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Sustainable biodiesel production from oil crops: The impact of bio-nutrient recycling on yield and farmer technology acceptance

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ABSTRACT

Circular utilization of biowaste through biofuel production is a key priority for many waste-producing facilities seeking to internally supply biofuels and to reduce greenhouse gases. This study assesses the role of biowaste sewage sludge (SS) and its combination with biomass ash (SS+BA) in fertilizing perennial castor beans in temperate regions, emphasizing circular waste management and biofuel production. A combined approach of field experimentation and biodiesel quality analysis was implemented using two castor bean genotypes, comparing the effects of biowaste against both unfertilized and traditional fertilized controls. The introduction of biowaste nutrients significantly enhanced various plant growth parameters, leading to notable increases in seed, oil, and biodiesel yields compared with the control group. The highest yields of biodiesel and solid oil cake were recorded in the second year, with SS treatment yielding 1549 L ha^{-1} and 1958 kg ha^{-1}, results that were comparable to those from SS+BA. The quality parameters of the castor bean biodiesel met established standards, with the exception of kinematic viscosity and flash point, which necessitate blending with diesel. Analysis using the Technology Acceptance Model (TAM) indicated that castor bean serves as an efficient biodiesel input, with the intention to use influenced by perceived benefits, barriers, and attitudes towards agricultural application. Ultimately, the study concludes that the proposed approach for biodiesel production offers a sustainable and promising option for on-farm utilization.

1. Introduction

The European Commission's current Green Deal targets, with the overarching goal of making Europe climate neutral by 2050, have brought with them aspects of clean and renewable energy and sustainability in agriculture by reducing fertilizer use and enabling nutrient cycling in the European Union. In past decades, first-generation biofuels have been used as primary raw materials to produce bio-based energy. In this context, non-edible energy crop production in marginal land or low-fertility soil that is not suitable for food crops has great potential to produce bio-based energy feedstock utilizing waste nutrient resources (Pehlivan et al., 2024). Biomass is considered carbon neutral because the CO_2 emitted during combustion is balanced by the CO_2 fixed by photosynthesis in the recent past (Pata et al., 2023). In this context, native oil crops are proposed the most popular alternative to solve the Green Deal policy requirements to supply solid, liquid, and gaseous forms of biofuels (Jabeen et al., 2022). Despite its potential, bio-based energy production primarily relies on traditional cultivation of edible crops. This strong dependence on food crops, combined with intensive cultivation inputs, has been a significant point of criticism regarding bioenergy crops. The Non-edible oils are accepted as environmentally and socially sustainable because they can be produced on non-cultivated lands and do not compete with food production (Munir et al., 2023). The upstream processes involved in producing crop-based energy significantly worsen the overall greenhouse gas emissions associated with bioethanol, biodiesel, and biogas production (Zinngrebe et al., 2024).

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For example, the agricultural phase of rapeseed cultivation is responsible for over 65 % of carbon emissions, largely due to the use of mineral fertilizers (Gupta et al., 2022). Thus, it is essential to pursue higher added value in a more sustainable manner, minimizing energy use, resource consumption, and greenhouse gas emissions (Ozdemir et al., 2019).

The castor bean (*Ricinus communis* L.) is an attractive vegetable oil plant because it occurs naturally under unfavorable environmental conditions, grows perennially, and produces a considerable biomass with a high oil yield. Castor oil is traditionally used for cosmetics, lamp lighting, as a raw material for biodiesel, plastics, lubricants, and biomass as a solid fuel. Although castor plant is perennial in its origin region and well adapted to tropical climate (Ali et al., 2020), it is successively grown in temperate regions (Soratto et al., 2012). As a naturally occurring plant on uncultivated land, its resistance to pests and diseases and its high yield potential make castor bean an ideal non-food test crop that has been the subject of numerous studies for soil remediation, phytoremediation of contaminated land, re-vegetation of marginal land, and the development of new uses and values for by-products from renewable bio-based materials and biofuel production (Carrino et al., 2020). In addition, castor oil is crucial for many industrial applications because the unique composition of the oil in terms of fatty acid composition, which contains about 90 % ricinoleic acid, makes castor bean a unique and the only commercial source in the world (Dias et al., 2013) because it can withstand high and low temperatures exclusively (Wang et al., 2021).

Biofuel resources and bioenergy plants are the most acceptable renewables to overcome the declining global supply of fossil fuels. In this context, castor bean can serve as multiple energy sources, both lignocellulosic biomass and castor oil, that can be used as primary raw materials for biodiesel. Biofuel production is still limited due to the lack of availability and accessibility of ample raw feedstock, which is responsible for 70–85 % of biodiesel production costs (Babadi et al., 2022). Unlike edible crops, non-edible plant oil and biomass production in marginal land using low-cost waste resource fertilizer, which is an environmentally friendly facility with integrated, efficient, and flexible biomass production and processing for various value-added products and energy, can overcome the economic barriers and lead to proficient biofuel production (Erat et al., 2021). The castor bean plant is a non-edible oilseed crop that tolerates various agro-climatic conditions and is responsive to soil fertility levels and cultural applications (Anastasi et al., 2015). Despite being a commercial crop, the biomass and seed oil yields are very limited. The current average castor seed yield is about 1.4 t ha^{-1}, with an annual production of 1865700 t (Setayeshnasab et al., 2024). Although reported yields are rather modest, it is believed to be a crop with potential under favorable environmental circumstances. Applying waste bio-fertilizer materials to the cultivation can increase seed yield to 4–5 t ha^{-1} (Ali et al., 2020), which could result in a promising oil productivity. Furthermore, castor beans are recognized as plants that thrive in hot areas. By this point, it could be a potential oil crop to increase biodiesel production in challenging climate conditions in the future.

Balanced nutrient application is the key factor in realizing the full yield potential of oil crops. Fertilization with waste-biofertilizer material could enhance the profitability and sustainability of castor bean production systems. The macro-nutrients (NPK) and micro-nutrients (Fe, Zn, and Mn) are essential for increasing the seed yield, oil content, oil yield, and hence biodiesel production (Hazrati et al., 2020). Most organic wastes hold a well-balanced quantity of plant nutrients in slow-release forms, which are bound to organic matter and become readily available for plants during vegetation (Ozdemir et al., 2019). This situation is specifically important for castor beans because of their perennial growing habit, and nutrient availability is vital for plant metabolism. The effect of fertilizer application on growth and yield of castor bean has been studied in many previous studies in different environmental conditions (Calcagno et al., 2023). Mukhtar et al. (2022) performed a study to observe the impact of S on the plant physiology and yield of castor bean and concluded that S application rates, namely 20, 40, and 60 kg S ha^{-1}, enhanced the yield over control in castor.

