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Comparative Life Cycle Assessment of Bioethanol Production from Different Maize Hybrids in a Semi-Arid Region

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Abstract

From an industrial perspective, maize plays an important role in the production of starch and bioethanol. In this study, a life cycle assessment (LCA) was performed on 5 different hybrid grain maize varieties (DKC5685, DKC5812, May Capuzi, P0920, and P0937) grown under semi-arid conditions (Konya, Turkiye). The system boundary covers the cradle-to-gate stages, including agricultural production, drying, and ethanol conversion. In this study, all agricultural inputs were kept constant, and the focus was on the effect of environmental impacts (climate change (GWP100), water depletion (WDP), fossil depletion (FDP), particulate matter formation (PMFP), agricultural land occupation (ALOP)) and terrestrial acidification (TAP100) on crop yield and the starch content of each maize. Impact assessment was performed using the ReCiPe Midpoint (H) method.

Results indicate that higher-yielding hybrids, such as DKC5812, significantly reduce environmental burdens per unit of product, with GWP100 values ranging from 0.038 to 0.046 kg CO2-eq per kg of fresh maize at the field stage. Nitrogen fertilizers (especially DAP and ammonium sulfate) and irrigation electricity were identified as the primary contributors to the environmental footprint. In the ethanol production process, increasing starch content improved conversion efficiency and reduced raw material requirements, thus lowering the cumulative effect. Most significantly, a net reduction of approximately 42% in the global warming potential of ethanol production from the application of the system expansion approach for Distillers Dried Grains with Solubles (DDGS). Additionally, sensitivity analysis on displacement factors (DF 0.3–0.9) showed that net environmental benefits are highly sensitive to byproduct substitution credits.

Keywords: Life cycle assessment (LCA), Bioethanol, Maize hybrids, DDGS, System expansion.

Introduction

Maize (*Zea mays L.*) is a strategically important agricultural product worldwide, widely used in both human and animal nutrition as well as in industrial applications. Maize also holds an important place in Turkiye's agricultural production patterns. Depending on its intended use and purpose, it comes in different varieties such as grain maize, silage maize, and popcorn. While Silage maize is widely used as roughage, Popcorn is mostly used for nutritional purposes. Grain maize, on the other hand, is highly valuable from an industrial perspective. Besides feed rations, it is a fundamental raw material for the starch industry and bioethanol production. It is reported that Turkiye produces an average of 5,700,000 tons of grain maize annually. Approximately 20% of this production comes from Konya province (Ministry of Energy and Natural Resources (MENR) 2024).

Given that maize is a basic raw material for the production of starch-based products and biofuels, a detailed examination of its environmental impacts is necessary. However, the environmental performance of maize production is directly dependent not only on the agricultural inputs applied, but also on crop yield, chemical composition, and the conditions of the region where it is grown. In Turkiye, maize is produced using irrigation systems. Maize, actively produced between April and September, requires high water and energy inputs, especially in semi-arid regions such as the Konya Plain. High seasonal temperatures and low rainfall also mean more water is needed to prevent disruption of plant development (Turkish State Meteorological Service (MGM) 2024). On the other hand, intensive use of mineral fertilizers is also present in these regions due to insufficient water supply.

Mechanization application in agriculture is among the main inputs determining the environmental footprint of maize production. However, most maize-based life cycle assessment (LCA) studies in the literature either address regions with different climates and production conditions (Boone et al. 2016; Dědina et al. 2024; Giusti et al. 2023; Kumar et al. 2022). Studies that holistically examine how differences in yield and grain composition of different maize varieties affect environmental impacts under Konya conditions are also quite limited (Dilay 2021a; Kayahan and Çarman 2023).

When it comes to ethanol production from corn, environmental considerations become even more complex. The process technology used in ethanol production is generally similar, but the amount of maize required per unit of ethanol production depends largely on the grain composition, particularly the starch content (Osman et al. 2021). This shows

that different maize varieties can exhibit different environmental impact profiles even under the same agricultural management. Furthermore, by-products generated during ethanol production, particularly distillers-dried grains with solubles (DDGS), can significantly alter environmental outcomes depending on how system boundaries are defined (Arora et al. 2011).

This study aims to present a life cycle assessment covering the field, drying, and ethanol production stages for five different hybrid maize varieties (DKC5685, DKC5812, May Capuzi, P0920, and P0937) grown under Konya Plain conditions. In the study, all agricultural inputs were kept constant; environmental impact differences were attributed only to crop yield and chemical composition. In the ethanol production stage, a system expansion approach was used to consider the feed replacement potential of DDGS, and a sensitivity analysis was performed via the displacement factor. In this way, the study provides a quantitative framework for optimizing hybrid selection to advance SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) in water-stressed regions."

In this respect, the study presents a region-specific agricultural production scenario. It also quantitatively reveals the environmental impacts of compositional differences among maize varieties on the field–ethanol system within a controlled and standardized management framework. Accordingly, this study hypothesizes that, under identical agricultural input conditions, differences in environmental impacts among maize hybrids are primarily driven by yield and grain composition (particularly starch content).

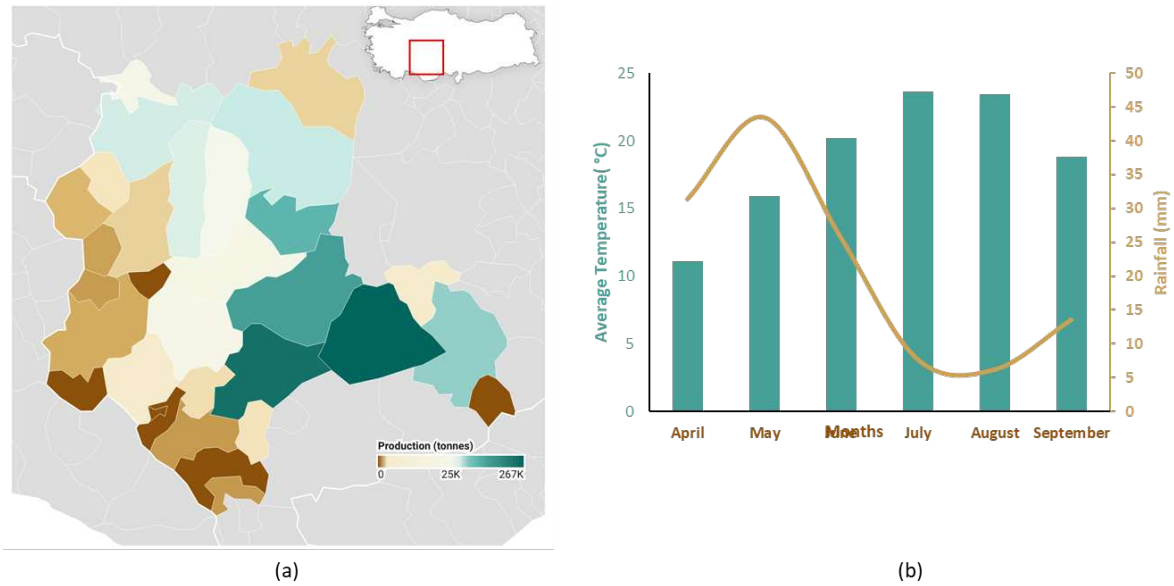
Materials and Methods

Study Area and Product Description

The study was conducted in Konya province, which represents a significant portion of Turkiye's maize production. Konya has a semi-arid climate. Maize production is largely carried out using irrigation and high levels of mineral fertilizers. Furthermore, field processes in the region rely heavily on mechanization. Figure 1 shows the maize grain production rates by district and climate data (1929–2024) covering the maize grain production process in the region.

The DKC5685, DKC5812, May Capuzi, P0920, and P0937 maize varieties examined in this study are hybrid grain maize varieties commonly grown in Konya and its surrounding areas. These varieties are preferred by both farmers and companies for commercial reasons. They were also included in the research because they differ from each

other in terms of yield levels and grain composition (especially starch content), and because of their potential for industrial use (feed and starch-based applications). This study does not aim to compare the genetic characteristics of the selected hybrid maizes. These are not types specifically developed for ethanol production. However, it is known that grain maizes with high starch content are widely used in biofuel production worldwide. The selected varieties exhibit differences in starch content, which is one of the reasons for their deliberate inclusion in the study to realistically assess the link between the field and the ethanol system. The yield and chemical composition values presented in Table 1 were obtained from actual field data. The yield and chemical content data used in the life cycle inventory (LCI) phase are representative of the conditions in Konya. Grain yield was used to normalize inputs from the field and drying stages on a functional unit basis of 1 kg of product.



(a) (b)

Fig.1 Geographic distribution of maize production (tonnes) across Konya districts (a) and monthly average temperature and rainfall patterns during the growing season (b) (Konya Provincial Directorate of Agriculture and Forestry 2024; Turkish State Meteorological Service (MGM) 2024).

The yield and chemical composition data (starch, protein, fat, and cellulose) for the five maize hybrids used in this study were obtained from the General Directorate of Agricultural Research and Policies, Bahri Dağdaş International Agricultural Research Institute. These values represent the results of two-year field trials conducted in a single growing season each year under the ecological conditions of the Konya Plain. The trials were carried out using a randomized complete block design (RCBD) with three replications to ensure statistical reliability. All hybrids were

grown under identical and controlled agricultural management practices (irrigation, fertilization, and pest control) as reported by the institute.

The starch content in the table was used as the basis for determining the feed replacement potential of ethanol yield and the DDGS formed during ethanol production. Field inputs and agricultural practices throughout the production process were kept constant for all maize varieties.

Table 1 Yield and chemical composition of maize varieties used as input data in the life cycle inventory.

