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Research Article

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Sustainable Agri-Energy Systems in Semi-Arid Regions: A Multi-Criteria Decision Analysis for Turgutlu, Türkiye

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Abstract

This study develops an integrated assessment framework for sustainable agri-energy systems in semi-arid regions. Using Turgutlu, Türkiye as a case study, eleven potential bioenergy crops—Agave americana, Opuntia ficus-indica, Miscanthus giganteus, Zea mays, Helianthus annuus, Cannabis sativa, Nicotiana tabacum, Olea europaea, Ficus carica, Vitis vinifera, and Cucumis melo—were evaluated. A hybrid methodology combining Multi-Criteria Decision Making (MCDM), Techno-Economic Analysis (TEA), Life Cycle Assessment (LCA), and Monte Carlo–based robustness analysis was employed. Results indicate that Agave americana and Opuntia ficus-indica represent the most sustainable options due to their low water demand, reduced greenhouse gas emissions, and stable economic performance. Miscanthus giganteus stands out as a long-term strategic option due to its high energy yield. Monte Carlo simulations demonstrated that Agave and Opuntia maintained the highest robustness under varying criterion weights. LCA results further revealed that these species occupy the "ideal environmental zone," characterized by low GHG emissions and high Net Energy Ratios (NER). The integration of TEA, LCA, and MCDM methods forms a structured basis for quantitative decision support framework for regional energy planning, emphasizing the prioritization of water-efficient energy crops in semi-arid ecosystems.

Keywords: Sustainable energy crops, Multi-criteria decision analysis (MCDM), Life cycle assessment (LCA), Semi-arid regions, Techno-economic analysis (TEA).

1. Introduction

Global climate change, rising temperatures, and irregular rainfall patterns have made agricultural production critically dependent on water. In Türkiye's semi-arid regions—particularly in microclimatic areas such as the inland parts of the Aegean and the Gediz Basin—pressure on water resources is increasing, directly affecting both food security and energy supply security. This triple interaction between the agricultural sector, energy production, and water use is now addressed within a new sustainability paradigm defined as the "water-energy-food (WEF) nexus" [1].

Recent studies show that energy crops in these regions can offer highly water-efficient alternatives and contribute to rural development. Integrating energy crops into agricultural production systems reduces dependence on fossil fuels and allows for the utilization of marginal lands [2]. However, not all energy crops offer the same level of environmental, economic, and technical sustainability. Therefore, determining which crops are both water-efficient and advantageous in terms of energy potential in semi-arid regions has become a strategic decision-making problem.

Studies on energy crops have primarily focused on traditional species such as corn (Zea mays), sunflower (Helianthus annuus), and rapeseed (Brassica napus) [3]. However, the high irrigation, fertilizer, and soil input requirements of these species limit environmental sustainability in semi-arid regions. Therefore, low water consumption species such as Agave, Opuntia, and Miscanthus have recently begun to be investigated as alternatives. Plants with CAM photosynthesis, such as Agave americana and Opuntia ficus-indica, minimize transpiration losses by opening their stomata at night; this feature provides a significant advantage in the low rainfall regions of the Aegean and Central Anatolia [4].
Life cycle assessment (LCA) is a widely used tool for evaluating the environmental performance of energy crops. Studies show that ethanol from Agave and Miscanthus produces 60–80% lower greenhouse gas

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emissions compared to fossil fuels [5]. However, the LCA approach has generally been addressed in a one-dimensional manner in the literature, and its integration with economic feasibility (TEA) and multi-criteria decision-making (MCDM) methods has been quite limited.

Multi-criteria decision making (MCDM) approaches such as AHP, TOPSIS, and VIKOR are widely used in energy system planning and resource selection problems [6]. These methods enable the weighting of different criteria (water, energy, economy, environment, etc.) and the ranking of alternatives. However, these methods have mostly been applied in single-sector analyses.

In the few studies conducted on agriculture-energy integration in semi-arid regions, quantitative analyses such as LCA and TEA are not considered in conjunction with the decision-making process. This gap makes it particularly difficult to determine sustainable product portfolios at the regional level.

In this context, the current study:

i. Models a semi-arid region such as Turgutlu-Manisa,
ii. Comprehensively evaluates criteria related to water, energy, economy, environment, and food contribution,
iii. Performs robustness analysis using AHP + TOPSIS + VIKOR + Monte Carlo methods,
iv. Integrates these analyses with TEA and LCA results,

proposing a pioneering decision support framework.