Biodiesel energy technology holds immense potential for sustainable energy transitions. However, its diffusion and acceptance are influenced by various factors. To address this, the Technology Acceptance Model (TAM) is a valuable framework that considers technology readiness and acceptance as critical factors in the adoption behavior of new energy technologies. The TAM emphasizes the importance of perceived usefulness and perceived ease of use in determining technology acceptance and subsequent diffusion in the new energy industry. Stakeholders have identified barriers and facilitators related to technology, economics, politics, and social-psychological aspects, but the TAM can integrate insights from these contexts to promote the acceptance of biodiesel energy technology (Dessi et al., 2022; Tran and Cheng, 2017). Therefore, the TAM is vital for understanding and promoting biodiesel energy technology's acceptance, which can play a crucial role in sustainable energy transitions (Sun and Wang, 2019). The TAM can provide a valuable framework for understanding and promoting the acceptance of biodiesel energy technology by considering various barriers and facilitators related to technology, economics, politics, and social-psychological aspects (Tillinghast, 2021).

Organic-based fertilizers enable better retention of plant nutrients in the soil due to the organic substance. Biowaste fertilizers release nutrients more slowly into the soil solution, primarily through biodegradation processes, which minimizes nutrient leaching in the soil and enhances nutrient availability to plant roots (Dede et al., 2023). For perennial crops such as castor bean, the lower solubility of biowaste fertilizers is the main advantage of long-term storage in the field. Their composition is thus delivered during the cultivation cycle of plant development. This can increase the efficiency of nutrient utilization, reduce the amount of fertilizer required, ensure the capturing of leaching elements by plants, and promote plant growth and oil yield. Therefore, the primary objective of the current research study is to address the gap in oilseed production by utilizing biowaste nutrients within the framework of closing nutrient loops. It also aims to assess stakeholder attitudes toward the adoption of biodiesel technology at the farm level, thereby facilitating the green transition and reducing reliance on fossil fuels in agricultural production systems. Furthermore, the analysis provides valuable insights into farmers' behaviors regarding the integration of biodiesel usage, particularly highlighting their willingness to adopt the system in their daily practices to promote sustainable agriculture.

2. Materials and methods

2.1. Sewage sludge and biowaste fertilizer preparation

Sewage sludge is widely used in the agricultural sector to substitute chemical fertilizer, mitigate the physical, chemical, and microbiological structure of soils, and irrigate cultivated crops. The sewage sludge used in the experiment was obtained from a Wastewater Treatment Plant (WWTP) in Karasu, Sakarya province, Turkey. This WWTP is treating 100 % domestic effluent using a biological treatment process. Excess sludge generated during the process separates the solid liquid fraction using a mechanically dewatered system. The obtained sludge sample was dried on concrete surfaces until the constant moisture content was archived during the summer period. Additionally, sewage sludge is mixed with biomass ash to obtain a NPK content of 7.0 % in biowaste fertilizer. The homogenously mixed materials were then incubated at room temperature (25 ± 2°C) for two weeks in order to solubilize plant nutrients by microbial action (Dede et al., 2023) and then solar dried to obtain dry biowaste fertilizer for bionutrient resources for energy crop fertilization.

2.2. Seed collection

In the experiment, two types of castor bean have been used; the small grey color seed genotype obtained from the roadside in Adana (36°58’29.6"N; 35°36’12.6"E) and large seed genotype collected from the Adana (37°02′57.2″N; 35°16′12.7″E) in southern Turkey.

2.3. Experimental design

The experimental site was selected near the wastewater treatment plant to evaluate the crop adaptation to the temporal climate black sea cost. The study was conducted on experimental plots (5 m×10 m) in Sakarya province (Northwest Turkey 41°06′35″ N 30° 39′23″W) using a randomized block design with three plots per treatment and 12 plants per plot. In the experiment, plants were arranged in three rows, each consisting of four plants. 3 plants are planted per square meter with a spacing of 1 m between rows and an interval of 0.33 cm within rows. Three treatments were tested, namely a control soil without any fertilizer application (T_0), solar dried sewage sludge from a municipal wastewater treatment plant at a dose of 5 t ha^{-1} (T_1), biowaste fertilizer produced from sewage sludge cake and biomass ash (T_2), and a mineral fertilizer treatment using NPK (15:15:15) at a dose of 142 kg ha^{-1} (T_3), and two castor bean genotypes (small grey seed and large brown seed). The application dose of treatments was selected on the basis of nitrogen content, mineralization rate of materials and the type of soil and climatic conditions (Ozdemir et al., 2021). The properties of the soil and SS have been presented in Table 1. The experimental design followed a randomized complete block design (RCBD) in a factorial arrangement. Castor bean genotypes were assigned to main plots under factor A, while factor B involved nutrient sources derived from waste materials. Castor bean experiments were established in the beginning of May 2021, transplanting the castor bean seedlings that were produced in a seedling tray using peat media. After plantation, no irrigation was applied, and plants grew in normal agro-climatic conditions.

The study area had an annual mean temperature of 13.4°C and an annual precipitation of 829.7 mm between 1959 and 2020. The temperatures during the study varied from a mean minimum of 0°C to a mean maximum of 32.3°C. Meteorological data for the experiment was collected from the nearest meteorological station in Karasu, Sakarya, Turkey as shown in Table 2. Soil samples were taken before planting during the first growing season. No weeding or pest control measures were taken during the experiment.(Table 3)

After the initial crop season in 2022, the castor bean plants were able to survive the fall-winter period due to their perennial nature. The plants demonstrated a level of tolerance to the winter conditions, which was likely due to the favorable thermal environment at the experimental location.

Plant growth and yield parameters such as plant height, raceme weight, capsules per plant, seeds per plant, seed yield per plant, hundred seed weight, and seed yield were determined following standard experimental procedures. Racemes were harvested when the color of the capsules turned brown. After harvesting, the racemes were sun-dried, and the seeds were separated manually from the capsules. Then, the clean seeds were weighed, and seed yield (kg ha^{-1}) was calculated for each plot. The extractable seed oil was extracted using a cold press, and the seed oil concentration was determined. Then, oil yield per hectare was calculated by seed yield with seed oil concentration. For a better understanding of the yield performance of the treatments, the biodiesel yield was calculated by multiplying the oil yield by the percentage of the biodiesel yield ratio of the oil.

Table 1
Properties of experimental soil, sewage sludge and biowaste fertilizer prepared from sewage sludge and biomass ash.