Maize Varieties	Yield (kg/da)	Protein MR (%)	Starch (%)	Fat (%)	Cellulose (%)
DKC5812	1800	7,41	64,72	4,69	2,16
P0937	1700	7,7	65,43	4,27	2,34
P0920	1650	7,4	63,75	5,35	2,11
May Capuzi	1500	7,52	63,83	5,31	2,4
DKC5685	1650	8,1	64,93	4,84	2,42

Functional unit and reference flow (Normalization)

In this study, the functional unit was defined as 1 kg of grain maize (fresh product) for the agricultural production process and 1 kg of anhydrous ethanol for the ethanol production subsystem. To ensure controlled execution of the entire process, comparisons were made based on agricultural production and the final energy product. All agricultural inputs (seed, fertilizer, pesticide, diesel fuel, irrigation electricity, and water use) were individually included in the model per hectare. The functional units used in the impact assessment are product-based. Hectare-based inventory data were converted into functional units using the grain yields determined for each maize variety. Fresh grain yield was expressed as y_{wet} in this study.

$$I_{unit} = \frac{I_{ha}}{y_{wet} \times 1000}$$

There;

I_{unit} *:* Input amount per functional unit (kg or L per kg of product)

I_{ha} *:* Total input amount per hectare (kg/ha or L/ha per kg of product)

y_{wet} : Wet maize yield (t/ha)

Ethanol yield was calculated using a formula that multiplied the starch content of the maize by the ethanol conversion efficiency from starch, and the amount of maize required per kg of ethanol was determined by taking the inverse of this value. Thus, the amount of maize used in the ethanol production process was defined using a dynamic and composition-sensitive approach instead of a fixed coefficient.

System Boundaries

The system boundary encompasses the entire process from planting the maize in the field to harvesting and post-harvest drying. Seed use, mineral fertilizer applications, pesticide inputs, fuel consumption throughout the process, electrical energy used for irrigation, and the energy inputs of the system used to dry the harvested grain maize in the field are evaluated within the system boundary. Shelling, transportation, storage, and final use stages after drying are excluded from the analysis in this section (Fig. 2).

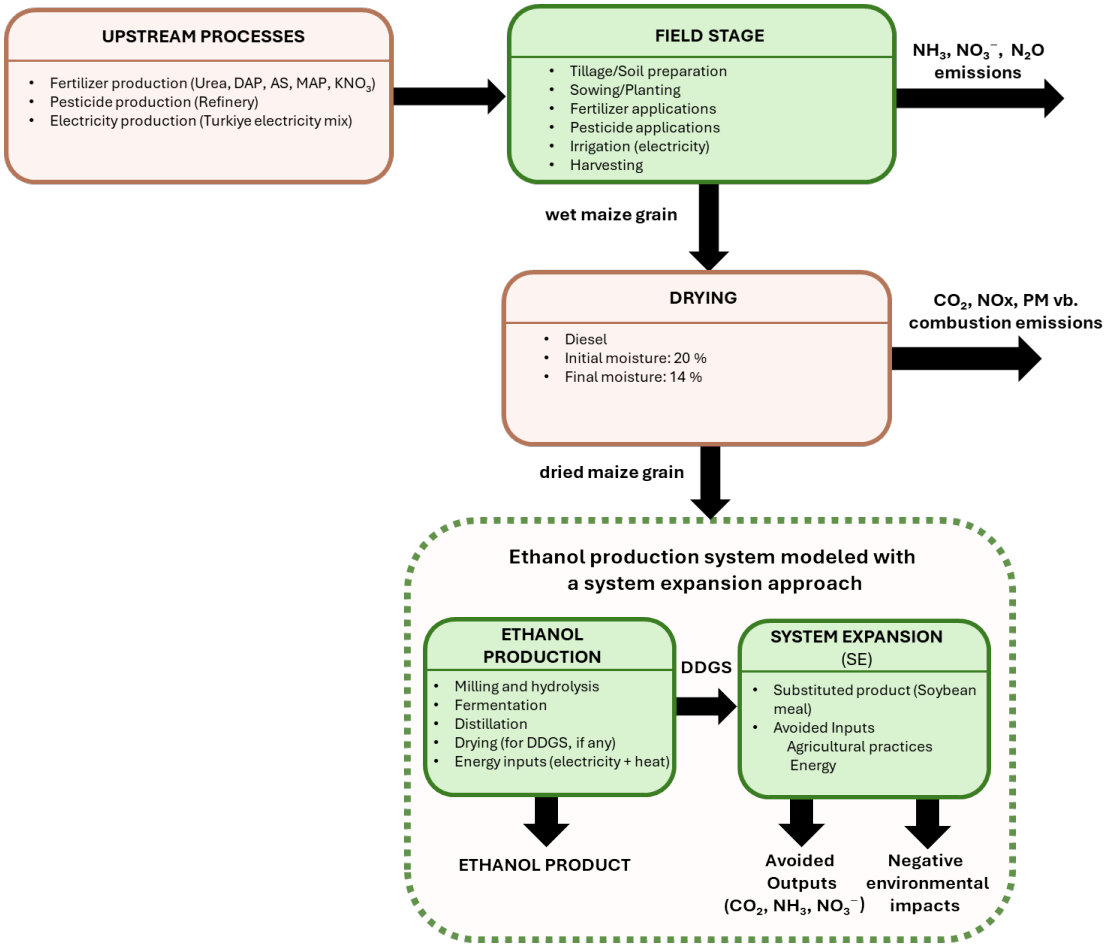


Fig.2 LCA flowcharts of ethanol production from Maize

The process up to drying was carried out within the framework of a cradle-to-farm gate system boundary. Indirect environmental impacts arising from the production stages of field inputs and energy inputs used in the drying process were included in the model. Subsequently, processes starting after drying were added to the model as separate product systems. Scenarios in the dried maize-ethanol production process were modeled independently of the field-drying stage. Ethanol production and the distillers-dried grains with solubles (DDGS) byproduct were evaluated under a separate product system. The system boundaries and functional units for ethanol and DDGS are explained in the following sections.

To ensure the comparability of agricultural management practices across maize varieties, all field and drying inputs were kept constant. To be more precise, seed quantity, fertilization process, irrigation schedule, fuel consumption, pesticide application, and drying conditions were considered the same for all varieties. This assumption was used to demonstrate the extent to which the observed differences in environmental impact among maize varieties were due to differences in yield and crop composition. Similar yield-driven effects have been reported in bioenergy LCAs, where lower crop yields lead to higher product-based environmental impacts due to increased land occupation and input requirements, even when total area-based emissions remain comparable (Jury et al. 2022).

The functional unit (1 kg of dried maize grain) was defined, and all inputs and emissions from the field and drying stages were normalized according to this unit. In scenarios where ethanol production was initiated, the functional unit was redefined to suit the relevant product system, and a separate evaluation was conducted taking into account the presence of the DDGS byproduct.

Life Cycle Inventory (LCI)

The life cycle assessment was conducted using openLCA version 2.5.0. Background life cycle inventory data were obtained from the ELCD (version 3.2) and the Environmental Footprint database (version 3.1). All foreground agricultural and ethanol production processes were modeled based on region-specific inventory data developed in this study.

Electricity Generation Mix and Modeling

This study models the environmental impacts of electricity used in irrigation and agricultural operations, considering Turkiye's specific national electricity generation mix. Real-time production data was obtained from the EXIST transparency platform. Considering the maize vegetation period (April-September), irrigation activities are most intensive in July and August (over 70% of the total). Therefore, using the electricity mix in July is more accurate than using the annual average of the Turkish grid. This approach is more accurate for reflecting the impact of national context differences on environmental impact indicators and the actual environmental burdens from agricultural production depending on country and regional conditions. Table 2 summarizes the data obtained by calculating the total hourly production throughout July 2025 and dividing it by source. According to official production statistics, fossil fuels still have a significant share. Natural gas and imported asphaltite and coal constitute the two highest sources with production rates of 27.6% and 25%, respectively. When Coal Brown (10.7%) is taken into account, it can be said that more than 63% of Turkiye's electricity mix (for July) comes from non-renewable sources. Hydroelectricity (18%) is also used in electricity production to an undeniable extent. Other renewable energy sources, wind (11.3%), solar (3.1%), biomass (2.3%) and geothermal (3.14%), have a more limited share.

Table 2 Turkish Electricity Generation Mix (July 2025)(Energy Exchange Istanbul (EXIST) 2025)

SOURCE	PRODUCTION (MWh)	SHARE (%)
Coal	7869181,32	25
Coal, Brown	3372855,3	10,7
Gas, Natural	8685663,62	27,6
Hydro Power	5674051,99	18
Fuel Oil	61629,32	0,2
Biomass	694005,18	2,3
Geothermal	756889,06	2,4
Solar	961607,19	3,1
Wind	3561447	11,3
Waste Heat	69003,79	0,2
International W.	-261294,32	-0,8

Total	31445039,45

Field Stage

This study, which covers irrigated maize cultivation under Konya plain conditions, considered all inputs from field preparation to harvest. Table 3 summarizes all inputs added to the model for the field stage and their quantities per hectare.

Table 3 Life cycle inventory (LCI) data for the agricultural production stage of five maize hybrids per hectare.

Inputs /Operations	Amount	Unit	Brief explanation
Maize seed	22.8	kg/ha	DKC 5685, DKC 5812, May Capuzi, P0920 ve P0937; same planting quantity assumed for all varieties.
Diammonium phosphate (DAP)	275	kg/ha	Pre-planting basal fertilizer
Urea	300	kg/ha	Top-dressing fertilizer during the vegetation season
Ammonium sulfate	600	kg/ha	Nitrogen source
Monoammonium phosphate (MAP)	50	kg/ha	Phosphorus supplement
Potassium nitrate	50	kg/ha	Potassium source
Zinc (Zn)	10	L/ha	Micronutrient support applied as a foliar application
Herbiside (Mix)	7.5	L/ha	Pre- ve post-emergence herbiside application; commercial product names are not specified.
İnsecticide	1	kg/ha	Applications against field pests; commercial product names are not specified.
Diesel (field operations)	59.46	L/ha	Tillage, sowing, fertilization, spraying and harvesting
Electricity (irrigation)	6075	kWh/ha	10–12 irrigation applications; pumping energy.

