



Environmental assessment of giant reed and Miscanthus for bioethanol and biomethane production on Italian marginal lands

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ABSTRACT

The Revised Directive EU/2023/2413 sets ambitious goals for 2030, requiring at least 42.5% of energy consumption to be supplied by renewable sources. Meeting bioenergy targets requires land allocation strategies that avoid significant competition with food production. In this context, marginal lands represent a promising solution for the cultivation of non-food energy crops, such as perennial grasses. However, assessment methods are essential to drive policymakers in land planning scenarios. This study proposes a cradle-to-gate life cycle assessment built on top of the ARUNGRO crop model to compare the environmental impacts of two lignocellulosic energy crops - giant reed and Miscanthus - from cultivation to the production of ethanol and biomethane. The experimental datasets represent three provinces in northern, central, and southern Italy, areas with a large extent of marginal lands and characterized by pedo-climatic and crop productivity constraints. The environmental footprint results of the agricultural phase, expressed per Mg of dry-weight biomass, identified land use change and human toxicity (carcinogenic) as the main hotspot impact categories out of sixteen, largely associated with annual harvesting operation for perennial grasses. Per GJ basis, biomethane outperforms ethanol, with central Italy showing the most favourable performance for both biofuels. The case study explores a projected 2044 deployment scenario, providing valuable insights into long-term environmental performance of perennial energy crops over 20-years. Overall, the findings highlight the importance of energy species production in marginal lands as optimal solutions for inedible feedstock intended for energy production. Policy reflections are offered at both European and national levels.

1. Introduction

Global greenhouse gas (GHG) emissions have risen due to unsustainable human activities connected to fossil demand, land use, and land-use change practices [1]. To reduce fossil energy dependence, ambitious policy targets have been set by governments for the adoption of renewable energy systems [2]. Within renewable sources, bioenergy, derived from organic materials and commonly referred to as biomass, represents over 6% of the global energy supply and accounts for 55% of the renewables sector, being acknowledged as a key energy source [3].

The sustainability performance of bioenergy systems depends critically on feedstock type and origin. Biomass can be sourced from edible

(food crops) or inedible feedstocks (lignocellulosic residues) [4], and converted into biofuels, biogas, heat, or electricity [5]. However, increased demand for agricultural biomass can exacerbate competition for land and water [6], induce indirect land-use change (iLUC) and deforestation [7], and contribute to higher food prices, underscoring the critical importance of land-use allocation in bioenergy strategies [8].

Marginal lands (MLs) offer a sustainable solution for growing energy crops while solving the food competition [9]. Yet a unified definition and classification is still debated across institutional and scientific domains (e.g., EEA, OECD, CGIAR, World Bank). MLs are areas where conventional agriculture is constrained by factors such as shallow soils, erosion risk, salinity, poor fertility, or limited access to irrigation and mechanization [10]. Despite progress, comprehensive and spatially

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Glossary			
AC	Acidification	GJ	Gigajoule
BioMA	Biophysical Model Applications	HT-c	Human Toxicity - carcinogenic
BO	Bologna	HT-nc	Human Toxicity - non-carcinogenic
CAP	Common Agricultural Policy	ICs	Impact Categories
CC	Climate Change	iLUC	indirect Land Use Change
CT	Catania	LCA	Life Cycle Assessment
EC	Ecotoxicity Freshwater	LCI	Life Cycle Inventory
EF	Environmental Footprint	LU	Land Use
ER	Energy Resources non-renewable	Mg	Megagrams
EU-f	Eutrophication - freshwater	MLs	Marginal lands
EU-m	Eutrophication - marine	OAT	one-at-a-time
EU-t	Eutrophication - terrestrial	PEF	Product Environmental Footprint
FU	Functional Unit	PI	Pisa
GHG	Global Greenhouse Gas	PO	Photochemical Oxidant Formation
		RED	Renewable Energy Directive
		SM	Supplementary Materials

coherent integrative database combining agronomic, economic, and infrastructural criteria remains scarce to date. A promising direction involves combining structural and economic criteria—such as land profitability, irrigation availability, and mechanization feasibility—beyond pedological degradation. In Italy, this concept has been operationalized through a validated dataset [10,11] and is implemented for spatially explicit crop modelling by Cappelli et al. [12]. Within this framework, MLs are characterized by low agricultural value, high risk of abandonment, and often low suitability for food production due to natural constraints or intensive human activities [10].

In MLs, perennial energy species are optimal as inedible feedstock. They are considered more environmentally friendly than edible ones since they require reduced inputs for growth [13]. Among permanent energy species, perennial energy grasses such as giant reed (*Arundo donax* L.) or Miscanthus (*Miscanthus x giganteus* Greef et Deu.) are proven to have several environmental and economic advantages [14]. Their high productivity under nutrient-poor, dry and/or degraded soils coupled with lower inputs and cost requirements, supports their high feasibility in Mediterranean contexts [15]. In degraded areas, additional co-benefits include nitrates scavenging close to polluted water [16] or carbon sequestration [17].