This approach aims to fill the methodological gap in the Turkish literature by offering a multidimensional assessment that is not only technically and optimization-based but also aligned with sustainable development goals [7] (particularly SDG 7 – affordable energy, SDG 12 – responsible production, SDG 13 – climate action).

2. Materials and Methods

Figure 1 presents the structured workflow of the study, covering the entire analytical sequence from data acquisition to the integrative sustainability assessment. The framework includes five main stages: (i) data collection and crop dataset construction, (ii) AHP-based criterion weighting, (iii) TOPSIS and VIKOR multi-criteria ranking, (iv) Monte Carlo–based robustness testing, (v) TEA–LCA integration and final sustainability scoring. This flowchart clarifies the decision-making pathway and ensures methodological transparency.

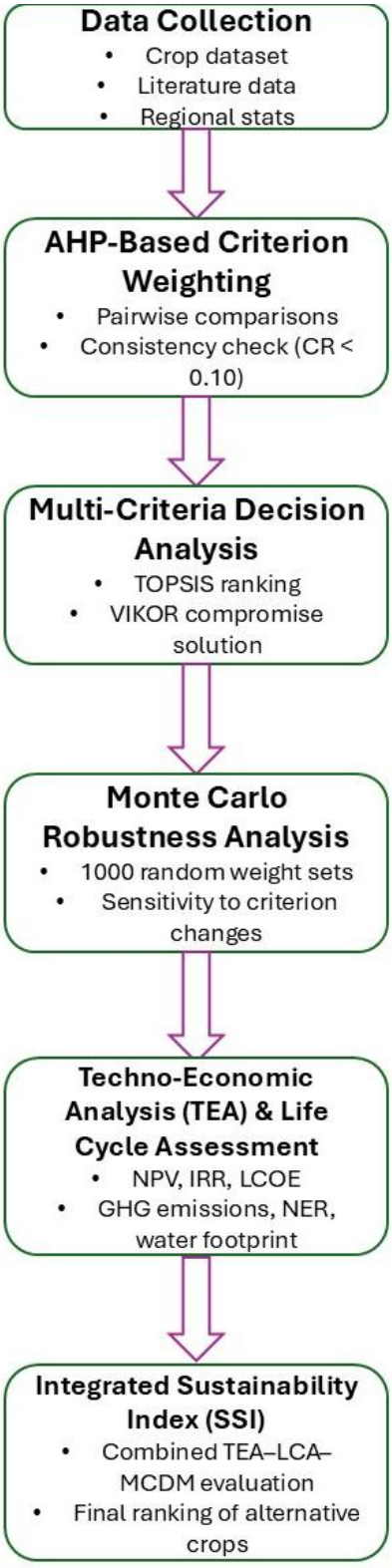


Figure 1. Workflow of the integrated MCDM–TEA–LCA framework used in the study.

This study was conducted to compare the environmental, economic, and technical sustainability levels of energy and agricultural crops that can be

grown in the Turgutlu-Manisa region, which has semi-arid climate characteristics. Methodologically, Multi-Criteria Decision Making (MCDM) approaches, Techno-Economic Analysis (TEA), and Life Cycle Assessment (LCA) methods were used together. The combination of MCDM–TEA–LCA has been increasingly discussed in recent agricultural energy research, particularly for evaluating sustainability under water-limited conditions. Previous studies emphasize the need to integrate decision-making algorithms with environmental and techno-economic metrics to improve the robustness of energy crop selection [2, 5, 11, 12, 29]. However, these studies often address each component separately. The present work extends this literature by operationalizing a fully coupled MCDM–TEA–LCA framework within a regional agricultural context.

2.1. Research Area: Turgutlu-Manisa

Manisa province is under the influence of the Mediterranean climate, with hot and dry summers and mild and rainy winters. The annual average temperature of Turgutlu district is 16.9–17°C, and the annual average rainfall is around 450–500 mm [8]. These climatic conditions create water stress, especially during the summer months, increasing the need for irrigation. The region has been assessed as representative of semi-arid areas under water scarcity pressure.

2.2. Plant Selection and Data Set

The study examined 11 plant species that could potentially be cultivated under Turgutlu conditions (Figure 2).