Seed usage

Maize seed input was defined as 22.8 $kg.ha^{-1}$ for all varieties (DKC 5685, DKC 5812, May Capuzi, P0920 and P0937). This value was determined by considering the recommended plant density and planting norms for irrigated grain maize

production under Konya Plain conditions (Dilay 2021a). In Turkiye, the target plant density for irrigated maize production is generally in the range of 75,000–90,000 plants·ha^{-1}. In commercial hybrid maize seeds, thousand-grain weight (TGH) generally ranges from 280–320 g, taking into account germination and emergence losses during sowing. Considering these parameters, the amount of seed applied in practice is in the range of 20–25 kg·ha^{-1} (Dilay 2021a). For this reason, the value of 22.8 kg·ha^{-1}, which is around the average value, was chosen as a representative value.

Fertilization Applications

Both basal fertilizer and top-dressing applications were included integrated into the LCI to ensure soil nutrient balance. Diammonium phosphate (DAP) was applied as a base fertilizer at a rate of 275 kg/ha before planting. Urea was used at a level of 300 kg/ha to meet the nitrogen requirement during the vegetation period. In addition, ammonium sulfate was added to the model at a rate of 600 kg/ha as an additional nitrogen source (secondary nitrogen source). Monoammonium phosphate (MAP) was defined at 50 kg/ha for phosphorus supplementation, and potassium nitrate at 50 kg/ha to meet the potassium requirement. Zinc (Zn), as a provider of micronutrients, was considered at 10 L/ha.

Direct and indirect nitrogen emissions arising from mineral nitrogen fertilizer application during maize production were calculated based on the emission factors recommended in the IPCC guidelines. Nitrogen emissions from fertilizers encompass direct N_2O-N emissions as well as indirect N_2O emissions resulting from NH_3 volatilization and NO_3^- leaching (Baasansuren et al. 2019). Direct N_2O emissions were calculated assuming that a certain percentage of the total applied nitrogen is converted to N_2O-N. Indirect emissions, on the other hand, were included in the model by assuming that NH_3 and NO_x released into the atmosphere via volatilization, and NO_3^- fractions leached from the soil profile, subsequently contribute to N_2O formation. This approach is widely used in agricultural LCA studies. Volatilization and leaching behaviors specific to different nitrogen forms were also reflected in the model (Baasansuren et al. 2019; Nemecek et al. 2007).

Herbicide and Insecticide Use and Exclusion of Pesticide Input

An herbicide mixture of 7.5 L/ha was included in the model for weed control during the pre- and post-emergence periods. The amount of insecticide applied against harmful insects was defined as 1 kg/ha. Pesticide use was excluded from the model due to the fact that pesticide use is not widespread or necessary in irrigated maize cultivation under regional conditions.

Field Operations and Fuel Consumption

Diesel consumption for field operations was modeled as a single total input. In other words, no operation-based decomposition was performed. This approach is a commonly used simplification method in the literature. (Bacenetti and Fusi 2015; Nemecek et al. 2007). Diesel fuel consumption for all field operations, including tillage, planting, fertilization, spraying, and harvesting, was calculated as 59.46 L/ha. This falls within the 50–70 L/ha range reported in the literature for maize production, and similar values have been used in studies focusing on Mediterranean climates and production systems with high levels of mechanization (Dilay 2021b; Kim and Dale 2005). In another study, the energy balance of grain maize grown under similar regional conditions reported a fuel consumption of 48.9 L/ha (Konak et al. 2004).

Irrigation and electricity consumption

Electricity consumption during the irrigation phase was calculated based on pump data. The specific energy consumption for submersible electric motors used in drip irrigation systems was taken as 0.81 kWh·m^{-3} (Öztürk et al. 2021; Semerci et al. 2019). The region requires 10–12 irrigations for maize cultivation, and it is assumed that 60–70 mm of water is consumed in each irrigation. In this context, the total amount of irrigation water applied throughout the season is accepted as an average of 750 mm. Since 1 mm of water = 10 m^3·ha^{-1}, the total irrigation water requirement has been calculated as 7,500 m^3·ha^{-1}. The electricity consumption associated with irrigation was determined by multiplying the volumetric water consumption by the specific energy consumption coefficient as follows:

$$E_{irrigation} = 7500\ \frac{m^3}{ha}.0.81\ \frac{kWh}{m^3} = 6075\frac{kWh}{ha}$$

Accordingly, electricity consumption for irrigation was included in the life cycle inventory as 6.075 kWh·ha^{-1}.

Calculation of Field-Related Nitrogen Emissions

Nitrogen emissions (NH_3, NO_3^-, and N_2O) from mineral fertilizer applications were calculated based on the total nitrogen input. Therefore, nitrogen content coefficients ($N_{fraction}$) were defined. Accordingly, nitrogen contents were taken as 0.46 for urea, 0.21 for ammonium sulfate, 0.18 for DAP, 0.11 for MAP, and 0.13 for potassium nitrate.

The fertilizer-based nitrogen inputs were calculated by multiplying the applied fertilizer amounts by these coefficients, and the total applied nitrogen amount ($N_{applied}$) was determined as 325.5 kg N ha^{-1}. Based on the IPCC Tier 1 approach, it was assumed that 10% of the total applied nitrogen was released into the atmosphere via NH_3 volatilization, 30% passed into the aquatic environment via leaching in the form of NO_3^-, and 1% was released directly into the atmosphere as N_2O–N (Baasansuren et al. 2019). N_2O emissions were calculated using a molecular weight coefficient of 44/28 for the conversion from the N_2O–N form to the N_2O form. The normalization process is as follows:

$$Emission\left(\frac{kg}{kg_{product}}\right) = Emission\,(\frac{kg}{ha})/(y_{wet,t,ha} * 1000)$$

Drying Stage

In this study, the harvest moisture content of maize grains was accepted as 20%, and the target moisture content as 14%. Potential moisture differences between varieties were neglected. Moisture percentages were included in the model within the range given in maize-based bioethanol LCA studies conducted by some studies (harvest moisture content in the range of 18–25%) (Cherubini and Ulgiati 2010; Gnansounou et al. 2009; Kim and Dale 2005). Diesel fuel was used as the energy input, and the defined diesel consumption per unit of product was represented by a cradle-to-use approach including the refinery stage and combustion emissions.

Mass and energy balances for the drying process

The basic equation in the drying process is determined based on the mass conversion ratio between fresh maize and dried maize. This equation is defined as:

$$\text{Mass conversion ratio} = \frac{1 - h_{harvest}}{1 - h_{target}}$$

This equation shows that approximately 1.075 kg of fresh maize is needed to produce 1 kg of dried maize. This coefficient was applied to all inputs for normalization in the drying process.

The amount of water removed during drying was added to the model according to the following equation:

$$water_{kg/ha} = y_{wet,t/ha} * 100 * \frac{h_{harvest} - h_{target}}{(1 - h_{target})}$$

The total drying energy required to remove this amount of water was calculated with the following equation:

$$Q_{dry,MJ/ha} = \frac{water_{kg/ha} * e_{water}}{\eta_{heat}}$$

There,

$e_{water} = 4\ MJ/kg$ (Specific energy for evaporation of water) (Eames et al. 1997)

$\eta_{heat} = 0.8$ (Thermal efficiency) (Food and Agriculture Organization of the United Nations (FAO) 2010)

Total diesel consumption was calculated as (LHV_{diesel} = 43 MJ/kg) (U.S. Energy Information Administration (EIA) 2023)

$$diesel_{dry,kg/ha} = \frac{Q_{dry,MJ/ha}}{LHV_{diesel}}$$

Modeling the Ethanol Production Process

The ethanol production process was modeled to include the stages of grain maize milling, starch hydrolysis, fermentation, distillation, and separation of by-products. The electrical and thermal energy inputs used throughout the process were defined based on the specific energy consumption values reported in the literature for corn-based ethanol production (Canter et al. 2016; Kim and Dale 2005; Pereira et al. 2019). The raw material requirement for ethanol production was calculated based on the starch content of the grain maize. In this context, ethanol yield was determined using the ethanol production coefficient per unit of starch. The compositional differences between different maize varieties were reflected in the ethanol production potential. The main product obtained in the ethanol production process is fuel ethanol, and Distillers Dried Grains with Solubles (DDGS) emerge as a byproduct after the fermentation and distillation stages. The environmental impacts of DDGS were evaluated within the scope of the system expansion approach integrated into the ethanol production system, and the relevant methodology is explained in detail in the following section.

The conversion yield of starch to ethanol was assumed to be 0.45 kg EtOH per kg starch (Vučurović et al. 2025). The ethanol yield for each maize variety is calculated as:

$$ethanol_{kg/kg\ maize} = \text{starch}_{\text{frac.}} * \text{yield}_{\text{EtOH}_{kg/kg\ starch}}$$

where $\text{starch}_{\text{frac.}}$ is the starch content of the product and $\text{yield}_{\text{EtOH}_{kg/kg\ starch}}$ is the conversion coefficient

mentioned. Using the obtained ethanol yield, the amount of maize required to produce 1 kg of ethanol was calculated:as:

$$maize_kg_per_kg_ethanol = \frac{1}{ethanol_kg_per_kg_maize}$$

Thus, ethanol production from maize has been directly linked to the chemical composition of the varieties.

α-amylase and glucoamylase enzyme inputs were added to the model and defined based on maize-based specific consumption values. Enzyme consumption per kilogram of maize was taken as 0.25 g α-amylase and 0.8 g glucoamylase, respectively. These values were converted into ethanol-based functional units and included in the model. Since the environmental impacts resulting from enzyme transport are considered negligible in the literature, they were not included in the model as a separate process. Electricity consumption was modeled on an energy basis, taking into account the lower calorific value of ethanol (26.8 MJ/kg). The electricity input for producing 1 MJ of ethanol was assumed to be 0.04 MJ. The amount of electricity required to produce 1 kg of ethanol was included in the model as the product of these values. Thermal energy inputs (steam) were similarly defined on a MJ ethanol basis and added to the model as process steam produced from natural gas.