Parameters	Experimental soil	Sewage sludge	Biowaste fertilizer
pH	7.03	6.71	8.04
EC (mS cm^{-1})	0.20	2.16	4.23
OM (%)	2.18	57.91	52.83
C/N	60.43	9.27	11.03
TN (%)	0.02	3.04	2.57
TP (%)	12.46	0.91	1.42
TK (%)	72.74	2.11	3.02
Ca (%)	1.80	5.10	6.41
Mg (%)	45.29	0.68	1.20
S (%)	4.70	0.70	0.64
Fe (mg kg^{-1})	29.20	18400	4973
Mn (mg kg^{-1})	32.80	471	558
Zn (mg kg^{-1})	3.00	329	553
Cu (mg kg^{-1})	0.88	76	87
Ni (mg kg^{-1})	0.57	27	46
Cr (mg kg^{-1})	1.17	173	156
Cd (mg kg^{-1})	0.48	1	4
Pb (mg kg^{-1})	0.03	16	5
Hg (mg kg^{-1})	ND	ND	ND

ND: not determined.

2.4. Synthesis of biodiesel

The process of transforming castor bean oil into fatty acid methyl esters involves several steps. Firstly, the oil is extracted, filtered, and then subjected to transesterification. NaOH mixed with a specific amount of methanol is added to the oil, which is then heated to a temperature of 65°C. A castor oil molar ratio of 6:1, a catalyst concentration of 2 wt%, a methanol ratio of 20 %, and a reaction time of 120 min are used. The mixture of methanol and catalyst is then added to the oil and stirred continuously at 400 rpm. After the transesterification process is complete, the reaction mixture is left in a separating funnel for 36 hours to settle down and evaporate any excess alcohol. The glycerin settles in the lower portion of the funnel, while the upper layer, consisting of fatty acid methyl ester, is collected separately. The remaining mixture is then neutralized, and any traces of catalyst and alcohol are washed out with distilled water until the water layer is completely translucent. Finally, the methyl ester is dried at 80°C for 180 min to evaporate any remaining water (Fig. 1).

After the production of biodiesel, it undergoes a process of analysis to determine various properties. These properties include density, kinematic viscosity, flash point, purity, oxidative stability, cetane number, heating value, linolenic acid methyl ester, and polyunsaturated methyl esters. The measurements are carried out in accordance with the ASTM standards by an accredited laboratory, which is specified for biodiesel analysis.

2.5. Self-administered questionnaire

A self-administered questionnaire with a cross-sectional survey design was used for this research. The study was conducted from April 1, 2024, until April 19, 2024. The questionnaire consists of three sections with twenty-seven questions (Supplementary Material). One section comprised of demographic questions regarding gender, age, education level, experience in farming, and status of membership in organizations. The other two sections covered the study model’s components; perceived ease of use, perceived usefulness, attitude, intention to use, perceived benefits, and perceived barriers (Fig. 2). A five-point Likert scale was used to gauge respondents’ levels of agreement with the statements, ranging from strongly disagree (1) to strongly agree (5), in order to quantify the responses to the assessed variables. A survey of the literature on renewable technology studies and technology acceptance research was used to design the questionnaire. To confirm the effectiveness of the questionnaire, a pilot study involving ten randomly selected people was conducted. With certain context-specific modifications, the questions from the pilot research helped to increase the questionnaire’s efficacy. The data was provided by farmers in Sakarya province, Turkey.

Perceived usefulness and perceived ease of use have been shown to

Table 2
The long-term average monthly temperature for an average sun hour and precipitation from 1959 to 2020 for Karasu county, Sakarya, Turkey.

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Mean Temp (°C)	5.4	5.9	7.9	11.3	16	20.6	23.2	23.7	20.4	16.1	11.7	7.4
Min. Temp (°C)	2.7	3	4.6	7.8	12.6	17.3	20	20.9	17.5	13.4	9	4.9
Max Temp (°C)	8.2	8.9	11.1	14.3	18.8	23.2	25.7	26.2	23	18.6	14.7	10.3
Precipitation (mm)	105	90	91	62	59	61	45	53	75	103	89	120
Sunshine (h/day)	5.4	6.0	7.1	8.7	9.8	10.6	10.4	9.6	8.3	6.5	6.2	5.4

Temp: Temperature

Table 3
Hypothesis statements.

Hypotheses	Paths	Explanation
H1	AT→IU	Attitude has a significant positive effect on the intention to use renewable energy.
H2	PU→AT	Perceived usefulness has a significant positive effect on attitude towards using renewable energy.
H3	PEOU→AT	Perceived ease of use has a significant positive effect on attitude towards the use of renewable energy.
H4	PEOU →PU	Perceived ease of use has a significant positive effect on the perceived usefulness of renewable energy.
H5	PBen→IU	Perceived benefits has a significant positive effect on the intention to use renewable energy.
H6	PBar→IU	Perceived barriers has a significant positive effect on the intention to use renewable energy.
H7	Age↔IU	There is a statistical difference between age and intention to use biodiesel in farming.
H8	Education↔IU	There is a statistical difference between education and intention to use biodiesel in farming.

AT: Attitude; IU: Intention to Use; PU: Perceived Usefulness; PEOU: Perceived Ease of Use; PBen: Perceived Benefits; PBar: Perceived Barriers.

have a major impact on intentions in the literature on technology acceptability. Thus, the model included two common constructs: perceived usefulness and perceived ease of use. The following hypotheses have been developed to test the technology acceptance of respondents based on the methodology described in Fig. 2. The study is conducted in Sakarya municipality, where it is highly efficient to produce biodiesel from castor bean plants. There are roughly a total of 47000 farmers in Sakarya. From those, it is estimated that around 1 % have used biodiesel technology at least once. Therefore, the total population for this study is around 470. The total number of 100 people as a sample would be sufficient to create a questionnaire considering the number of people in the population. The sampling method for this study is selected as random sampling to reach the audience as fast as possible with the least cost.

2.6. Data analysis

This research employs quantitative data analysis techniques, including descriptive statistics, Student's T-Test, and regression analysis, to demonstrate the correlation between independent and dependent variables. The dataset was analyzed using SPSS version 25.0. To ensure the experiment's quality, reliability was assessed using Cronbach's Alpha, content validity was evaluated with a pretest, construct validity was measured using the Pearson Correlation test, and external validity was satisfied by representing25 % of the population.