Agave americana is a succulent species that can grow with high water efficiency in semi-arid and arid regions. Thanks to its high fructose content, it is an important biofuel feedstock for ethanol production. Its fibers are also valued in biocomposite materials with high mechanical strength [9].

Opuntia ficus-indica is a cactus species with CAM (Crassulacean Acid Metabolism) photosynthesis. It maintains its photosynthetic efficiency under extremely arid conditions. With its low water consumption and high biomass production, it has potential as a bioenergy and forage crop [4, 10].

Miscanthus giganteus is a perennial herbaceous plant with C4 photosynthesis. It is one of the leading species in terrestrial biomass energy production due to its high biomass yield and low input requirements. It has been well documented in LCA studies in Europe and Asia [11, 12].

Zea mays is an annual energy and food crop with C4 photosynthesis. It is widely used in ethanol production, but its sustainability in semi-arid regions is limited due to high water and fertilizer inputs [5].

Helianthus annuus is a preferred species for biodiesel production due to its high oil content. It is also valued for its soil-improving effect in circular agriculture systems [3].

Cannabis sativa is notable for its high lignocellulosic biomass, low pesticide requirement, and short growth cycle. It has versatile potential for use in fiber, oil, and biofuel production [13].

Nicotiana tabacum is an agricultural product with high economic value but high environmental inputs. Research is increasing on obtaining bioethanol and biopolymer derivatives from leaf biomass [14].
Olea europaea is a perennial tree native to the Mediterranean climate. Agricultural waste (pits, pomace) can be utilized for energy production. Its low water requirements and long-lived root system reduce soil erosion [15, 16].

Ficus carica is a species adapted to semi-arid conditions and is economically important for food and industrial uses. Fruit and pruning waste can be utilized for biomass-based energy production [17].

Vitis vinifera is a high value-added agricultural product. Vineyard waste (vine shoots and pomace) can be used for second-generation biofuel production. It can adapt to semi-arid climates with moderate water requirements [18, 19].

Cucumis melo is a short-term, high-yield annual plant. Although its yield declines rapidly under water stress, it is valuable for its flexibility in agricultural rotation systems [20].

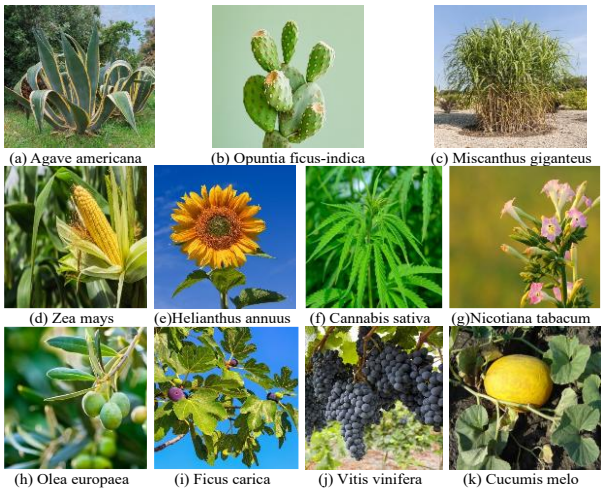


Figure 2. Study plants [3, 5, 9-11, 13-15, 17, 19, 20].

Data for the criteria in Table 1 for each crop type were compiled from the literature and national agricultural statistics [3, 9, 12, 14-19, 21, 22].

Here;

- Water consumption (m^3/ha·year); irrigation requirement for water scarcity criterion.
- Yield (t/ha·year); annual biomass/product quantity.
- Economic value ($/kg); market price.
- Energy content (MJ/kg); product energy potential.
- Environmental impact (kg $CO_{2\text{-eq}}$/kg); LCA input.
- Investment cost – CAPEX ($/ha)
- Operating cost – OPEX ($/ha·year)
- Annual income ($/ha); sales revenue.
- Greenhouse gas emissions (GHG, kg $CO_{2\text{-eq}}$/ha)

Table 1. Study criteria.