System Expansion Approach and Modeling of DDGS

During ethanol production, in addition to the main product, fuel ethanol, a byproduct called Distillers Dried Grains with Solubles (DDGS) is produced. DDGS is a widely used feed raw material in animal nutrition due to its high protein content and is particularly valued as a substitute for protein sources such as soybean meal (Mohammadi Shad et al. 2021). In this study, the environmental impacts of an ethanol production system were modeled using the system expansion (SE) approach in accordance with the ISO 14044 standard. This approach is based on the principle of avoiding environmental impacts arising from the production of reference products (e.g., soybean meal) that are substituted for the dried maize produced during ethanol production when used as animal feed. The mass ratio of DDGS formed during ethanol production was defined in accordance with widely accepted values in the literature. Additionally, quality correction coefficients were used to account for quality differences with substituted feed products (da Silva Timm et al. 2023).

The system expansion approach was applied only to the ethanol production system to show effects of co-product

substitution (Lahtinen et al. 2025). The amount of DDGS was calculated assuming that 33% of the dried maize used for ethanol production is recovered as a byproduct.

Different displacement factor (DF) values were also tested in this study. DF represents the percentage of the reference feed production that the produced DDGS could theoretically replace that is actually displaced in practice. Literature reports that this parameter can vary between 0.3 and 0.9 depending on market conditions, regional feed use, and the feed quality of the DDGS (Liska et al. 2009; Wang et al. 2012).

Life Cycle Impact Assessment (LCIA)

Impact assessment for the study was performed using the ReCiPe Midpoint (H) method. Some impact categories were evaluated to represent the environmental performance of agricultural production and biofuel systems. There are global warming (GWP100), terrestrial acidification (TAP100), freshwater eutrophication (FEP), particulate matter formation (PMFP), water depletion (WDP), and agricultural land occupation (ALOP). The selected impact categories were determined to holistically reflect the environmental pressures (water use, air emissions, and land use) of irrigated agricultural systems in semi-arid regions.

Results

Environmental Impacts at the Field Stage

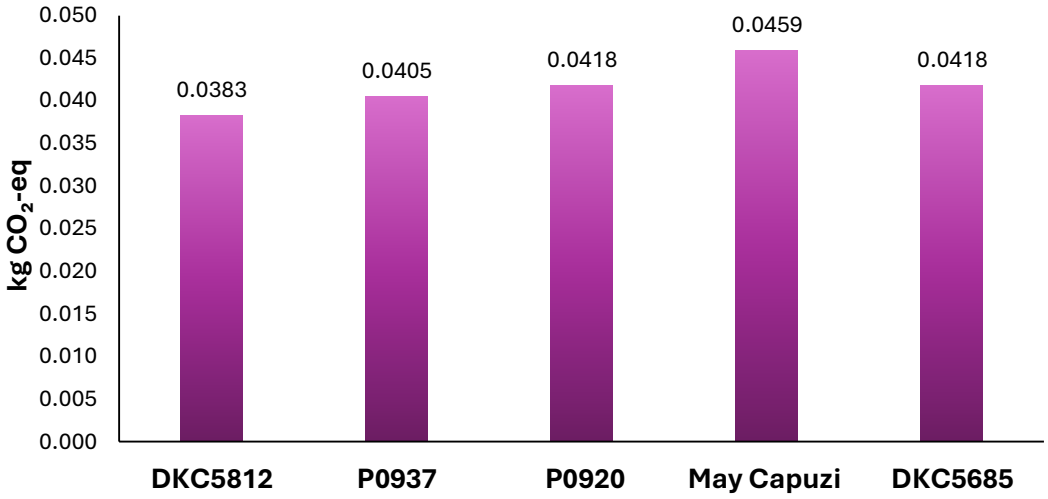


Fig. 3 Comparison of the climate change impact (GWP100) of maize hybrids per functional unit of 1 kg fresh maize at the field stage.

Fig. 3 presents the field-stage GWP100 results for each maize variety. The results range from 0.038–0.046 kg CO_2-eq. kg^{-1} fresh maize. The lowest climate change impact was observed in the DKC5812 variety, while the May Capuzi variety had the highest GWP100 value. Variations P0937, P0920, and DKC5685 fall between these two extremes and yield very similar results. The main reason for these differences is that while input amounts (fertilizer, diesel, irrigation electricity, etc.) were kept constant for all varieties, the yield per hectare values varied. In higher-yielding varieties, inputs per unit of product decrease, leading to lower GWP100 values.

Field-stage global warming effects (GWP100) exhibit a similar contribution structure for all maize varieties (Fig. 4). In terms of individual inputs, the highest contribution for most varieties comes from diammonium phosphate (DAP) application. DAP is followed by diesel consumption, ammonium sulfate, and urea applications, respectively. Herbicide use offers a more limited contribution compared to other inputs. For example, for the DKC5685 variety, GWP100 contributions are DAP (0.011 kg CO_2-eq.), diesel (0.0096 kg CO_2-eq.), ammonium sulfate (0.0076 kg CO_2-eq.), and urea (0.0076 kg CO_2-eq.). Similar trends have been observed for other varieties, with absolute differences between varieties mainly stemming from differences in yield levels.

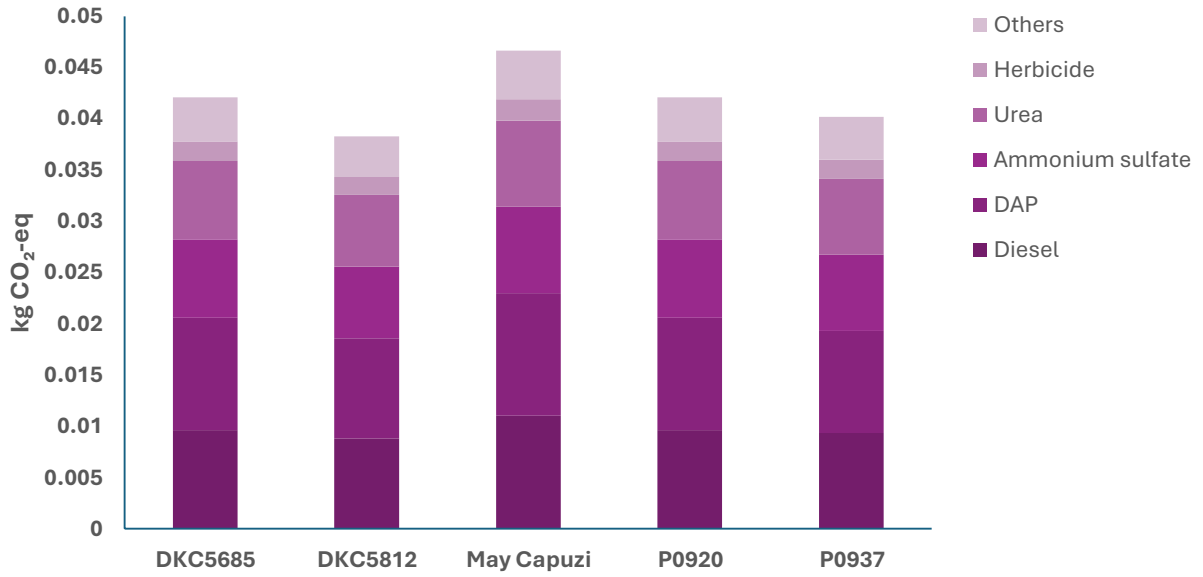


Fig. 4 GWP contribution distributions of maize hybrids

When examining the processes involved in maize cultivation individually, DAP stands out as the input providing the highest contribution (range 0.0098-0.12 kg CO2 eq). Furthermore, when nitrogen fertilizers are considered as a whole (DAP, urea, and ammonium sulfate), they are found to have the highest proportion of total greenhouse gas impact at the field stage (e.g., DKC5685: 62.4%). This is because DAP was modeled with a life cycle dataset that includes not only the field application but also the production stages, including ammonia production (steam reforming), phosphoric acid synthesis, process steam, and electricity consumption. In contrast, diesel consumption (e.g., DKC5685: 22.8%), while having high specific CO_2 emission factors in terms of direct combustion emissions, provides a lower total GWP contribution compared to DAP due to the limited amount of total energy consumed per functional unit. Therefore, in this study, the effect of nitrogen fertilizers was evaluated not through individual inputs, but from a total contribution perspective. This magnitude is comparable to the 36–52% contribution of nitrogen fertilizer to total agricultural GHG emissions reported by (Gao et al. 2023). Looking at the literature, an LCA study conducted in Alborz province revealed that chemical fertilizers are the biggest source of environmental impacts in maize production. According to the study, while nitrogen fertilizers consume more energy than diesel in the production process, electricity and fertilizers have a larger share than diesel in terms of global warming potential. In particular, phosphate fertilizers (DAP content) were identified as the most polluting input in the aquatic ecotoxicity category, creating a much higher negative impact than diesel in this area (Hossein et al. 2024). In a study, researchers investigated the

