PAN
POLSKA AKADEMIA NAUK
JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
ITP-PIB
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2025.156035
2025, No. 67 (X–XII): 9–15

The assessment of GHG emissions from the cultivation of feedstocks for biofuel production in Poland

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RECEIVED 09.05.2025 ACCEPTED 14.08.2025 AVAILABLE ONLINE 29.10.2025

Abstract: The shift towards renewable energy sources (RES) is crucial for promoting sustainable growth in the EU, aiming to achieve at least a 42.5% contribution of RES to gross final energy consumption by 2030. The transportation sector must also adhere to emission reduction targets, owing to its significant contribution to greenhouse gas (GHG) emissions. This research examines the GHG emissions linked to the cultivation of feedstocks for biofuel production in Poland, specifically analysing wheat, triticale, rye, and maize. To assess and delineate the GHG emissions throughout the lifecycle of biomass production on selected Polish farms, the methodology endorsed by the Polish certification framework for sustainable biofuels and bioliquids (KZR INiG system) was employed, as validated by the European Commission. Data were gathered from 294 questionnaires distributed across large-scale agricultural operations in 91 diverse locations throughout Poland. Findings reveal that emissions varied from 14.3 g $CO_{2eq}·kg^{-1}$ for maize to 386.5 g $CO_{2eq}·kg^{-1}$ for triticale. The highest average emissions were recorded for wheat at 115.0 g $CO_{2eq}·kg^{-1}$, followed closely by rye at 113.8 g $CO_{2eq}·kg^{-1}$, triticale at 108.7 g $CO_{2eq}·kg^{-1}$, and maize at 81.8 g $CO_{2eq}·kg^{-1}$. Primary sources of emissions included the fuel consumption of farming machinery, the production of fertilisers and pesticides, and soil emissions resulting from crop cultivation, which collectively accounted for 80–87% of total emissions, depending on the crop. The kind and amount of fertilisers used significantly influenced emissions. Furthermore, it was observed that lower crop yields were associated with elevated GHG emissions per unit of biomass produced.

Keywords: biofuels, biomass, cultivation, emissions, greenhouse gases, plants, Poland

INTRODUCTION

Utilising renewable energy sources (RES) is a key element of sustainable development, yielding significant economic, ecological, and social benefits. Promoting the use of RES has become a fundamental goal within the European Union (Blok, 2006; Paska, Sałek and Surma, 2009; Grzebyk and Stec, 2023; Osuma and Yusuf, 2025). As outlined in the Renewable Energy Directive III (Directive, 2023), the target for the share of renewable energy in the EU's gross final energy consumption is at a minimum of 42.5% by 2030. The directive also emphasises increasing renewable energy usage and reducing greenhouse gas (GHG) intensity in the transportation sector. Each member state must mandate fuel suppliers to ensure that the volume of renewable fuels and renewable electricity provided to the transport sector contributes to at least 29% of renewable energy in the sector's final energy

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consumption by 2030. Additionally, there is a target for a GHG intensity reduction of at least 14.5% by the same year.

The innovative and technical activities specified in the Strategy for Sustainable Transport Development until 2030 in Poland (Ministerstwo Infrastruktury, 2019) include, among others, the use of second- and third-generation fuels and biofuels with biocomponents. Second-generation biofuels are based on biochemical or thermochemical processes to convert agricultural lignocellulosic biomass to fuels. Lignocellulosic feedstocks for second-generation biofuels include by-products (e.g., cereal straw, agricultural and forest residues), wastes, and dedicated feedstocks (purpose-grown vegetative grasses, short rotation forests, and other energy crops). Third-generation biofuels are primarily derived from algae and cyanobacteria, which can produce alcohols and lipids for biofuel production. Marine biomasses such as seaweed, hyacinth, diatoms, duckweed, kelp, and salvinia are particularly promising for producing biofuels, especially biodiesel. The latest biofuel generation, termed fourth-generation biofuels, encompasses genetic engineering to increase desired traits of organisms used in biofuel production. These are based on petroleum-like hydroprocessing, oxy-fuel combustion, or thermochemical processes and focus on genetically optimised feedstocks geared towards capturing and storing carbon at the feedstock level and during processing technology (Renzaho, Kamara and Toole, 2017; Cavelius *et al*., 2023). According to the Energy Policy of Poland until 2040 (Ministry of Climate and Environment, 2021), Poland declares a 14% share of renewable energy in transport in 2030, as well as an increase in the use of advanced biofuels in this sector and electromobility.