3. Results and discussions

3.1. Basic properties of soil and treatments

Among the most important elements in fertilizers, BA is a significant source of phosphorus and potassium, while SS mainly contributes nitrogen. The addition of BA has significantly increased the organic-mineral content of SS (Table 1). Incineration at high temperatures turns the plant nutrients in the ash into a crystal structure that is no longer bioavailable for plant uptake (Turp et al., 2023). The incubation of ash with sewage sludge significantly increased the availability of the most important plant nutrients in the biowaste fertilizer. For example, the plant-available form of P and K in the biowaste fertilizer was 45 % and 72 %, respectively. These results clearly indicate that the amount of accessible P and K in the biowaste fertilizer treatment was significantly increased as a result of microbial solubilization. The reported contents of

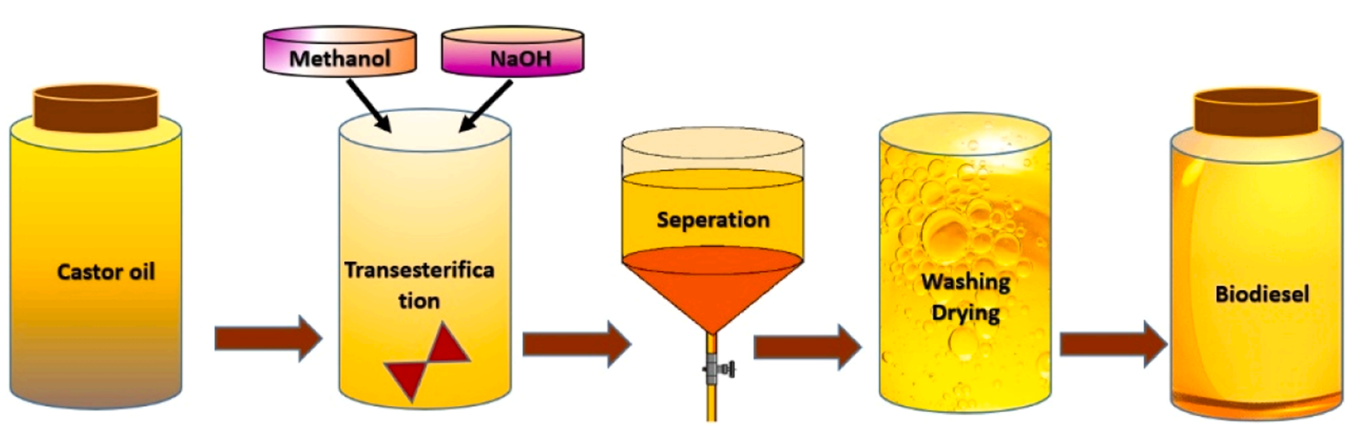

Fig. 1. Schematic representation of biodiesel synthesis.

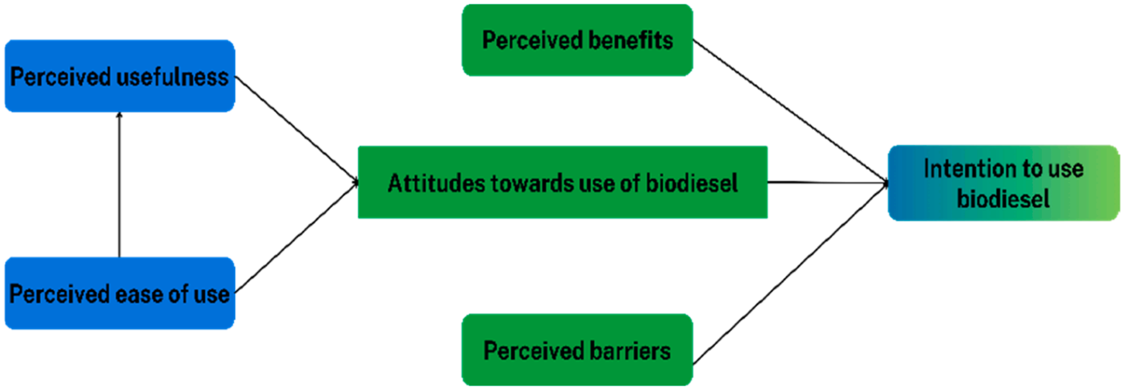

Fig. 2. The framework of the technology acceptance model.

organic matter, TN, exchangeable K, accessible P, and biomass ash content were comparable to those of the biowaste fertilizer made from biomass ash. The nutrients N, P, K, and other plant nutrients present in biowaste resources decomposed only slowly to release nutrients for a longer period, which accelerated growth and biomass production in many species of plants (Ozdemir et al., 2021). Perennial plants like castor bean are more adapted to slow-release nutrient resources through an active growing period that absorbs the nutrients in the soil (Dede et al., 2023). Acid extraction is the most commonly used method for recovering phosphorus and potassium from biomass ash. However, dissolving the nutrients in an acidic solution and the evaporation process are energy-intensive. In this regard, a biological method such as composting biomass ash with sewage sludge, which is rich in microbial communities, may be the most environmentally friendly method for solubilizing plant nutrients from biomass ash.

3.2. Seed and oil yield

According to the results of the variance analysis, the main and interactive effects of the cultivar (A), nutrient source (B), and year were significant on the castor bean seed yield. The application of nutrient sources considerably increased the seed yield in both years. In general, the seed yields of castor bean were increased by applications of sludge and SS+BA compared with the control and mineral fertilizer treatments. Additionally, the observed seed yields were higher in the second year for all treatments. The highest seed yield (3560 kg ha^{-1}) was observed in SS in the second growing season for large seed castor beans. However, this treatment did not have significant differences with SS+BA in both years (Fig. 3A). This may be due to the increase in nutrient use efficiency provided by biowaste that acts as a slow nutrient release and perennial properties of castor bean, which causes the improvement of photosynthesis rate and growth of plants (Ozdemir et al., 2019). The stimulating effects of SS and biomass ash were attributed to the increase in the activity of microorganisms and enzymes that could transform nutrients into available forms for plants' entire crop vegetation period (Turp et al., 2023), resulting in plant growth increase.

Both varieties exhibited frost resistance in the winter conditions of the experimental location. The plant heights were 132 ± 18 cm for the large seed genotype and 130 ± 17 cm for the small seed genotype in the first year (2022), but the mean heights reached 182 ± 15 cm in the second year (2023) for both varieties due to the rapid growth in the second year. Increased plant growth, branching, number of racemes, and