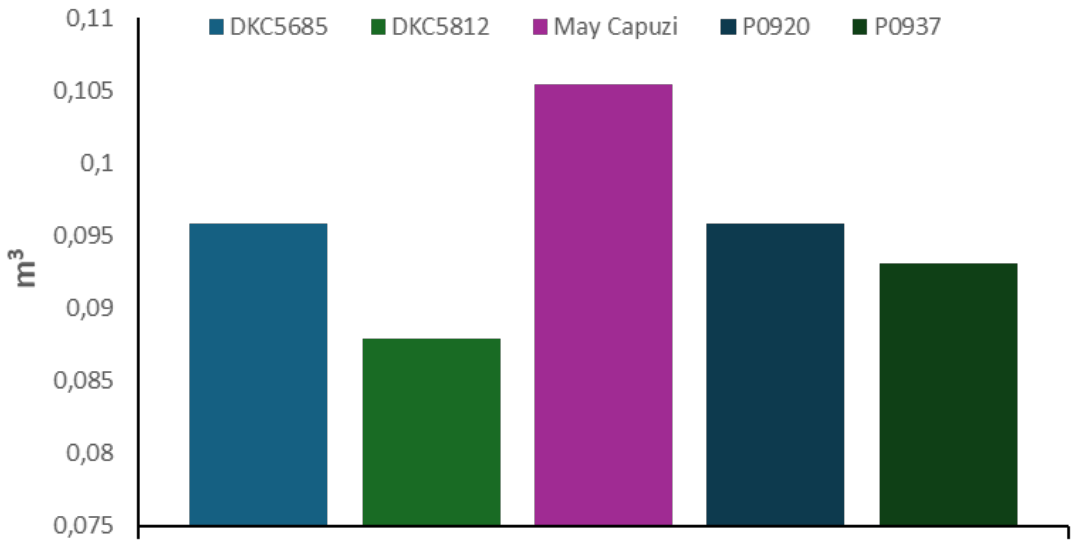
comparison of diesel fuel and chemical fertilizers (especially nitrogen and phosphate/DAP content) for grain maize and silage maize, their energy consumption and environmental impacts. With the data they obtained, they reported that fertilizers (including DAP components) have a greater impact and share than diesel fuel (with a 59-63% share) in both energy consumption (with a 19-26% share) and potential for environmental damage (Shahbazi et al. 2024). This study, which examines maize and soybean production in South America, evaluated the environmental impacts of agricultural inputs using life cycle analysis (LCA). According to the analysis results, fertilizer consumption (nitrogen and phosphorus) was determined as the most dominant environmental impact source in all impact categories, including global warming potential, while diesel fuel use (mechanization) remained secondary except for the fossil resource scarcity category (Costantini and Bacenetti 2021). Similarly, Holka and Bieńkowski (2020) reported that nitrogen fertilizers were the largest source of greenhouse gas emissions in maize cultivation systems. Their findings confirm that fertilizer production and field-related nitrogen emissions structurally dominate the carbon footprint compared to mechanization-related diesel use (Holka and Bieńkowski 2020). In addition, the combined effect of low-level inputs from background processes, such as seed production, micronutrient (e.g., zinc) applications, and machinery and equipment use, constitutes the 'Other' GWP contributor. Although these inputs individually have limited effects, when considered together, they make a significant contribution. This is important for a more holistic understanding of greenhouse gas emissions at the field stage. Overall, the GWP100 results show that fertilizer production and fuel consumption are key factors at the field stage, while differences between varieties primarily affect the environmental load per unit of crop through yield differences. A similar dominance pattern has been reported in some previous studies. One of which shows that electricity accounted for up to 46.2% of global warming impacts and phosphate fertilizers contributed up to 56.3% in selected midpoint categories under irrigated maize systems. This structural similarity confirms that irrigation energy and fertilizer production consistently act as primary environmental drivers across different climatic and system-boundary conditions (Hossein et al. 2024).

The present field-stage GWP100 results (0.038–0.046 kg CO_2-eq kg^{-1} fresh maize) appear lower than common cradle-to-farm-gate assessments. This difference primarily arises from some structural factors, mostly the definition of system boundaries, the functional unit specification, and the exclusion of soil carbon dynamics. For instance, Silva et al. (2024) reported maize GHG intensities from −0.7 to 1.0 kg CO_2-eq kg^{-1}. Their study explicitly included long-term soil organic carbon (SOC) sequestration within a field-to-farm-gate boundary (Silva et al. 2024). Similarly, Holka

and Bieńkowski (2020) quantified emissions between 1868 and 2353 kg CO_2-eq ha^{-1} (approx. 0.15–0.22 kg CO_2-eq kg^{-1}). Their analysis incorporated upstream machinery production and fertilizer manufacturing. In contrast, this study evaluates strictly field-stage impacts per unit of fresh maize (Holka and Bieńkowski 2020). Soil organic carbon (SOC) stock changes and machinery production were not included within the system boundary of the present study. This narrower system boundary and the fresh-weight functional unit substantially reduce the absolute emission intensity. Nevertheless, the relative contribution structure remains consistent with empirical findings. Nitrogen fertilizers are the dominant source ($\approx$62% of total field-stage GWP), followed by diesel use. For example, long-term measurements in the North China Plain showed that nitrogen management alone can alter total GWP by 8.9–13.3% (Gao et al. 2023). This confirms the central role of fertilizer-related emissions. Therefore, the observed numerical differences stem from system-boundary definitions rather than inconsistency with the literature.

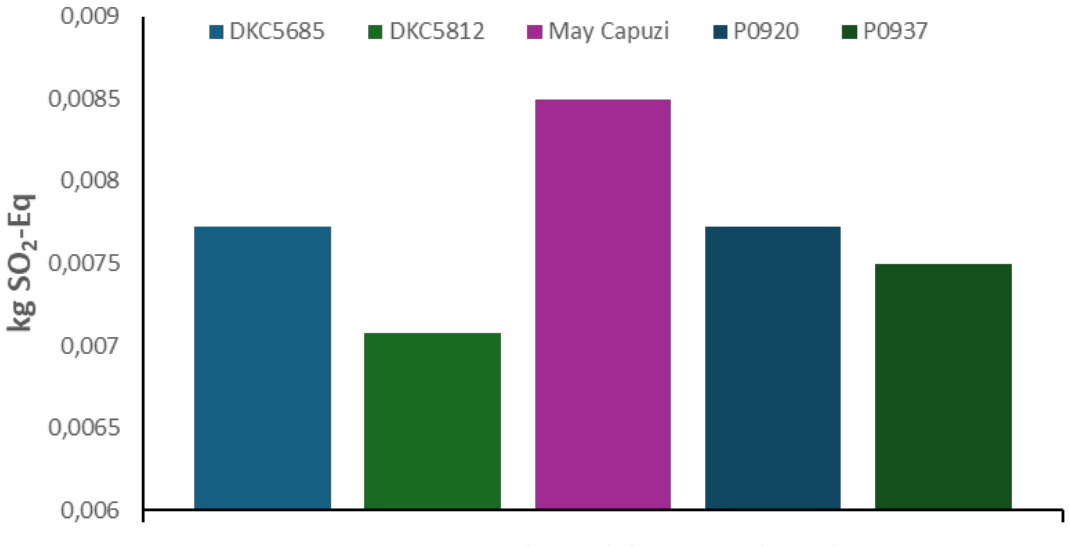
Effects of Field Stage on Other Impact Categories

In addition to the effects of global warming, the study also examined impact categories, namely terrestrial acidification, water depletion, freshwater eutrophication, and particulate matter formation. WDP shows freshwater resource consumption in cubic meters (m^3). According to WDP results, the May Capuzi variety had the highest water consumption value, while DKC5812 had the lowest value. It is known that irrigation practices are the same for all varieties in this study. Thus, this difference is explained by the fact that water consumption per kg of product is inversely proportional to yield. In varieties with lower yields, the WDP value increases because the same absolute irrigation amount is allocated to fewer products. This situation highlights the importance of variety selection in reducing water footprint in irrigation-intensive regions (Fig. 5a). TAP100 results exhibit the same ranking pattern as WDP. This similarity is not coincidental. TAP100 is sensitive to emissions primarily from the production of nitrogen fertilizers (urea and ammonium sulfate) and diesel use in the field. Since these inputs are constant for all varieties, the TAP100 values are also directly normalized to yield and show a trend parallel to WDP. Therefore, evaluating water consumption and acidification effects together reveals the field management–yield relationship more clearly (Fig. 5b).



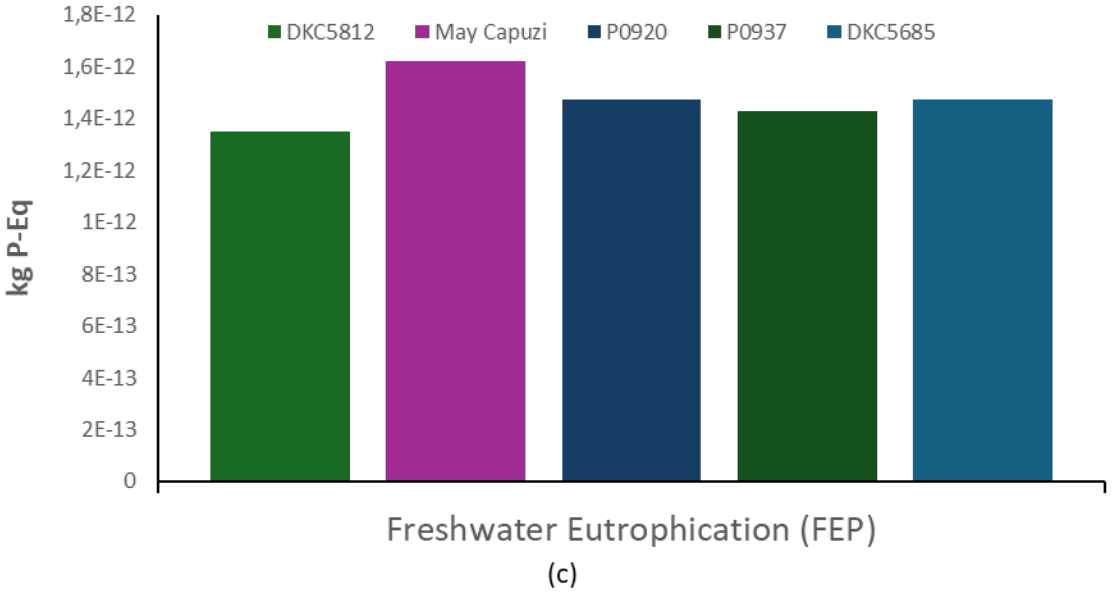
Water Depletion (WDP)