Crop	Water consumption	Yield	Economy	Energy content	Environmental impact	CAPEX	OPEX	Revenue	GHG
Agave americana	1500-2500	20-50	0,05-0,1	15-17	0,1-0,3	3000-6000	500-1000	1000-5000	2-15
Opuntia ficus-indica	1000-2000	15-40	0,2-0,8	14-16	0,05-0,2	2500-5000	400-900	3000-15000	1-8
Miscanthus giganteus	4000-7000	15-35	0,04-0,08	17-19	0,05-0,15	3500-7000	600-1200	600-2800	1-5
Zea mays (Corn)	5000-8000	8-15	0,2-0,35	15-16	0,3-0,6	1000-1500	1500-2500	1600-5250	3-9
Helianthus annuus (Sunflower)	4000-6500	2-4	0,4-0,7	18-22	0,4-0,8	1000-1500	1200-2200	800-2800	1,5-4
Cannabis sativa (Hemp)	3000-6000	8-15	0,1-10	16-18	0,2-0,5	1500-2500	1000-4000	25000-40000	2-7,5
Nicotiana tabacum (Tobacco)	4000-6000	2-3,5	3-6	15	1,5-3	2000-3500	2500-5000	6000-21000	3-10,5
Olea europaea (Olive)	2500-5000	4-10	0,5-1,5	19	0,5-1,2	8000-15000	1500-3000	2000-15000	2-12
Ficus carica (Fig)	5000-8000	10-25	0,8-2,5	2,8-3,2	0,4-1	7000-12000	2000-4000	8000-50000	4-25
Vitis vinifera (Grape)	4500-7500	10-20	0,6-2	2,7-3	0,6-1,5	15000-30000	3000-6000	6000-40000	6-30
Cucumis melo (Melon)	6000-9000	30-60	0,3-0,8	1,3-1,6	0,3-0,7	2500-5000	4000-7000	9000-48000	9-42

The data were normalized in the MATLAB [23] environment to make them comparable. For missing or intermittent data, average values from regions with similar climatic conditions in the literature were used.

2.3. Criterion Determination and Weighting (AHP)

The relative importance levels of the criteria were determined using the Analytic Hierarchy Process (AHP) method [24].
Following the principles of analytical hierarchy modeling, the study established a three-level hierarchical structure consisting of the goal (sustainability assessment), main criteria groups, and the set of alternative crops. This hierarchical representation ensures that each criterion contributes explicitly to the global decision structure in a traceable and systematic manner.

Five main criteria groups were defined:

i. Water efficiency – combination of minimum water consumption and high yield,
ii. Energy potential – biomass and energy content,
iii. Economic performance – revenue, CAPEX, OPEX,
iv. Food contribution – impact on the food chain in the agricultural system,
v. Environmental impact – GHG, NER, water footprint.

In the AHP matrix, each criterion pair was compared using Saaty's 1–9 scale (Equation 2.1) [24]. The obtained eigenvector weights were normalized by checking the consistency ratio using the λmax method (CR < 0.10).

As a result of this process, the following weight distribution was obtained as an example: Water = 0.30, Energy = 0.25, Economy = 0.20, Environment = 0.15, Efficiency = 0.10.

$$w_i = \frac{GM_i}{\sum_{j=1}^{n} GM_j}, GM_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{1/n} \quad \textbf{(2.1)}$$

2.4. Multi-Criteria Decision Analysis (TOPSIS & VIKOR)

The weights obtained with AHP were applied in two different ranking algorithms:

- TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) calculates the relative proximity value (Ci**) using the Euclidean distances of each alternative to the ideal (best) and anti-ideal (worst) solutions (Equations 2.2-2.6) [25]:

Normalized matrix:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad \textbf{(2.2)}$$

Weighted matrix:

$$v_{ij} = w_j r_{ij} \quad \textbf{(2.3)}$$

Ideal solutions:

$$v_j^+ = \max(v_{ij}), v_j^- = \min(v_{ij}) \quad \textbf{(2.4)}$$

Distances:

$$S_i^+ = \sqrt{\sum_j (v_{ij} - v_j^+)^2}, S_i^- = \sqrt{\sum_j (v_{ij} - v_j^-)^2} \quad \textbf{(2.5)}$$

Score:

$$C_i = \frac{S_i^-}{S_i^- + S_i^+} \quad \textbf{(2.6)}$$

- The VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) method produces a compromise solution (Qi) by considering the best and worst performance values for each criterion (Equations 2.7, 2.8) [26].

Best f^+ and worst f^- for each criterion;

$$S_i = \sum_j w_j \frac{f^+ - f_{ij}}{f^+ - f^-}, R_i = \max_j \left[w_j \frac{f^+ - f_{ij}}{f^+ - f^-} \right] \quad \textbf{(2.7)}$$

Score:

$$Q_i = v \frac{S_i - S^+}{S^- - S^+} + (1 - v) \frac{R_i - R^+}{R^- - R^+}, (v = 0.5) \quad \textbf{(2.8)}$$

The ranking results obtained with both methods were compared, and consistency and deviation ratios were evaluated.