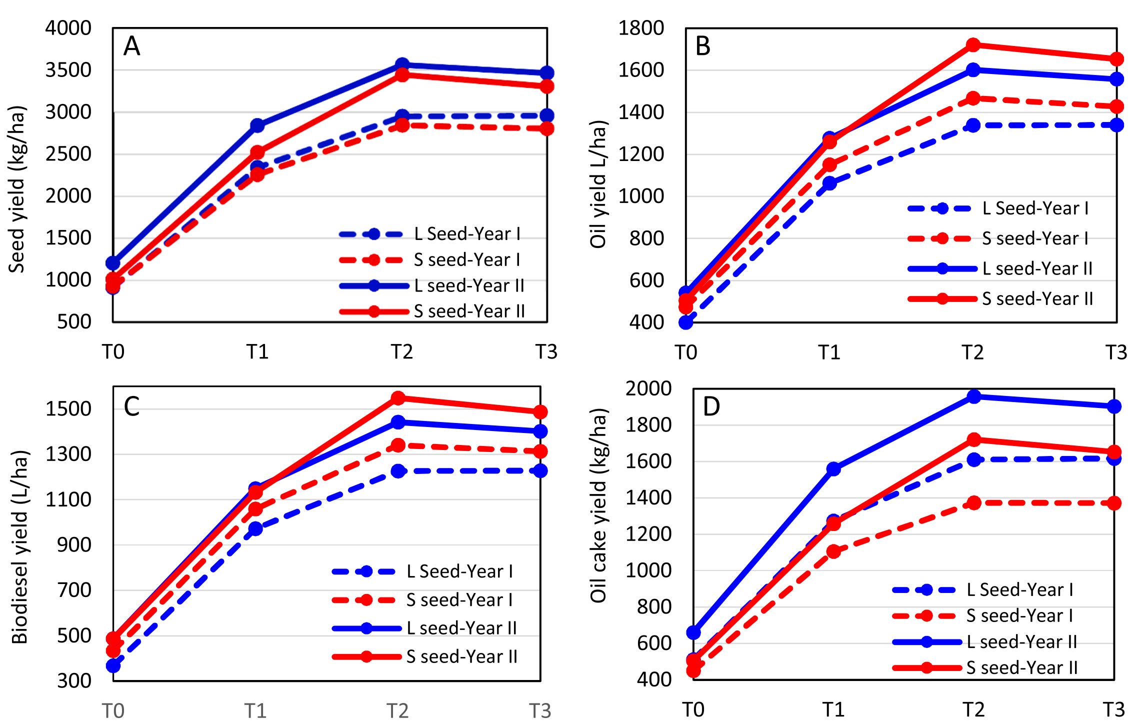

Fig. 3. Influence of year, nutrient source and genotype on the yield of castor seed (A), oil (B), biodiesel (C) and de-oiled cake (D).

seed yield can explain the increased seed yield. Other researchers also reported improved growth and increased seed yield of castor beans with N application (Calcagno et al., 2023). Accordingly, Hazrati et al. (2020) reported that plant growth parameters and seed yields of castor beans were significantly increased by the application of vermicompost and nitrogen fertilizer compared with the control, mainly due to the increased seed number per plant. Hazrati et al. (2020) reported that plant growth, branch numbers, inflorescence growth, seed yield, and its components were significantly increased by foliar application of N, P, and S. The higher seed yield that has been obtained from treatments with SS and SS+BA explains the response of castor plants to biowaste nutrients that contain all plant nutrients at a balanced level.

According to the statistical analysis, the main effects of cultivar and fertilizer treatment and year effects were significant, and the interactive effects of nutrients were not significant on oil yield. The main reason for oil yield variation was the seed oil concentration of varieties and increasing seed yield in chemical fertilizer, SS, and SS+BA as a nutrient resource. The oil concentration in the small seed genotype was 51 $\pm$ 1.14 %, and the large seed genotype was 45 $\pm$ 2.01 %. The nutrient treatments did not affect the seed oil concentration since the oil content of castor seeds is a high heritability trait (Soratto et al., 2012), did not change over the cropping season, and applied agronomic input (Anastasi et al., 2015). The oil yield is obtained by multiplying the seed yield by the percentage of oil content in the seeds. Due to the increased seed yield, applying the waste nutrient resources SS and SS+BA significantly improved castor bean oil yield compared with the fertilizer and unfertilized control treatments (Fig. 3B). Other researchers have reported increased seed oil yields with fertilizer application (Carrino et al., 2020). Nasr et al. (2019) observed a considerable increase in castor oil yield by applying aerobic-treated SS. The maximum oil yield (1721 L ha^{-1}) was obtained from the treatments of SS in the second year from a small seed genotype that did not have a significant difference with the treatment SS+BA, which gave the oil yield of 1653 L ha^{-1} in the second year of the experiment (Fig. 3B). The positive effects of nutrient treatments on increasing oil yields in biowaste treatments may be due to the improvement of soil biological, physical, and chemical characteristics by using SS and BA (Barra Netto-Ferreira et al., 2023), which could result in higher and continuous nutrient uptake by perennial plants by releasing nutrients slowly (Ozdemir et al., 2021). In addition, castor beans have a very high oil content (45–51 %) compared with traditional oil crops such as soybeans (15–20 %), sunflowers (25–35 %), or rapeseed (38–46 %). High seed and oil content can reduce the cost of biodiesel production by up to 50 % compared with rapeseed (Carrino et al., 2020). In this context, adapting a closed nutrient cycle and introducing internal procurement of liquid fuel at the farm level can further contribute to the sustainability of the rural economy. The cost of biodiesel production mainly depends on feedstock (Ali et al., 2020), and the proposed strategy aims to reduce this cost.

3.3. Biodiesel and oil cake yield

The ANOVA results showed that the effects of genotypes and treatment effects were significant on biodiesel yield. Furthermore, the biodiesel yields were significantly higher in the second cultivation year for both genotypes, depending on the oil yield and concentration of the seed (Fig. 3C). Similar to the oil yield, the highest biodiesel yield (1549 L ha^{-1}) was obtained from the small seed genotype under SS application in 2023. The SS treatments gave the highest biodiesel yields in both genotypes; however, these yields were not significantly different from SS+BA. Balanced fertilization with macro and micro plant nutrients had a significant effect on crop growth and plant yield parameters in perennial castor bean. Mineralization of sludge organic matter and solubilization of biomass ash nutrients as a function of microbial activity underpin the positive contribution of waste nutrients to castor bean biodiesel yields. The significant increase in biodiesel yield by the application of SS could be attributed to the optimal nutrient supply of the perennial castor plants by SS and SS+BA. Anastasi et al. (2015) also reported that the aerobic-treated SS application improved plant growth, seed yield, and seed oil concentration through N translocation from the vegetative parts to the grain during the grain filling period.