Biomass plays a crucial role in the EU's policy support for renewable energy sources (RES), where specific targets serve as key drivers alongside comprehensive biomass guidelines that address environmental constraints (Banja *et al*., 2019). To evaluate the effectiveness of the criterion regarding GHG emission reduction associated with biofuels, bioliquids, and biomass-derived fuels, it is essential to understand the GHG emissions generated throughout their entire lifecycle, including those linked to the cultivation of raw materials. This study aims to estimate the GHG emissions from the cultivation of selected crops (wheat, triticale, rye, and maize) used for biofuel production in Poland and to analyse the emission structure from biomass production. The study is based on the premise that emissions from the cultivation of raw materials constitute a significant portion of the total GHG emissions in the biofuels' lifecycle.

STUDY MATERIALS AND METHODS

STUDY MATERIALS

The study covered large-scale farms in 91 locations, from nine voivodeships (acc. to Nomenclature of Territorial Units for Statistics – NUTS level 2), mainly from the northwestern part of Poland and the central and southern parts (Fig. 1). More than half of the locations (50) are located in the West Pomeranian Voivodeship, 9 of them in the Kuyavian-Pomeranian Voivodeship, 8 each in the Lubusz and Greater Poland Voivodeships, 6 in the Pomeranian Voivodeship, 4 in the Lodz Voivodeship, 3 in the Lower Silesian Voivodeship, 2 in the Lesser Poland Voivodeship and 1 in the Subcarpathian Voivodeship.

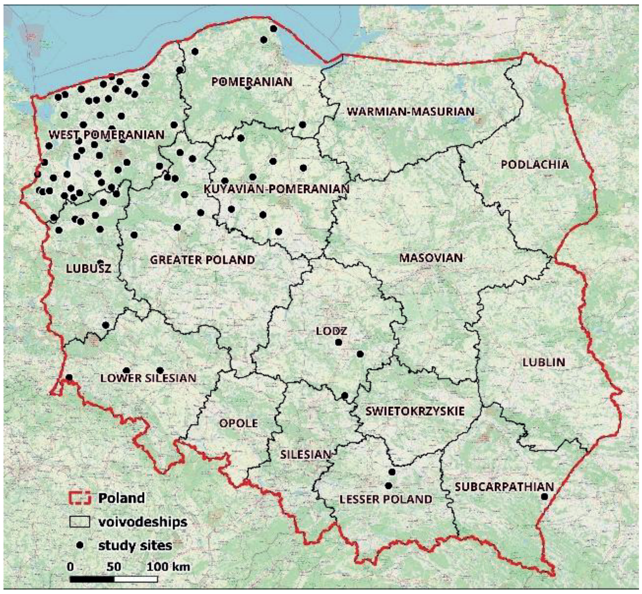

Fig. 1. Location of study farms; source: own elaboration

The farms included in the study exhibit varying natural conditions for agricultural production. The area under investigation is situated within a temperate warm transitional climate zone, influenced by air masses from the Atlantic Ocean and the continental Eurasian landmass. The average annual precipitation totals range from approximately 500 to 650 mm. The number of days with precipitation (>0.1 mm) varies, with about 150 days per year recorded on the Inowrocław Plain and Kuyavian Lakeland, and up to 180 days on the Szczecin Coastland and Koszalin Coastland (Błażejczyk, 2006; Solon *et al*., 2018). The soil cover of the studied area is dominated by Brunic Arenosols, Cambisols, Haplic Luvisols, and Podzols. The Fluvisols occur in river valleys (Kabała *et al*., 2019). The farms selected for the study are located in areas with the highest share of cereals and a high share of rapeseed in the sown area (Bański, 2010). However, they are representative of broader regions, if only because of the varying quality index of the agricultural production space (Stuczyński *et al*., 2007).

The study utilised surveys collected from agricultural producers of raw materials for biofuel production. Two hundred ninety-four surveys were received, comprising 90 for triticale, 82 for wheat, 68 for maize, and 54 for rye. The surveys provided information on the cultivation area, types and quantities of fertilisers used, names and amounts of plant protection products (pesticides), seed quantities, fuel consumption for agricultural machinery, and other energy sources utilised during cultivation. This data was essential for calculating the GHG emissions associated with the cultivation of raw materials.