2.5. Sensitivity and Uncertainty Analysis (Monte Carlo)

A sensitivity analysis was performed to measure the stability of the ranking against changes in criterion weights.

The weight of each criterion was varied within a range of ±20%, and the change in ranking was observed.

A Monte Carlo simulation [27] generated 1000 random weight combinations, and the TOPSIS and VIKOR rankings were recalculated at each iteration.

This determined which plants remained among the "best" or "top three" in different scenarios.

2.6. Techno-Economic Analysis (TEA)

The following indicators were calculated for each alternative, considering the investment (CAPEX) and operating (OPEX) costs, revenue, discount rate (r), and production life (n) parameters [28]:

- Net Present Value (NPV) (Eq. 2.9)

$$NPV = \sum_{t=1}^{T} \frac{R_t - C_t}{(1+r)^t} - CAPEX \quad \textbf{(2.9)}$$

- Internal Rate of Return (IRR) (Eq. 2.10)

$$0 = \sum_{t=1}^{T} \frac{R_t - C_t}{(1+IRR)^t} - CAPEX \quad \textbf{(2.10)}$$

- Levelized Cost of Energy (LCOE) (Eq. 2.11)

$$LCOE = \frac{CAPEX + \sum_t OPEX_t}{\sum_t E_t} \quad \textbf{(2.11)}$$

This analysis revealed the comparative economic sustainability levels of the products.

2.7. Life Cycle Assessment (LCA)

All stages from production to energy conversion for each plant were evaluated within the scope of the "five-stage LCA model" [29]:

i. Soil preparation and planting,
ii. Fertilization and irrigation,
iii. Harvesting,
iv. Processing (conversion to biofuel or biomass),
v. Transportation and energy conversion.

The analysis was conducted using GHG emissions (kg $CO_{2\text{-eq}}$/ha), energy balance, and water footprint indicators (Equations 2.12, 2.13).

$$E_{GHG} = \sum_i A_i \times EF_i \quad \textbf{(2.12)}$$

$$NER = \frac{E_{out}}{E_{in}} \quad \textbf{(2.13)}$$

The LCA results obtained were combined with TEA outputs to enable a simultaneous comparison of environmental and economic performance.

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2.8. Integrative Assessment Approach

In the final stage, AHP–TOPSIS–VIKOR results were correlated with TEA and LCA indicators to create an "integrated sustainability score (SSI)".

This score is an index that balances economic and environmental indicators. The obtained SSI values were used to determine short-term (e.g., tobacco, melon), medium-term (e.g., corn, sunflower, hemp), and long-term (e.g., agave, miscanthus, olive) sustainable product strategies for Turgutlu.

3. Results and Discussion

3.1. Multi-Criteria Decision Analysis

TOPSIS and VIKOR results (Figures 3 and 4) comprehensively reveal the sustainability performance of energy crops under semi-arid conditions.

These findings correspond closely with multiple earlier studies reporting that CAM plants such as Agave and Opuntia exhibit superior performance under high-temperature, low-precipitation conditions due to reduced evapotranspiration and high carbohydrate accumulation [1, 4, 9, 10]. Likewise, the environmental drawbacks of tobacco, melon, and grape production have been highlighted extensively in LCA literature focusing on carbon intensity and water footprint [5, 12, 17, 19]. By aligning the model outputs with previous evidence, this study reinforces the scientific validity of the integrative assessment.

In both methods, Agave americana and Opuntia ficus-indica achieved the highest scores with their low water consumption and environmental impact values. Miscanthus giganteus remained at a medium level despite its high energy content due to its high water requirement. Zea mays (corn) and Helianthus annuus (sunflower) yielded economically acceptable results but appeared weak in terms of sustainability due to their high water and input requirements. Cannabis sativa (hemp) stood out with its high economic potential but lagged behind in the overall ranking due to its environmental burden.