During castor oil production, large quantities of solid residues, the so-called seed cake, are produced after oil extraction. The seed cake is closely related to the oil yield that remains after oil extraction from the seed tissue. The oil cake yield was lower than the oil yield in the small seed genotype but higher in the large seed genotype (Fig. 3D). Among the different treatments, the highest oil cake yield (1958 kg ha^{-1}) was observed in SS, followed by the combination of SS+BA (1903 kg ha^{-1}) for the large seed genotype in the second year of growth. The results showed that fertilization with SS and SS+ BA had a significantly similar effect on oil cake yield in both growing years but significantly increased the yield compared with the fertilized and unfertilized controls. The high oil cake yield could be due to the increased nutrient availability of SS and BA, which improved plant growth and seed yield (Turp et al., 2023). Despite its high protein content, castor bean cake could not be used as a protein supplement due to the toxicity of glycoprotein ricin, alkaloid ricinin, agglutinin toxicity, and the allergen in animal feed. Because of this toxin, the castor bean is underutilized but has potential as a solid fuel or energy process for pyrolysis or gasification. The high heating value of the deoiled cake of both genotypes was 20.42 MJ kg^{-1} and was thus in the range of the values of 19.20–21.58 MJ kg^{-1} reported for deoiled castor seed cake (Rajpoot et al., 2022).

3.4. Correlation analysis

Previous research has shown that the yield of castor bean seed and oil greatly depends on the location and cultivation practices. Castor bean has a higher potential yield than other bioenergy crops, and various plant growth factors play a crucial role in determining the yield. The correlation between different plant growth and yield components in castor bean is illustrated in Fig. 4. According to the correlation network, oil yield is highly significant and positively correlated with plant height, raceme weight, capsules per plant, seeds per plant, and seed yield per plant. When it comes to biodiesel yield, the oil content and seed yield are the two essential factors that determine the oil and biodiesel yield. Since small seed genotypes have a high oil content, the correlation between the weight of 100 seeds is negative, which results in low oil yield in large seed genotypes, even though they have a high seed yield.

Previous researchers, indicated a positive relationship of different intensity between plant characteristics and seed, oil and biodiesel yields. Among the yield components, branching, raceme number, capsules per plant, seed per plant, oil content were reported significantly correlated with oil yield (Armendáriz et al., 2015; Hazrati et al., 2020).

3.5. Properties of biodiesel

The large seed genotype yielded 91 % biodiesel from castor bean oil, while the small seed genotype produced 90 %, consistent with Karmakar et al., (2018)) findings of 91 % yield from castor beans. Halek et al. (2013) reported even higher yields of 94 % with acid catalyst transesterification of castor seed oil. These genotypes also had higher biodiesel yield per hectare due to superior oil content and conversion rates, surpassing reported values for the Mediterranean, Asia, and Africa regions.

Table 4 presents important biodiesel properties that must meet industry standards after converting castor oil samples into biodiesel. The density of the castor oil biodiesel was 885 kg m^{-3}, within the range specified in the ASTM D6751 standard. This density was also consistent with reported values for soybean, canola (Negm et al., 2016), and cottonseed oil biodiesel (Abdulvahitoglu and Kilic, 2022).

The quality of biodiesel as a fuel is assessed through its kinematic viscosity, a fundamental characteristic. Castor bean biodiesel typically has a higher kinematic viscosity than the ASTM standard due to the

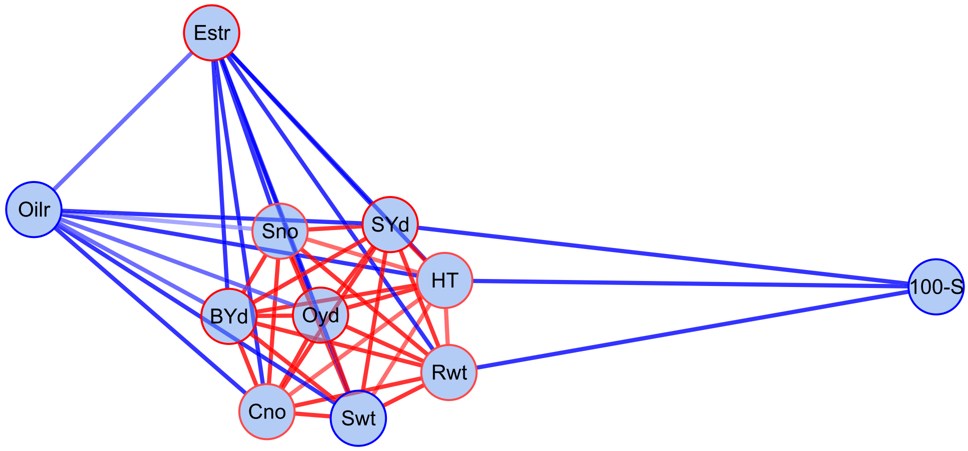

Fig. 4. Pearson correlations network among parameters that affecting Syd, OYd, and BYd of castor bean.SYd: Seed yield, OYd: oil yield, BYd: biodiesel yield, HT: plant height, Rwt: raceme weight, Cno: capsule number per plant; Sno: seed number per plant, Swt: seed weight, 100-S: hundred seed weight, Oilr: oiSWTl content, Estr: esterification rate.

Table 4
Physical and chemical properties of castor oil biodiesel compared with ASTM.

Property	Units	Biodiesel from castor oil	Limits	Reference Method
Density	kg m^{-3}	885	860–900	ASTM D6751
Kinematic viscosity	mm^{-2} s^{-1}	18.72	1.9–6	D445
Flash point	°C	120	Min 130	D93
Water and sediment	vol%	0.02	Max 0.05	D2709
Oxidation stability	h	60	Min 8	EN 14112
Cetane number	–	49	Min 47	D613
Heating value	MJ kg^{-1}	38.91	35	DIN 51900
Linolenic acid methyl ester	%wt	7.64	Max 12	EN 14103
Polyunstatured methyl esters	%wt	0.28	Max 1	EN 15779

presence of hydroxyl groups. As the fatty acid chain increases, the viscosity of biodiesel also tends to increase. Bueno et al., (2017)) research discovered that soybean and castor bean biodiesel had viscosities of 4.16 and 14.50 mm^2 s^{-1}, respectively. The observed kinematic viscosity of biodiesel was 18.72 mm^2 s^{-1}, which exceeded the upper limit of the ASTM standard (Table 4), possibly because of the hydroxyl group in ricinoleic acid. Some non-edible oil biodiesels, such as that derived from *Ailanthus altissima*, comply with these standard limits (Jabeen et al., 2022). According to Dias et al. (2013), castor biodiesel has a considerably higher kinematic viscosity, which ranges from 18.3 to 60.9 mm^2 s^{-1}, depending on the biodiesel conversion method, reaction temperature, and reaction time. Nonetheless, it's feasible to blend castor biodiesel with diesel up to 20 % and still maintain the standard range for diesel density (Amin et al., 2016).

The flash point for biodiesel is defined as the lowest temperature at which a liquid releases enough vapors to ignite in the presence of an ignition source. In the present study, the measured flash point is 120, which is slightly lower than ASTM standard and previously reported values for castor biodiesel. The flash point of the castor biodiesel is below the ASTM6751 (>130°C) but above the EN14214 (>101°C) permissible range.