STUDY METHODS

The estimation of GHG emissions resulting from the cultivation of raw materials for biofuel production on the farms above was conducted following the methodology recommended by the KZR INiG system (INiG, 2023). This Polish certification system is designed for the sustainable production of biofuels, bioliquids, and raw materials and is managed by the Oil and Gas Institute – National Research Institute (Pol.: Instytut Nafty i Gazu – Państwowy Instytut Badawczy). The European Commission

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endorsed this system in 2014 to demonstrate compliance with sustainability criteria. The detailed rules used for calculating GHG emissions, adopted by the KZR INiG system, are consistent with the methodology of Directive (EU) 2018/2001 of the European Parliament and the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (Directive, 2018) and are intended to ensure that economic entities provide accurate data on GHG from biofuels, biomass fuels and bioliquids.

The methodology for calculating GHG emissions for biomass grown mainly for broadly understood energy purposes is specified in Directive (EU) 2018/2001 of the European Parliament and the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (Directive, 2018), as well as in Commission Implementing Regulation (EU) 2022/996 of 14 June 2022 on rules to verify sustainability and greenhouse gas emissions saving criteria and low indirect land-use change-risk criteria (Commission Implementing Regulation, 2022). Following the above documents, GHG emissions from the biomass cultivation stage are calculated by the following formula:

$$e_{\mathrm{ec}} = e_{\mathrm{seed}} + e_{\mathrm{chem}} + e_{\mathrm{lim}} + e_{\mathrm{field}} + e_{\mathrm{mm}} \tag{1}$$

where: e_{ec} = emissions from the cultivation of feedstocks (g CO_{2eq}·kg^{-1} dry mass); e_{seed} = GHG emissions from the production of seeding material for crop cultivation; e_{chem} = GHG emissions from the production of fertilisers and pesticides; e_{lim} = GHG emissions from fertiliser acidification and liming application; e_{field} = soil emissions from crop cultivation; e_{mm} = GHG emissions from the provision of the fuels for farm machinery used.

Emissions from the production of seeding material for crop cultivation include emissions generated during the production, storage, and transport of seeds. The default values for emission factors set out in Annex IX of Regulation 2022/996 (Commission Implementing Regulation, 2022) should be used to estimate the GHG emissions associated with seed. For the crops analysed in this paper, these coefficients (in g CO_{2eq}·kg^{-1}) are: 310.6 for maize seed, 283.9 for wheat seed, 312.1 for rye seed, and 300.2 for triticale seed.

GHG emissions from fertiliser and pesticide production (including herbicides, insecticides, fungicides, etc.) include all related emissions caused by chemical fertilisers and pesticides (Bouter *et al.*, 2025). Fertiliser and plant protection product application rates depend on, among other things, the type of crop, climate, soil conditions, and agricultural practices. Emissions related to fertilisation have the largest share in the total carbon footprint associated with crop cultivation. The selection of fertiliser types (especially nitrogen fertilisers) and the correct, balanced application rate will impact the possibility of reducing emissions from the life cycle of a given crop. GHG emissions associated with the use of fertilisers and plant protection products are calculated using the following formula:

$$e_{\mathrm{chem}} = Q_{\mathrm{chem}} \cdot F_{\mathrm{chem}} \tag{2}$$

where: e_{chem} = GHG emissions from chemical fertilisers and pesticides; Q_{chem} = quantity of fertiliser or agrochemical applied per unit of land area; F_{chem} = GHG intensity (emission factor) of fertiliser or agrochemical production and transport, expressed in mass of CO_{2eq} per unit of fertiliser or agrochemical.

The emission factors for fertilisers and plant protection products used in the calculations are presented in Table 1.

Table 1. Greenhouse gas (GHG) emission factor for fertiliser or plant protection products

Type of fertiliser	GHG emission factor (g CO_{2eq}·kg^{-1})
Ammonium nitrate (AN)	3 469
Ammonium sulphate (AS)	2 724
Ammonium nitrate sulphate (ANS)	3 162
Anhydrous ammonia	2 832
Calcium ammonium nitrate (CAN)	3 670
Calcium nitrate (CN)	4 348
Urea	1 935
Urea ammonium nitrate (UAN)	1 935
Triple superphosphate (TSP)	544
Rock phosphate 21% P_2O_5 23% SO_3	95
Mono ammonium phosphate (MAP) 11% N 52% P_2O_5	1 029
Diammonium phosphate (DAP) 18% N 46% P_2O_5	1 552
Muriate of potash (MOP) 60% K_2O	413
NPK 15-15-15	5 013
MgO (kg MgO)	769
Sodium (Na) fertiliser (kg Na)	1 620
CaO-fertiliser (calculated as kg $CaCO_3$)	39.1
Plant protection product	12 011

Source: own elaboration based on Commission Implementing Regulation (2022), BioGrace-II (2024).