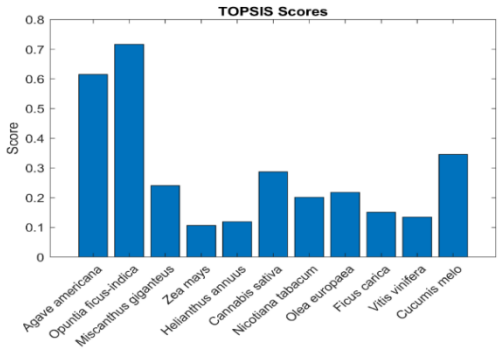


Figure 3. TOPSIS Scores.

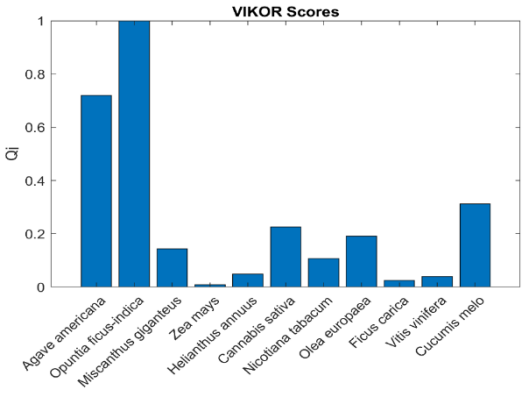


Figure 4. VIKOR Scores.

The high consistency between TOPSIS and VIKOR (above 85%) supports the decision consistency of the model.

The ranking outcomes are consistent with previous theoretical and empirical studies reporting superior water-use efficiency and environmental performance of CAM species in semi-arid regions [1, 4, 9]. Similarly, the relatively unstable sustainability profiles of conventional crops such as corn and sunflower align with findings emphasizing their high irrigation and fertilizer dependency [3, 5]. This demonstrates that the integrated MCDM–TEA–LCA structure is capturing well-established relationships between crop physiology, environmental footprint, and economic feasibility.

3.2. Monte Carlo Robustness Analysis

The Monte Carlo analysis (Figure 5) examined the ranking robustness of alternatives under random variations in criterion weights.

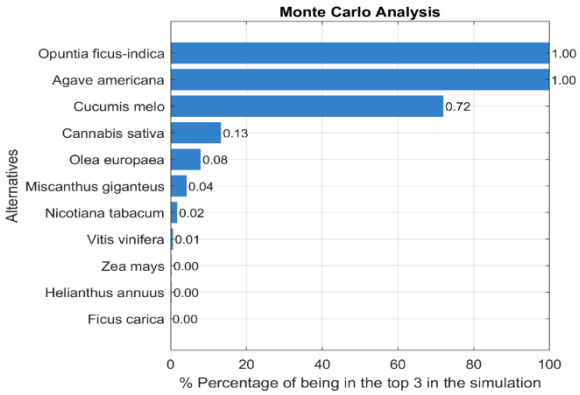


Figure 5. Monte Carlo Analysis.

The analysis reveals the percentage of 1000 simulations in which each plant ranked in the top three and the corresponding stability index (in the range 0–1).

This distribution shows that Agave and Opuntia are the most stable energy crops in semi-arid regions under varying criterion conditions. The low robustness indices indicate that other species are highly sensitive to criterion weights, thus rendering their sustainability performance unstable.

3.3. Techno-Economic Analysis (TEA)

The Net Present Value (NPV) comparison (Figure 6) reveals significant economic differences.

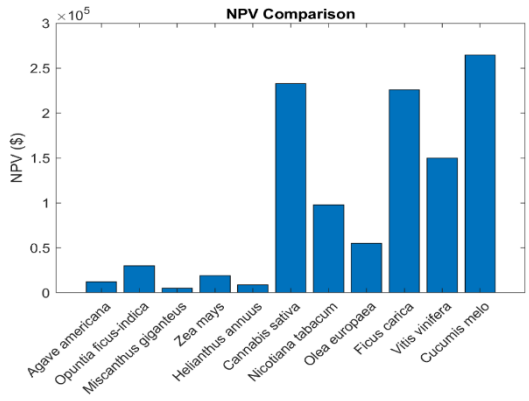


Figure 6. NPV Comparison.

Cannabis sativa achieved the highest NPV due to its high market value; however, its environmental impacts overshadowed this advantage. Agave and Opuntia offer a more sustainable investment profile in the long term thanks to low CAPEX and OPEX, despite their moderate income levels. This situation demonstrates that high income potential does not always correspond to sustainable profitability.

3.4. Life Cycle Assessment (LCA)

Figure 7 shows the LCA results in a two-dimensional representation of the GHG emissions–NER relationship.

