous studies, this model emphasizes the need for tailored fertilization strategies based on soil types, providing a more efficient approach.

The research supports sustainable fertilization practices and agricultural waste recycling. Future work should refine the model's assumptions, include more soil types, and incorporate smart fertilization techniques to enhance accuracy and applicability.

Overall, this study advances green agriculture by optimizing fertilization strategies, with implications for both productivity and sustainability.

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