Emissions resulting from acidification from using nitrogen fertilisers in the field will be included in the emission calculations based on the quantity of nitrogen fertilisers applied. For nitrate fertilisers, the nitrogen neutralisation emissions in the soil are set at 0.806 kg CO_2 per kg of nitrogen (N). For urea fertilisers, the neutralisation emissions are calculated at 0.783 kg CO_2 per kg of nitrogen (N) (Commission Implementing Regulation, 2025). Regarding soil emissions from liming (using aglime), the amount of aglime utilised must be documented appropriately. Emissions will be calculated as follows:
- in acid soils with a pH of less than 6.4, aglime is dissolved by soil acids, predominantly producing CO_2 rather than bicarbonate, resulting in the release of nearly all the CO_2 from the aglime (0.44 kg CO_2 per kg of $CaCO_{3eq}$ aglime).
- for soils with a pH of 6.4 or higher, an emission factor of 0.98/12.44 = 0.079 kg CO_2 per kg of $CaCO_{3eq}$ aglime applied should be included in the calculation, in addition to the emissions resulting from the neutralisation of acidification caused by the fertiliser.

Per the European Commission (Edwards *et al.*, 2019) recommendation and KZR INiG system guidelines (INiG, 2023),

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the Intergovernmental Panel on Climate Change (IPCC) methodology can account for N_2O emissions from soils, including both direct and indirect emissions. This paper uses the BioGrace-II (2024) tool, which is used to calculate N_2O emissions for crops used as feedstock for biofuel production, using the IPCC (2006; 2019) methodology and data (Besseau, Hurtig and Scarlat, 2025). The input data required for the calculations includes, among others, the crop type, crop yield, moisture content, irrigation details, the amount of fertilisers applied, and information regarding post-harvest residues. This tool following three N_2O emission sources that occur during the agricultural step: direct N_2O emissions from the field (from the application of mineral and organic fertiliser and from above and below ground residues), indirect N_2O emissions due to leaching and runoff and indirect N_2O emissions due to NH_3 and NO_x volatilisation. The parameters necessary to estimate the nitrogen input from crop residues are defined in the Joint Research Centre report (Edwards *et al.*, 2019).

Emissions from fuel (diesel oil, gasoline, heavy fuel oil, biofuels, or other fuel) use in agricultural machinery are calculated according to the equation:

$$e_{\mathrm{mm}} = Q_{\mathrm{mmf}} \cdot F_{\mathrm{t}} \tag{3}$$

where: e_{mm} = emissions from use of agricultural vehicles, expressed as CO_{2eq} per unit area per year; Q_{mmf} = fuel consumption of agricultural machinery, expressed in units of mass, volume or energy per unit area per year; F_{t} = GHG emission factor from fuel production and consumption, expressed as CO_{2eq} per fuel unit (energy).

Emission factors for fuels are utilised to calculate emissions from agricultural machinery, as outlined in Annex IX of the Commission Implementing Regulation (2022). When biofuels are employed, the default values specified in Directive (2018) are applied.

RESULTS AND DISCUSSION

The estimated emissions from biomass production on the farms studied ranged from 14.3 g $CO_{2eq}·kg^{-1}$ of dry matter for maize cultivation to 386.5 g $CO_{2eq}·kg^{-1}$ for triticale cultivation. The relatively low emission value for maize in the farm located in Inowrocław (Kuyavian-Pomeranian Voivodeship) is primarily due to the absence of mineral fertilisers during the cultivation stage. In contrast, the highest GHG emissions associated with triticale cultivation on a farm in Kicko (West Pomeranian Voivodeship) are primarily attributed to the amount of fertilisers used and a relatively high field emission of nitrous oxide (expressed as g $CO_{2eq}·ha^{-1}$), which was estimated at 661,794 g $CO_{2eq}·ha^{-1}$ using the BioGrace-II tool. Moreover, the highest variability of emissions for triticale (the difference between the highest and lowest emissions is 340.0 g $CO_{2eq}·kg^{-1}$) results primarily from significant differences in yields and the use of mineral fertilisers on individual farms. The average GHG emissions from biomass production are highest for wheat cultivation at 115.0 g $CO_{2eq}·kg^{-1}$. Rye follows with an average emission of 113.8 g $CO_{2eq}·kg^{-1}$, while triticale and maize have lower averages of 108.7 g $CO_{2eq}·kg^{-1}$ and 81.8 g $CO_{2eq}·kg^{-1}$, respectively (Fig. 2).