(a)



Terrestrial Acidification (TAP)

(b)



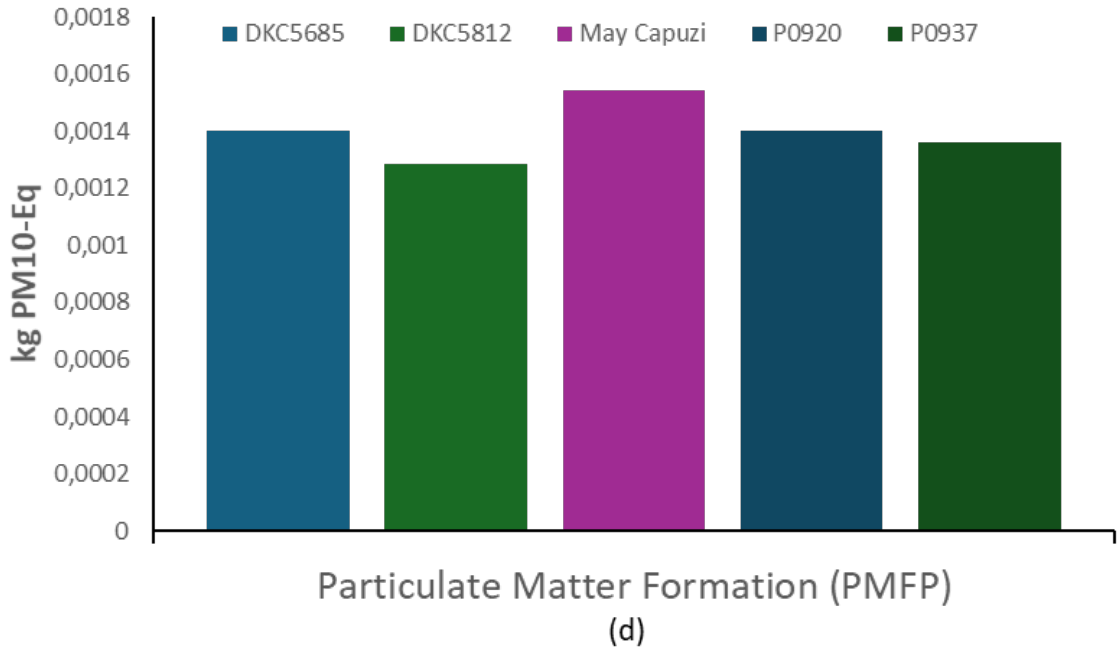


Fig. 5 Four environmental impact categories selected for the field stage of maize production: (a) Water Depletion (WDP), (b) Terrestrial Acidification (TAP100), (c) Freshwater Eutrophication (FEP), and (d) Particulate Matter Formation (PMFP)

FEP results show more limited variability among varieties. The main reason for this is that this category of effect is largely dependent on phosphorus-based fertilizer inputs (DAP and MAP), and these inputs are used in the same amounts across all varieties. FEP's sensitivity to yield is lower compared to WDP and TAP. Therefore, FEP results

reflect the environmental impact of fertilization strategies rather than a comparison between varieties (Fig. 5c). PMFP values are similar for all varieties, but relatively higher values are observed in the May Capuzi variety. PMFP is particularly related to diesel combustion and fertilizer production processes. Here, the differences in PMFP are mainly explained by the energy intensity per product. This indicates that the effects of mechanization and input production processes on air quality should be evaluated together with the yield parameter (Fig. 5d).

The results presented in Fig. 5 show that although the environmental impact categories selected at the field stage were largely based on the same agricultural inputs, the normalized environmental loads per crop could differ significantly among maize varieties. In particular, the similar ranking patterns exhibited by the Water Consumption (WDP) and Terrestrial Acidification (TAP100) categories suggest that these two effects are determined by a common dominant mechanism at the field stage. This common mechanism involves keeping inputs such as irrigation energy and nitrogen fertilizer use constant for all varieties, while the input intensity per unit of crop varies depending on the yield level. In other words, in lower-yielding varieties, since the same absolute input amounts are shared with less yield, both water consumption and acidification potential are higher per kg of product. This clearly demonstrates that environmental performance at the field stage is directly related not only to the inputs applied, but also to the variety-specific yield capacity. In contrast, intervaried differences were observed to be more limited in the categories of Freshwater Eutrophication (FEP) and Particulate Matter Formation (PMFP). FEP's high sensitivity to phosphorus-based fertilizer applications and the consistent use of these inputs across all variety's limits yield variation. Similarly, since PMFP is primarily caused by diesel use and fertilizer production processes, intervaried variability is mainly shaped by differences in energy intensity per crop. When these findings are considered together, it appears that some impact categories (particularly WDP and TAP100) are strongly driven by yield at the field stage, while categories such as FEP and PMFP are more sensitive to input type and production technology.

These findings are in line with previous maize LCA studies reporting that nitrogen fertilizers and irrigation energy are dominant contributors to field-stage impacts (Costantini and Bacenetti 2021; Holka and Bieńkowski 2020). Since input amounts were kept constant in the present study, differences among varieties are primarily explained by yield normalization. Similar normalization effects have been observed in studies comparing product-based and area-based indicators (Boone et al. 2016). Therefore, the variation observed in WDP and TAP100 reflects yield-driven intensity differences rather than changes in input structure.

Effect of Drying Stage on Field Results

As shown in Fig. 6, field inputs were rescaled on a mass basis during the transition from wet to dry crop. Diesel fuel consumption during the drying stage was the largest input item.

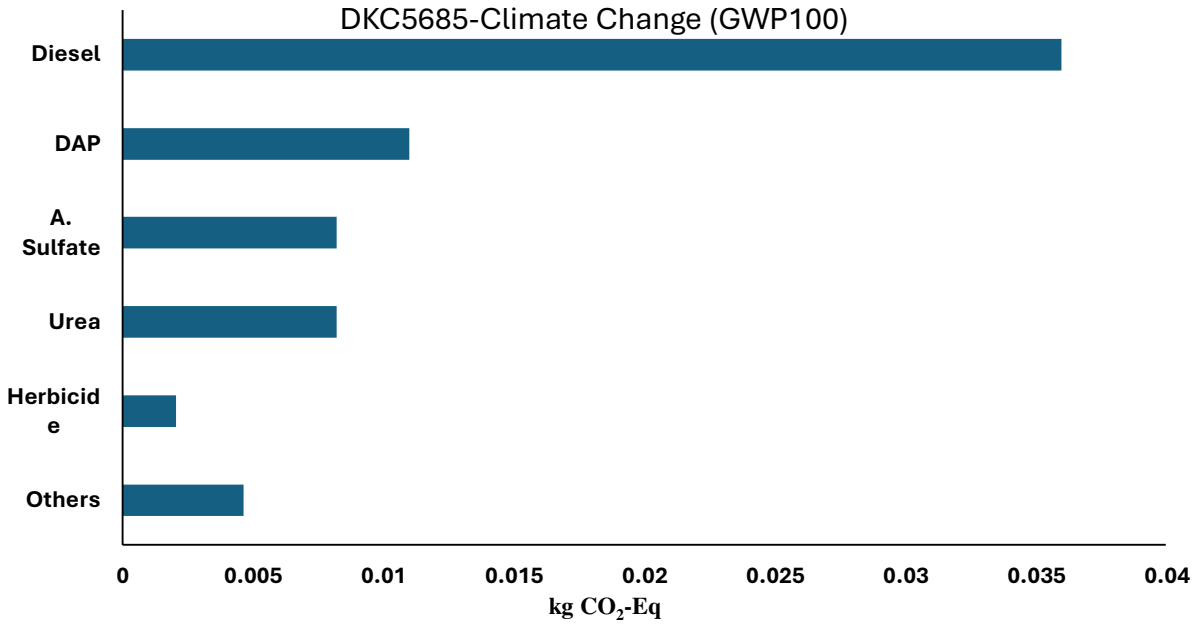


Fig. 6 Main inputs contributing to GWP100, including drying, for the DKC5685 maize variety.

Table 4 shows how the drying stage, both with and without the field stage, affects the four impact categories. The results demonstrate that absolute increases at the field + drying system limit compared to the field stage are limited but consistent for all maize varieties. Increases in the terrestrial acidification (TAP100) category ranged from 0.00053–0.00064 kg SO_2-Eq, with the primary source of these increases being SO_2 and NO_x emissions from the combustion of diesel fuel used in the drying process. When the freshwater eutrophication (FEP) results are examined, it is seen that the increases in phosphorus equivalent remain at the level of 1.01×10^{-13}–1.22×10^{-13} kg P-Eq, and the dominant fertilizer-derived contribution in the field stage increases only to a limited extent in the drying stage. Similarly, the increases observed in the particulate matter formation (PMFP) category, ranging from 9.6×10^{-5}–1.16×10^{-4} kg PM10-Eq, are explained by the addition of particulate and precursor gas emissions from diesel combustion to the system. Water depletion (WDP) results show that the drying phase leads to an additional virtual water consumption of 6.6×10^{-3}–7.9×10^{-3} m^3. This situation is particularly noteworthy from an environmental perspective, especially for regions with high water stress. The similar increases observed across all impact categories among maize varieties are because

the environmental burden of the drying process is largely based on a single energy input (diesel).