The cetane number is known as a measurement of the combustion quality of diesel fuel. In the present study, the observed cetane number of 49 confirmed the lower limit of the ASTM standard, which was stated as > 47. A higher cetane number indicates the fuel has better spontaneous combustion performance, starts burning earlier, reduces the ignition delay time, and helps to increase combustion efficiency (Zheng and Cho, 2023). One possible reason for the low CN of castor biodiesel has been attributed to the branching of the hydroxyl group in ricinoleic acid. However, this value can be adjusted according to biodiesel and diesel blends. This result is parallel to the viscosity value, which indicates that it is challenging to ignite castor oil biodiesel.

The biodiesel's purity is used to determine whether it contains water or sediment, which can lead to problems with fuel and filter systems. This test shows whether the biodiesel was well dried after washing. The water and sediment values were below the ASTM standard's limit of 0.05 percent (Table 4).

It is desired to have a higher calorific value for the release of more energy during the combustion of biodiesel. Generally, the calorific value of biodiesel is lower than that of petro-diesel due to its high oxygen content, which results in increased fuel consumption (Yaşar, 2020). The present study found that the calorific value of castor oil biodiesel was 38.91 MJ kg^{-1}, which is similar to the calorific values of other biodiesels referenced in publications (Amin et al., 2016; Keera et al., 2018).

It is important for biodiesel fuel to have high oxidative stability so that it can be stored for a longer period without degradation. However, biodiesel fuel is more susceptible to oxidation than regular diesel fuel, and its properties can deteriorate quickly during long-term storage due to its chemical composition. As per ASTM standards, the minimum oxidative stability value should be 8 hours. In a recent study, the oxidative stability of castor oil biodiesel was found to be 60 hours, which is excellent (Table 4). The oxidative stability value observed in this study is consistent with the findings of other researchers studying castor beans (Dias et al., 2013). Machado et al. (2021) reported that soybean biodiesel is more negatively impacted than castor oil biodiesel during one-year storage due to its chemical composition.

The biodiesel from castor beans had a linolenic acid methyl ester value of 7.64 % and a polyunsaturated methyl ester value of 0.28 %, respectively. These values were found to be below the maximum limits set in the ASTM standard (Table 4).

3.6. *Technology acceptance and user attitudes*

A study was conducted in which 262 questionnaires were distributed by iOS users, and 62 % of them were returned. Some of the surveys that were returned had inconclusive findings, while others were not returned at all. As a result, the analysis had to be performed on 114 respondents who completed the questionnaires. The demographic distribution of responses is presented in Fig. 5. The male and middle-aged population showed a high level of participation. Bachelor's degrees were the most common educational attainment among the respondents. Over 81 % of the participants held bachelor's or graduate degrees. More than half of the respondents had less than ten years of experience. 78 % of the respondents did not have any farm-related organizational membership.

This study employed the Cronbach Alpha test to evaluate its reliability. A coefficient greater than 0.7 is acceptable for the Cronbach Alpha test, which ranges from 0 to 1 (Wong et al., 2024). The Cronbach's Alpha values are in between 0.794 and 0.901 for all variables and overall 0.897. These results indicate the scale's reliability. Additionally, to ensure validity, various types of validity such as external validity, construct validity, and content validity were evaluated.

In order to ensure that the survey questions are clear and free of any ambiguity, a pre-test was conducted to test the content validity and to avoid any double-barreled questions. To assess the construct validity, the research used a Pearson Correlation test. The main purpose of performing this test was to determine the degree of correlation between two sets of data and constructs. Finally, external validity, which is also known as the generalizability of the study, was the last component of validity that the research examined (Hair et al., 2003). With a total population of approximately 470, the 114 respondents who participated in the study could be adequate for external validity.

The Pearson correlation indicates the pairwise correlation between each variable (Table 5). The results are all below 0.8, which indicates none of the variables can be used interchangeably. Therefore, it satisfies the construct validity.

The minimum values for attitude, intention to use, perceived ease of use, and perceived barriers were found to be 1.0, whereas the minimum values for perceived usefulness and perceived benefits were 2.0 for total respondents. For all variables, the maximum value was recorded to be 5.0. Among all the variables, the smallest mean value was observed for perceived barriers, which was 3.64, while the highest mean value was recorded for perceived benefits and intention to use, which was 4.25. A detailed information is available for a more in-depth understanding of the results. Hypotheses in between 1 and 6 were accepted with a *p*-value of less than 0.05, as shown in Table 6. Others were rejected. The results indicate a significant positive effect on the intention to use biodiesel fuel. This finding suggests that biodiesel produced from castor beans can be easily used on individual farms. Furthermore, the perceived ease of use is a critical factor in encouraging the adoption of biodiesel technology and promoting a more significant sense of usefulness.

This finding may reflect a broader trend influenced by socioeconomic factors and policy incentives. For instance, access to information and resources about biodiesel may be more critical than educational attainment in shaping farmers' intentions (Kânoğlu-Özkan and Soytaş, 2022). In regions where biodiesel production is promoted through subsidies or educational programs, both younger and older farmers, regardless of their educational background, might feel encouraged to consider this alternative fuel. Furthermore, socioeconomic status can affect how farmers perceive the costs and benefits of biodiesel. Those in economically challenged areas may prioritize immediate savings from biodiesel, while more affluent farmers might weigh factors such as environmental sustainability and long-term investments.

Policy incentives, such as grants for sustainable farming practices or tax breaks for using biodiesel, can also play a significant role in influencing farmers' decisions (Wong et al., 2024). If such policies are more accessible to certain demographics, they could lead to varying adoption rates across different age groups and education levels, even if the statistical analysis suggests otherwise. Thus, while the results show no significant differences in intention based on age and education, the broader socioeconomic context and the effectiveness of policy measures are vital for understanding the dynamics of biodiesel adoption in farming.

The study conducted Student's T-Test analysis on the intention to use biodiesel in farming in relation to age and education. The age was divided as older and younger people from 30 years old, and the education was divided as graduates of primary and high school whereas graduates of bachelor's, master's, and PhD. education. The results are clear; there is no statistical difference between these two factors. This means that farmers of all ages and educational backgrounds are equally

Table 5
Pearson correlation between variables.

	AT	IU	PU	PEOU	PBen	PBar
AT	1					
IU	0.68	1				
PU	0.44	0.6	1			
PEOU	0.46	0.39	0.41	1		
PBen	0.46	0.63	0.62	0.48	1	
PBar	0.36	0.31	0.16	0.27	0.36	1

AT: Attitude; IU: Intention to Use; PU: Perceived Usefulness; PEOU: Perceived Ease of Use; PBen: Perceived Benefits; PBar: Perceived Barriers.