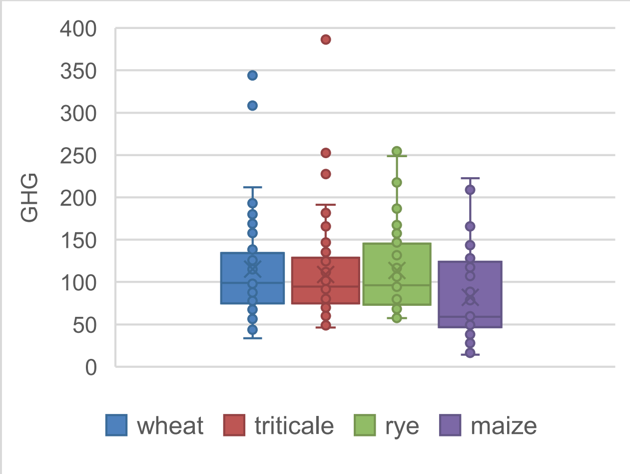

Fig. 2. Boxplots illustrating the range of greenhouse gas (GHG) emissions from the cultivation of feedstocks for biofuel production (in g $CO_{2eq}·kg^{-1}$), including the average and median values; source: own elaboration

The observed sequence of GHG emissions from the cultivation of wheat, rye, triticale, and maize aligns with the findings of Rajaniemi, Mikkola and Ahokas (2011) and Sapkota *et al.* (2018). However, Tongwane *et al.* (2016), in their study of GHG emissions from various crop production and management practices in South Africa, reported emissions from maize cultivation that were nearly 50% higher than those from wheat. The highest average field emissions (e_{field}) are recorded for maize at 171,258 g $CO_{2eq}·ha^{-1}$, followed by wheat at 117,644 g $CO_{2eq}·ha^{-1}$, rye at 103,048 g $CO_{2eq}·ha^{-1}$, and triticale at 73,720 g $CO_{2eq}·ha^{-1}$. It is important to note that other studies have also identified maize cultivation as having the highest field emissions, particularly in comparison to winter wheat, spring wheat, winter rapeseed, and sugar beet in an arable farm in eastern Poland, as assessed using the Global Nitrous Oxide Calculator (GNOC tool) by Syp, Gębka and Żukiewicz (2016). Conversely, Jarosz and Faber (2016a), while estimating GHG emissions from wheat, maize, and rapeseed cultivation using the BioGrace calculator, found that rapeseed cultivation produced the highest N_2O emissions, followed by wheat and maize. In a case study in Eastern Romania (Brinkman *et al.*, 2018), rapeseed biodiesel potential and GHG emissions were calculated for four scenarios. It was found that indirect land-use change can severely impact the GHG balance of biofuels.

The calculations show that emissions from the provision of the fuels for farm machinery used (e_{mm}), from the production and transport of fertilisers and agrochemicals (e_{chem}), as well as field emissions of nitrous oxide (e_{field}), are the key components of GHG emissions from biomass production. The dominant share of these sources in the structure of GHG emission is characteristic for all the examined crops and amounts on average to 39.5% for rye, 39.4% for triticale, 34.0% for wheat, and 30.8% for maize in the case of emission from fuel use in agricultural machinery, as well to 34.5% for maize, 33.5% for wheat, 29.6% for rye, and 29.2% for triticale in the case of emission from the chemical fertilisers and pesticides. In the case of soil emissions from crop cultivation, its share in total emissions is 21.3% for maize, 15.8% for rye, 14.9% for wheat, and 11.2% for triticale. For comparison, the analysis of GHG emissions in winter wheat farms conducted by Syp *et al.* (2015) in south-central Poland indicates that field