Table 4 Changes in some impact categories in the maize production system with the inclusion of the drying stage

Impact Categories	Maize Varieties	Field	Field + Drying	Difference
TAP100 (kg SO_2-Eq)	DKC5685	0.007722	0.008300842	0.000579
	DKC5812	0.007078	0.007609119	0.000531
	May Capuzi	0.008494	0.00913091	0.000637
	P0920	0.007722	0.008300842	0.000579
	P0937	0.007494	0.008056704	0.000562
FEP (kg P-Eq)	DKC5685	1.47E-12	1.58479E-12	1.11E-13
	DKC5812	1.35E-12	1.45273E-12	1.01E-13
	May Capuzi	1.62E-12	1.74327E-12	1.22E-13
	P0920	1.47E-12	1.58479E-12	1.11E-13
	P0937	1.43E-12	1.53818E-12	1.07E-13
PMFP (kg PM10-Eq)	DKC5685	0.001401	0.001506375	0.000105
	DKC5812	0.001284	0.001380847	9.64E-05
	May Capuzi	0.001541	0.00165701	1.16E-04
	P0920	0.001401	0.001506375	1.05E-04
	P0937	0.00136	0.001462071	1.02E-04
WDP(m^3)	DKC5685	0.095869	0.103059088	7.19E-03
	DKC5812	0.08788	0.094470831	6.59E-03
	May Capuzi	0.105456	0.113364997	7.91E-03
	P0920	0.095869	0.103059088	7.19E-03
	P0937	0.093049	0.100027939	6.98E-03

Drying operations are widely reported as energy-intensive post-harvest stages in maize and bioethanol systems, primarily due to thermal energy demand for moisture removal. Previous studies indicate that grain drying typically

requires substantial heat input, and that fuel-based heat generation contributes to acidification and particulate emissions through SO_2, NO_x and combustion-related precursors. In integrated corn processing configurations, drying is often linked to waste heat recovery through secondary steam; however, recovered heat is frequently insufficient to fully satisfy downstream evaporation demand, necessitating supplementary fresh steam and thereby increasing overall thermal energy consumption (Geng et al. 2025). These findings support the structural interpretation that drying-related impacts are primarily driven by additional energy demand rather than by nutrient-related emissions. Accordingly, the limited but consistent increases observed across acidification, particulate formation, and water depletion categories align with previously reported energy-driven burden patterns in maize processing systems (Martinello and Giner 2010)

Ethanol Production and the Impact of System Expansion

Climate change (GWP100)

When comparing greenhouse gas emissions (GWP100) from ethanol production among different maize varieties, significant but limited differences are observed. According to ethanol production results calculated without system expansion, the lowest GWP100 value was obtained in the DKC5812 variety (0.237 kg CO_2-eq./kg ethanol). The highest value was calculated in the May Capuzi variety (0.269 kg CO_2-eq./kg ethanol) (Fig. 7). For the other varieties, DKC5685, P0920, and P0937, the GWP100 values ranged from 0.249, 0.254, and 0.243 kg CO_2-eq./kg ethanol, respectively. These numerical differences between varieties stem from the variation in the amount of dried maize required per unit of ethanol production, even though the process technology used in ethanol production was kept constant. In varieties with higher starch content (e.g., DKC5812 and DKC5685), the amount of maize required to produce 1 kg of ethanol decreases. Consequently, the environmental loads transferred from the field and drying stages to the ethanol system are reduced. In contrast, in the May Capuzi variety, which has a relatively lower starch content, the increased raw material requirement resulted in higher GWP100 values.

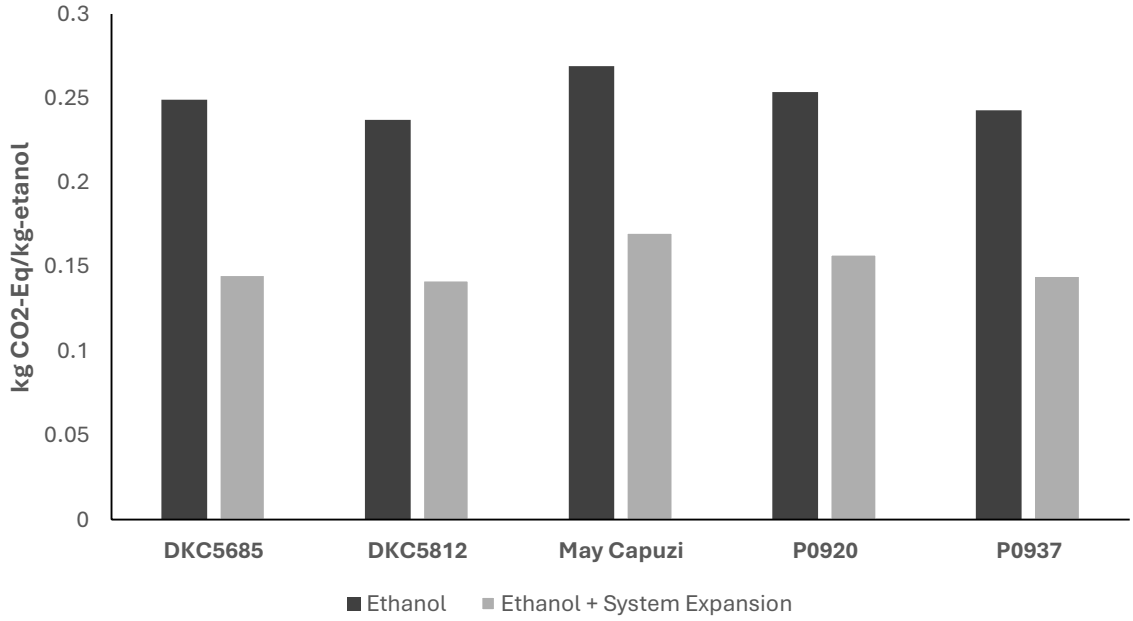
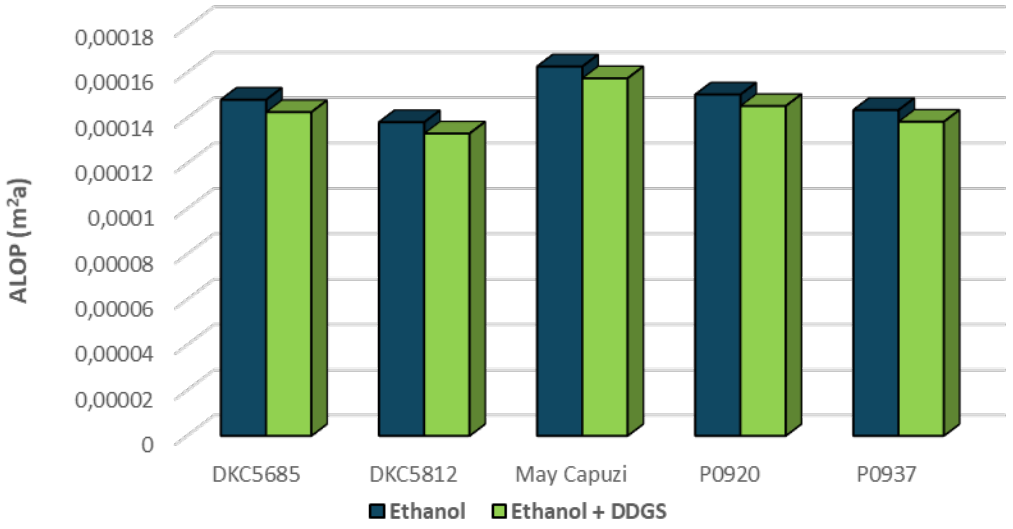


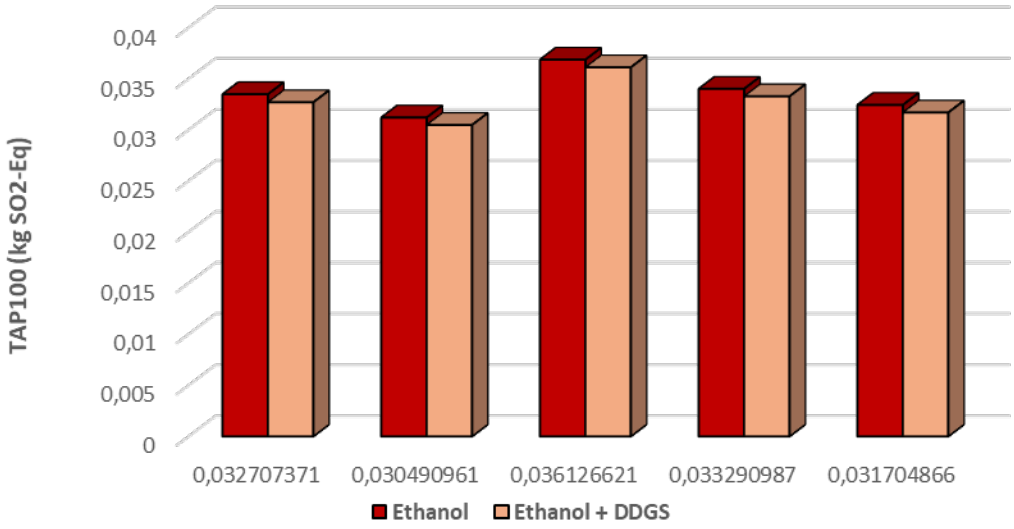
Fig. 7 GWP100 results for ethanol production (before and after system expansion (SE)).

With the application of the system expansion approach, it has been observed that net greenhouse gas emissions from ethanol production are significantly reduced for all types. This reduction is related to the substitution of the DDGS byproduct, which is generated during ethanol production, as animal feed, without any changes to the process technology. The effects of system expansion via using co-products have been reported in a recent study too (Trapé et al. 2024). Under the assumption that DDGS replaces the production of high-carbon-intensity protein sources, particularly soybean meal, the agricultural production, fertilizer use, and land-based emissions associated with these products are pushed outside the system's limits. Therefore, the decrease in GWP100 values is due more to how byproducts are handled at the system level than to direct emissions from the ethanol production process. Recent corn-ethanol LCA evidence shows that co-product credits under system expansion can materially shift results; for example, system expansion and co-product credits were reported to drive negative land-use impacts, with DDGS credited as displacing corn production for animal feed (Geng et al. 2025; Gerrior et al. 2022).