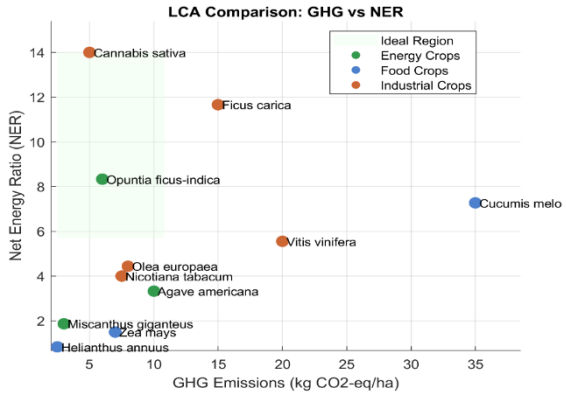


Figure 7. LCA Comparison (GHG vs NER)

In the scatter plot, the “ideal zone” (low GHG, high NER) is marked in green, and the plants are color-coded according to three categories: energy, food, and industrial plants.

In this distribution:

- Agave americana and Opuntia ficus-indica are located closest to the ideal zone, indicating that they offer both a low carbon footprint and a high energy conversion rate.
- Miscanthus giganteus is located in the middle zone, indicating that GHG impacts during the production process can still be reduced despite its high energy content.
- Tobacco, fig, grape, and melon, with both high GHG and low NER values, represent the most environmentally risky group.

The LCA display facilitates a multidimensional reading of environmental performance. Color coding and highlighting the ideal zone directly show which plants exceed the environmental sustainability threshold.

3.5. Overall Assessment

When all analyses are considered together, Agave americana and Opuntia ficus-indica stand out as the most suitable species for sustainable agri-energy systems in semi-arid regions. These species present a favorable combination of low water use, low GHG emissions, and moderate economic returns. Miscanthus giganteus should be considered an important reserve in terms of energy density in the long term. Crops such as tobacco and melon, while providing short-term economic gains, are not strategically suitable due to their environmental costs.

The study demonstrates that TEA–LCA–MCDM integration can be used as a decision support tool in regional energy-agriculture planning. Furthermore, Monte Carlo-based stability analysis provides methodological contributions by making visible the dimension of decision uncertainty, which is often overlooked in the literature.

4. Conclusion and Recommendations

This study provides a comprehensive assessment of sustainable agriculture and energy integration in semi-arid regions. The Multi-Criteria Decision Analysis (MCDM), Techno-Economic Analysis (TEA), Life Cycle Assessment (LCA), and Monte Carlo-based stability analysis conducted using the Turgutlu example have revealed the environmental and economic performance of energy crops in a holistic manner. The findings indicate that species with high water efficiency, low GHG emissions, and moderate economic returns are

the most suitable options for sustainability in semi-arid areas.

In this context, Agave americana and Opuntia ficus-indica stand out by demonstrating stable performance in both environmental and economic indicators. While Miscanthus giganteus is a promising species in terms of energy density, water consumption and investment costs must be carefully managed. High-yield species such as Cannabis sativa should be considered as short-term economic opportunities due to their environmental costs.

According to the analysis results, Cannabis sativa, Nicotiana tabacum, Zea mays, and Helianthus annuus appear economically attractive due to their high market value or short-term income potential. However, these species are weak alternatives in terms of long-term ecological and economic sustainability due to their high water consumption, input dependency, and greenhouse gas emissions. In particular, tobacco and corn, although they generate high income in the short term, are not recommended for long-term planning due to high OPEX and low net energy ratio (NER).

Agave americana and Opuntia ficus-indica have been identified as the two species with the highest water efficiency. These plants have CAM photosynthesis, meaning they perform their stomatal activity at night and keep water loss to a minimum during the day. Therefore, in regions prone to water stress during the summer months, such as Turgutlu, these two species are in the most advantageous position both environmentally and economically. Monte Carlo analyses have also shown that these plants maintain their decision stability even under conditions of uncertainty.

Considering Turgutlu's semi-arid climate conditions, a three-phase strategy is proposed for sustainable energy-agriculture integration:

- Short term (1–3 years): Temporary energy production can be achieved using existing agricultural infrastructure with species such as corn and sunflower. This period can be considered a process of technological learning and investment preparation.
- Medium term (3–7 years): Species such as Miscanthus giganteus and Cannabis sativa can be integrated with the aim of higher energy yield and economic income. However, water use and carbon footprint should be monitored at this stage.
- Long term (7 years and beyond): Agave americana and Opuntia ficus-indica should be positioned as the region's core energy crops due to their low water consumption, high environmental stability, and circular economy potential.