Table 6
Hypothesis testing on technology acceptance and user attitudes.

Hypothesis	Paths	p-values	Status
H1	AT→IU	0.000	Accepted
H2	PU→AT	0.000	Accepted
H3	PEOU→AT	0.000	Accepted
H4	PEOU →PU	0.000	Accepted
H5	PBen→IU	0.000	Accepted
H6	PBar→IU	0.001	Accepted
H7	Age↔IU	0.27	Rejected
H8	Education↔IU	0.29	Rejected

Rejected: non-significant, and accepted: significant at $P < 0.05$, probability levels, respectively.
AT: Attitude; IU: Intention to Use; PU: Perceived Usefulness; PEOU: Perceived Ease of Use; PBen: Perceived Benefits; PBar: Perceived Barriers.

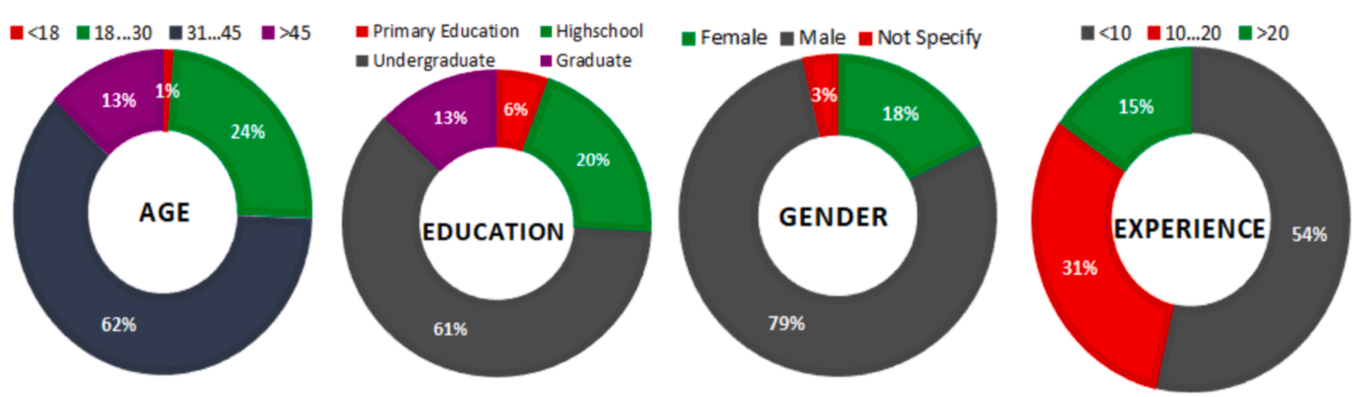

Fig. 5. Demographic information of respondents.

likely to use biodiesel in their farming practices. The results of the hypothesis testing showed that H1 to H6 were supported in the extended TAM. It means that the perceived usefulness and ease of use had significant and positive impacts on the attitude towards the use of biodiesel fuel and the intention to use renewable energy. A study by Lv et al. (2020) used an innovative approach called the Mutual Information approach to identify the most significant independent variable that affects the dependent variable. The findings indicated that perceived benefits, perceived barriers, and attitudes toward biodiesel energy play significant roles in influencing the intention to use biodiesel. Notably, the analysis revealed that attitude has the greatest impact, as determined by the mutual information technique.

The findings of this study underscore the critical role of individual beliefs and predispositions toward renewable energy solutions in shaping behavioral intentions. While perceived benefits such as environmental sustainability and cost-effectiveness play a motivating role, perceived barriers, including economic costs, technical challenges, and limited infrastructure, can significantly dampen adoption enthusiasm. The inclusion of perceived benefits and barriers in the model provides a more comprehensive understanding of biodiesel adoption dynamics, highlighting the need to address both the advantages and potential hurdles simultaneously. By utilizing the mutual information technique, the study effectively prioritizes factors, emphasizing attitude as a pivotal determinant that warrants targeted interventions such as awareness campaigns, training programs, and incentive policies to foster positive perceptions. Moreover, these insights offer valuable guidance for policymakers and agricultural stakeholders aiming to promote sustainable farming technologies at scale.

4. Conclusions

The findings of the proposed study suggest that biodiesel produced from perennial castor plants oil could be a superior choice due to its numerous benefits when produced sustainably with nutrients obtained from waste resources. When successfully adapted, castor oil biodiesel offers a more sustainable and environmentally friendly solution that can help reduce our reliance on fossil fuels. Based on the experimental findings, the main conclusions were drawn as follows:

(1) The castor bean plant well adapted to the black sea coast of Turkey, survived during the winter period and continues to grow in the second year. In the second year, mean seed yield and biodiesel yield increased by 17 and 14 % for large seed and small seed genotypes, respectively.

(2) Both genotypes of castor beans showed positive responses to the application of chemical fertilizer and nutrients derived from biowaste. The utilization of sole SS and SS+BA had a substantial impact on the growth and yield parameters of castor bean plants. The yield of seed (3442 kg ha^{-1}), oil (1634 L ha^{-1}), and biodiesel (1470 L ha^{-1}) showed a significant increase of 27 %, 22 %, and 30 %, respectively, when compared with the control fertilizer.

(3) The castor biodiesel meets the standards set by ASTM and EN for the majority of its fuel properties, with the exception of kinematic viscosity and flash point. However, the diesel blends can improve the mentioned parameters. According to the results, castor biodiesel has the potential to partially replace fossil fuel-based diesel.

(4) Overall, there were no significant differences in the treatment of SS and SS+BA for both genotypes in both years. The yield results indicate that sewage sludge and biomass ash are viable alternatives to reduce the use of chemical fertilizers, and their application is an excellent recycling practice for waste management that can increase castor oil production.

(5) Castor bean is highly efficient biodiesel input and intention to use are affected by perceived benefits, perceived barriers, and attitude. In addition, there is no difference among farmers in terms of age and education when it comes to adopting the new technology in their processes.

(6) Attitude towards biodiesel technology is highly effective among farmers when they intend to use the technology. Furthermore, perceived benefits and perceived barriers are also effective since the target audience's primary motives need to be satisfied.

In order to consolidate the castor biodiesel studies with social acceptance, an integrated model production line, from the analyzing life cycle assessment of seed oil production by fertilizing bio-waste nutrients, to the upgrading of biodiesel, is suggested as a guide for future work towards highly efficient biodiesel production.

CRediT authorship contribution statement

Serkan Ozdemir: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hasan Ozer:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Saim Ozdemir:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Omer Hulusi Dede:** Writing – review & editing, Visualization, Validation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2025.120541.

Data availability

The authors do not have permission to share data.

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