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N_2O emissions accounted for the largest share of total emissions (49–52%), followed by nitrogen fertilisers (31–33%) and diesel fuel (11–13%). Similarly, Brock *et al.* (2012), in their research on GHG emissions from the production of 1 Mg of wheat (considering the entire life cycle) in the Central Zone (East) of New South Wales, found that 54.7% of emissions occur on the farm, with 25.7% attributed to fertilisers and 13.5% resulting from the combustion of diesel in tractors and harvesters. Konieczna *et al.* (2021), based on research from 13 operating family farms ranging in size from 2 to 13 ha, located in the Podlachia Voivodship (podlaskie) in Poland, found that the most substantial impact on the environment, due to the GHG emissions to the atmosphere, thus contributing to the greenhouse effect, is due N fertilisation, both mineral and natural. On average, 61% of the total GHG emissions came from fertilisation in the technologies studied by these authors. The variability in these data arises from various factors related to weather and management practices, including local rainfall and temperature, timing and frequency of irrigation, the history and method of fertiliser application, and the type of crops and soil management employed (Bouwman, 1996; Wiśniewski, 2019). The cultivation stage carries the largest share of overall GHG emissions and comprises the biggest differences also in the study by Bouter *et al.* (2025). Therefore, utilising an appropriate tool for estimating emissions from cultivation is crucial. Enhancing the accuracy of field emission estimations is vital for reducing agricultural emissions throughout the entire life cycle of biofuels (Jarosz and Faber, 2016b; Wiśniewski and Kistowski, 2020; Bouter, Duval-Dachary and Besseau, 2024).

When considering the emissions associated with the production and transport of fertilisers and agrochemicals, it is essential to recognise that both the amount of fertilisers applied and their type (including manufacturer, composition, and emission factor) significantly influence the overall GHG emissions from biomass production. Consequently, it is essential to enhance farmers' awareness of these factors and encourage fertiliser manufacturers to focus more on reducing GHG emissions (Rogowska, 2017). Additionally, it is necessary to analyse how existing eco-innovations in the fertiliser sector could potentially reduce the carbon footprint of fertilisers without negatively impacting crop productivity.

The average share of emissions from fertiliser acidification and liming application (e_{lim}) in the total emissions from raw material cultivation is 11.9% for triticale, 11.3% for maize, 11.2% for wheat, and 9.1% for rye. The overall GHG emissions from biomass production are significantly less influenced by emissions resulting from seed production, storage, and transport (e_{seed}). The average contribution of these emissions to the total emissions from cultivation is 7.3% for triticale, 5.5% for wheat, 4.6% for rye, and 1.0% for maize. For comparison, research on yield gaps and ecological footprints of potato production systems in Chile by Haverkort, Sandaña and Kalazich (2014) showed that main sources of emission (75%) were those related to fertiliser production (35%), fertiliser-induced field emission (25%), and seed production (15%).

It is important to note that individual crops' yield levels also impact biomass production's GHG emissions. Calculations and studies conducted by other researchers (Brock *et al.*, 2012; Skowrońska and Filipek, 2014; Jarosz, Księżak and Faber, 2017) indicate that lower yields lead to an increase in estimated GHG emissions associated with the cultivation of feedstocks, expressed per unit of dry matter.

The results presented in this article estimate GHG emissions associated with the cultivation of raw materials for biofuel production using the methodology described in the paper, which requires verification and comparison with values measured during the field study (field emission). The co-authors of this article are currently conducting such research, and their results will be published in a subsequent article. These studies consider the temporal variability of environmental conditions and agricultural practices (e.g., no-till farming and conventional tillage), which will also allow for long-term forecasts.

CONCLUSIONS

Key contributors to the greenhouse gas (GHG) emissions profile include emissions from fuel used in agricultural machinery, emissions from chemical fertilisers and pesticides, and soil emissions from crop cultivation, which collectively account for a dominant part (80–87%) of total emissions across all examined biofuel crops. The dominance of these sources underscores the importance of targeted interventions in agricultural practices to mitigate GHG emissions. Moreover, the results indicate that the type and dosage of fertilisers play a crucial role in determining the carbon footprint of biomass production. This necessitates a shift towards greater awareness among farmers regarding fertiliser usage and the exploration of eco-innovations that can reduce GHG emissions without compromising crop yields. The emissions produced during seed production, storage, and transportation stages have a significantly lesser impact on the total GHG emissions associated with the cultivation of raw materials for biofuel production. Additionally, crop yield plays an essential role in the results observed; a decrease in yield leads to an increase in the estimated GHG emissions from biomass production.

The results of this study offer valuable insights into the extent and composition of GHG emissions from feedstocks, underscoring essential areas for enhancement and the potential for innovative practices within agricultural management. Future research should focus on refining emission estimation tools (including long-term projections) and exploring sustainable farming practices that can effectively reduce the GHG emissions from the cultivation of raw materials for biofuel production while maintaining productivity.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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