Additionally, considering regional climate and soil characteristics, the use of Agave americana, Opuntia ficus-indica, Miscanthus giganteus, Zea mays, Helianthus annuus, Cannabis sativa, Nicotiana tabacum, Olea europaea, Ficus carica, Vitis vinifera, and Cucumis melo offers significant potential in the Turgutlu region for both reducing soil contamination and producing biomass-based energy. Some of these species can contribute to phytomining applications by accumulating heavy metals and toxic elements through their hyperaccumulator properties, while others can enhance soil structure and chemical balance through phytoremediation [30]. Fast-growing species such as Helianthus annuus, Miscanthus giganteus, and Cannabis sativa provide rapid biomass returns, whereas drought-tolerant species like Agave americana and Opuntia ficus-indica, as well as long-lived woody plants (Olea europaea, Ficus carica, Vitis vinifera), contribute to long-term soil stabilization, carbon sequestration, and ecosystem resilience. In this context, evaluating the hyperaccumulator and phytoremediator properties of these species in an integrated manner with energy production represents a feasible strategy for environmental sustainability and strengthening local renewable energy systems.

This mixed strategy provides economic returns in the short term while ensuring environmental sustainability in the long term. Thus, Turgutlu can become a regional energy agriculture model that maintains the water-energy-food balance.
In semi-arid regions such as Turgutlu, agricultural production should be planned to create synergy rather than compete with energy crops. Xerophytic (drought-resistant) species such as agave and opuntia can be used to evaluate marginal non-agricultural land. The waste from these plants can be used in biogas, bioethanol, or biochar production, thereby supporting circular carbon management. Support policies for low water consumption energy crops can maintain the balance between food security and energy supply.

Future studies can develop multidimensional decision models by combining TEA–LCA data with artificial intelligence-based optimization (e.g., multi-objective genetic algorithms or Pareto analysis). The models to be developed should include local climate data, soil moisture dynamics, and the effects of agro-photovoltaic systems. This study evaluated static data; however, scenario analysis for the future (2050–2100) based on climate change is important to test decision stability in the temporal dimension. University–municipality–producer partnerships can create an effective platform for integrating energy crops into the regional economy.

This study has several limitations that should be considered. First, the dataset relies partly on literature-derived averages, which may not fully capture micro-regional variability in soil texture, irrigation practices,

or farmer-specific management. Second, TEA and LCA values represent static conditions; dynamic year-to-year variations were not modeled. Third, market prices, labor costs, and input availability can change depending on policy and global trade conditions. Future studies could integrate dynamic economic forecasting, spatial soil modeling, and long-term climate projections to reduce these uncertainties.

Furthermore, to maximize the end-use efficiency of the biomass produced from the recommended crops (such as Agave americana or Miscanthus giganteus), the adoption of Pech heating systems (high-thermal-mass masonry heaters) in rural residential areas is highly recommended. These systems are characterized by their ability to store heat within high-mass structures and release it slowly, significantly increasing thermal efficiency compared to conventional stoves. Integrating locally produced biomass pellets or briquettes with Pech systems could minimize the local carbon footprint, enhance rural energy independence, and provide a cost-effective solution for heating in semi-arid rural settlements. Future research should focus on the combustion performance of CAM-based biomass specifically within these high-efficiency traditional heating configurations.

In conclusion, Agave americana and Opuntia ficus-indica have been identified as the most suitable species for sustainable agri-energy systems in Turgutlu's semi-arid climate conditions. These species offer an optimal solution from an environmental and economic perspective by maintaining a “low input – low carbon – medium income” balance. The study provided a quantitative decision support model for strategies to be developed for energy-agriculture integration at the regional scale and demonstrated that multi-criteria approaches can produce reliable results even under uncertainty.

Author’s Contributions

Mert Ökten: Drafted and wrote the manuscript, performed the experiment and result analysis.

Declaration of Competing Interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The author also acknowledges the use of the DeepL translation tool solely for assisting with the language translation of the manuscript.

Ethics

There are no ethical issues after the publication of this manuscript.

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