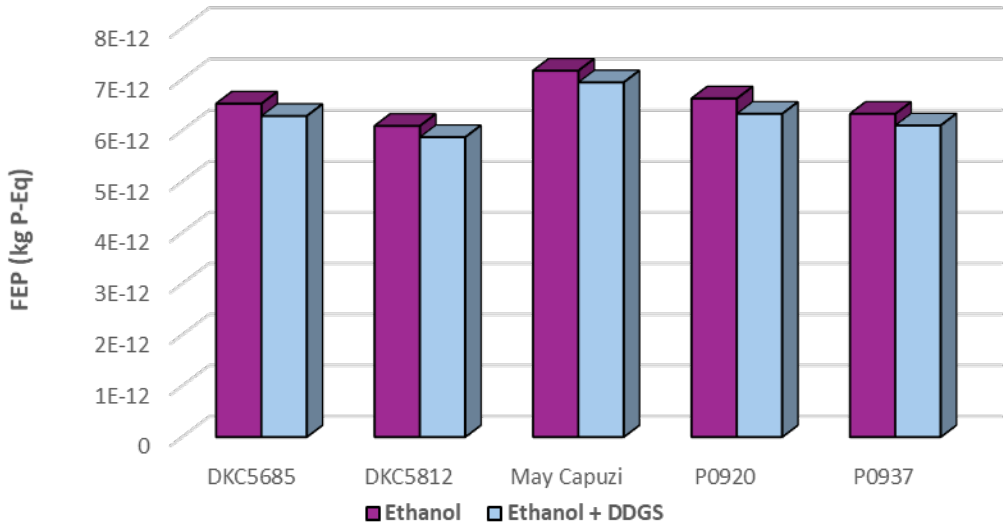
For the DKC5685 variety, this resulted in a decrease in the GWP100 value of ethanol from 0.249 kg CO_2-eq kg^{-1} to 0.145 kg CO_2-eq kg^{-1}, providing a net reduction of approximately 42% (Fig. 7). This result demonstrates that environmental performance in ethanol production is strongly dependent not only on process energy but also on how byproducts are handled at the system level.


ALOP (m²a)
0,00018
0,00016
0,00014
0,00012
0,0001
0,00008
0,00006
0,00004
0,00002
0
DKC5685
DKC5812
May Capuzi
P0920
P0937
Ethanol
Ethanol + DDGS

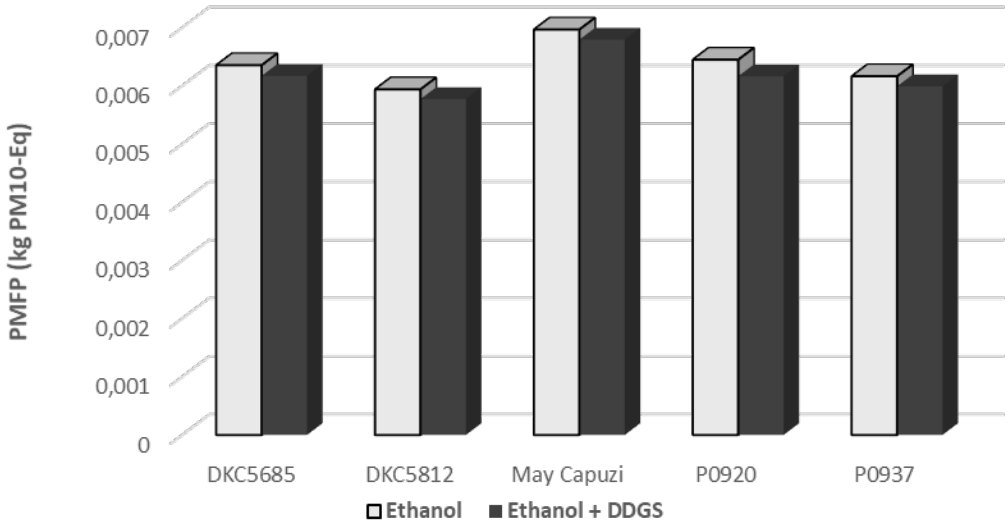
(a)


TAP100 (kg SO2-Eq)
0,04
0,035
0,03
0,025
0,02
0,015
0,01
0,005
0
0,032707371
0,030490961
0,036126621
0,033290987
0,031704866
Ethanol
Ethanol + DDGS

(b)



(c)



(d)

Fig. 8 The effect of the system expansion (SE) approach on agricultural land occupation (ALOP) (a) terrestrial ecotoxicity (TAP100) (b) freshwater eutrophication (FEP) (c) and particulate matter formation (PMFP) (d)

Fig. 8 shows that the system expansion (SE) approach creates a consistent decreasing trend in its effect on different effect categories related to ethanol production, regardless of maize variety. This decrease occurred in the same direction, although not of the same magnitude across all impact categories. ALOP (Fig. 8a) results show that with SE application, the agricultural land occupation indicator decreased by approximately 2–4% in all varieties.

While this decrease is limited in absolute terms, it is consistent with DDGS reducing the need for indirect agricultural production through feed substitution. The small size of the effect can be explained by the fact that land use in ethanol production systems is primarily determined at the field stage. The observed decrease in TAP100 (Fig. 8b) and PMFP (Fig. 8d) results is more pronounced. A decrease of approximately 7–8% occurred in these categories after SE. This is related to the removal of inputs contributing to acidification and particulate matter formation (especially from fertilizer use and energy consumption) in the protein feed production processes that DDGS substitutes.

FEP (Fig. 8c) results show that the effect of SE on freshwater eutrophication is limited but consistent. Given that nitrogen and phosphorus-based emissions are largely determined at the field stage, it is to be expected that the impact of the SE approach integrated into the ethanol production system on this category will remain relatively low. Overall, the SE approach appears to provide a small but systematic improvement in absolute terms across all impact categories. This finding suggests that system expansion does not dramatically alter environmental performance in ethanol production, but rather highlights the importance of how byproducts are handled on net environmental accounting.

Displacement Factor

In the calculations performed within this scope, the GWP100 value for ethanol production for DF = 0.3 was obtained as 0.197 kg CO_2-eq/kg ethanol. This scenario represents a conservative approach where DDGS is evaluated to a limited extent, and therefore, the substitution effect is weak. In contrast, under the assumption of DF = 0.9, the GWP100 value drops to 0.093 kg CO_2-eq/kg ethanol. This corresponds to an upper-bound scenario where DDGS almost completely replaces the reference feed production, but which is often considered optimistic under real market conditions (Table 5).

Table 5 DF sensitivity analysis (GWP100) as part of system expansion

Displacement Factor	GWP100 (kg CO_2-Eq)
0.3	0.197122256
0.6	0.145128388
0.9	0.09313452

The intermediate value chosen, DF = 0.6, yielded a GWP100 result of 0.145 kg CO_2-eq/kg ethanol for ethanol production. This value represents the most widely accepted scenario in the literature, where DDGS provides significant

but incomplete substitution. With the selection of DF = 0.6, the system expansion approach neither overestimates nor underestimates the environmental benefit of DDGS. Therefore, DF = 0.6 was chosen as the main scenario in this study. This sensitivity analysis clearly demonstrates that the environmental performance of ethanol production is strongly correlated not only with process energy or agricultural inputs, but also with how byproducts are handled at the system level. The observation of an approximately 53% decrease in GWP100 when the DF value is increased from 0.3 to 0.9 shows that the DDGS-induced substitution effect plays a decisive role in the ethanol lifecycle outcomes. Therefore, this study quantitatively demonstrates that the system expansion approach can structurally alter ethanol LCA outcomes and that the selection of the displacement factor must be clearly justified.

Conclusions

This research analyzed the environmental effects of five hybrid maize varieties cultivated in the Konya Plain during the field, drying, and ethanol production phases, employing a life cycle assessment method. Maintaining all agricultural inputs constant during the field stage clearly demonstrated that the variations in environmental impacts seen among the varieties were primarily due to crop yield. In types with increased yields, the decrease in inputs per product unit resulted in diminished outcomes in impact areas like climate change, water use, freshwater eutrophication, terrestrial acidification and agricultural land occupation. The addition of the drying phase to the system led to a steady yet modest rise in environmental effects for all types of maize. The growth noted in the chosen impact categories, between 7–8%, is linked to the emissions from burning diesel fuel during the drying process and aligns with findings in comparable research documented in the literature. These findings indicate that the drying process represents a secondary environmental impact relative to the field stage, yet it must not be overlooked, particularly in semi-arid and energy-demanding areas.

The primary factor causing the variations in greenhouse gas emissions among maize varieties was the starch content in the grain. In types with elevated starch levels, the quantity of dried maize needed for each unit of ethanol production decreases. It means, the environmental performance of ethanol production relies not just on energy inputs but also on the attributes of raw materials. By employing the system expansion method, a notable decrease in the environmental effects of ethanol production was noted. This decrease is attributed not to the ethanol production process, but to the removal of the products that the byproduct DDGS substitutes for as animal feed within the system

boundary. The sensitivity analysis conducted for the displacement factor clearly indicated that this parameter is crucial in the ethanol life cycle outcomes. The DF = 0.6 value, which provides a balanced perspective between conservative and excessively optimistic assumptions, was favored as the primary scenario in this analysis. In general, it can be stated that maize varieties with high yields and elevated starch levels offer greater environmental benefits. Additionally, this research demonstrates that the management of byproducts at the system level can significantly impact the LCA outcomes. The results suggest that regional agricultural and biofuel policies must be designed considering not just the amount produced but also the characteristics of the products and the definitions of system limits.

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Author contribution Ö.A. performed data collection, LCA modeling, and analysis and wrote the first draft of the manuscript. F.A. conceived and supervised the study and revised the manuscript. H.O. contributed to data interpretation and manuscript revision. All authors read and approved the final manuscript.

Data availability The datasets used and/or analyzed in this study are available on request from the corresponding author.

Declarations Ethics approval No ethical issues were involved in this study.

Consent to participate Not applicable.

Consent to publication Not applicable.

Competing interests The authors declare no competing interests.

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