Conversion of perennial energy grasses to biomethane and bioethanol relies on established biochemical routes. Biomethane is typically produced via anaerobic digestion of whole or mechanically processed biomass, with conversion efficiency driven by volatile solids content, lignocellulosic accessibility, and harvest timing [18]. For giant reed and Miscanthus, reported methane yields exhibit consistently low variability across studies, even under differing reactor configurations and pretreatment intensities. Bioethanol production involves pretreatment, enzymatic hydrolysis, and fermentation. A wide range of pretreatment technologies—such as dilute acid, alkaline treatments, and steam explosion—have been investigated to enhance fermentable sugar recovery [19]. High ethanol yields have been reported under optimized laboratory settings for giant reed and Miscanthus [20,21]. These studies reflect optimized experimental configurations and provide insights into potential upper-bound performances, while remaining consistent in magnitude with the broader range of values reported in the literature. In addition, recent research advances in pretreatment, saccharification efficiency, and process optimization for perennial grasses have been reported [22]. Further improvements—such as advanced saccharification pathways—have been demonstrated for Miscanthus under optimized conditions [23]. However, such configurations are not yet representative of commercially deployed systems at regional scale and therefore remain difficult to integrate consistently into spatially explicit assessments. Owing to heterogeneous technologies, large-scale analyses typically rely on literature-based average conversion coefficients to

ensure comparable bioenergy yield estimates [12].

To assess bioenergy systems comprehensively along their supply chain [24], a particularly suited tool is life cycle assessment (LCA), a widely recognized approach to perform environmental analysis. The interpretation of LCA results identifies trade-off identification and potential burden shifting. It provides scientific evidence-based solutions to policymakers [25] and supports land use planning scenarios [26]. As such, LCA is even reported in the EU Renewable Energy Directive (RED) [27] as the main tool to perform environmental analyses.

A wide range of feedstocks and conversion pathways has been evaluated across different regions using LCA. In agricultural systems, López i Losada et al. [28] assess the introduction of grass leys in Swedish crop rotations through an agent based LCA, while Parajuli et al. [29] evaluate a mixed crop–livestock system integrated with a green biorefinery. Clarke et al. [30] assess the environmental impacts of the cultivation of bioenergy crops in Ireland focusing on land-use change with the support of Geographic Information System (GIS). Morales et al. [31] review 60 LCA studies on lignocellulosic feedstocks—including dedicated crops, agricultural and forest residues, and municipal waste—mainly from Europe and North America, with additional studies from other regions such as Asia, Africa, and Latin America. In addition, recent works have increasingly focused on marginal lands. Córdoba et al. [18] analyse methane potential of energy crop in the Argentine Pampas under rainfed conditions, focusing on harvest timing and ensiling. Yu et al. [32] provide a global assessment of *Jatropha curcas*, whereas Liang et al. [33] evaluate the sustainability of sorghum, switchgrass, and reed canary grass in China. Liu et al. [34] propose a modelling framework for assessing economic–environmental performance of energy crops in the northeastern United States.

Despite the broad range of biomass sources assessed, substantial attention continues to focus on Miscanthus [33–37] and giant reed [18, 38–40] in different conversion pathways.

Although the scientific literature on bioenergy production from perennial energy grasses and the associated LCA has been broadly investigated (see Table S1 in Supplementary Materials (SM)) [13], several gaps persist. Reported results still show high variability based on the modelling choices, the system boundary definition, and the impact assessment [41]. Energy balance and GHG emissions dominate the literature, while other impact categories (ICs) - such as acidification, eutrophication, and ecotoxicity - receive less attention despite their sensitivity to feedstock characteristics (Morales et al., 2014; [42]). Moreover, LCAs of giant reed and Miscanthus have typically focused on single conversion pathways, often a pilot scale, limiting the comparability of results across contexts, technologies and crops [43]. Integrated studies combining spatially explicit crop simulations with LCA assessments remain rare, especially for perennial energy grasses cultivated in

real MLs under structural and agronomic constraints [14].

Addressing these limitations, the present study advances the literature by integrating spatially explicit crop simulations on MLs with cradle-to-gate LCA to compare ethanol and biomethane from giant reed and Miscanthus across three Italian NUTS-3 (nomenclature of territorial units for statistics) provinces (Bologna, Pisa, and Catania). It provides (i) a consistent comparison of ethanol and biomethane production due to heterogeneous conversion coefficients; (ii) geographically explicit inventories grounded in a MLs dataset [10,11] and ARUNGRO-based primary agronomic inputs [12,14]; and (iii) an impact profile beyond energy balance and GHG, including acidification, eutrophication, and ecotoxicity, using the Environmental Footprint (EF) 3.1 method. By jointly analysing bioenergy production for giant reed and Miscanthus on real MLs, the study quantifies trade-offs and identifies conditions under which one route outperforms the other, thereby supporting land-use planning and bioenergy policy at sub-regional scale. The investigation spans a timeframe of 20 years, consistent with the techno-economic estimation of the cropping system and enabling appraisal of both short- and medium-term viewpoint.

2. Material and methods

This study introduces a method for applying ARUNGRO cropping model results in an LCA analysis to assess the productivity and environmental impacts of giant reed and Miscanthus across their supply chains in MLs. Hence, the following section describes the case study and provides insights of ARUNGRO simulation model from Cappelli et al. [12]. Following, the LCA phases of goal and scope, inventory, and impact assessment are presented. The results and discussion section provides the last LCA phase of interpretation.

2.1. Previous knowledge on the case study

The analysis focuses on giant reed and Miscanthus production in MLs of three Italian NUTS provinces of Bologna (BO, Emilia-Romagna), Pisa (PI, Tuscany), and Catania (CT, Sicily) – see Fig. 1. Field data on crop yields derives from Cappelli et al. [12] in which experimental datapoints of daily simulation growth are modelled by ARUNGRO [44] process-based model considering soil water availability and management practices (i.e., stand density, transplanting, and cutting times). The

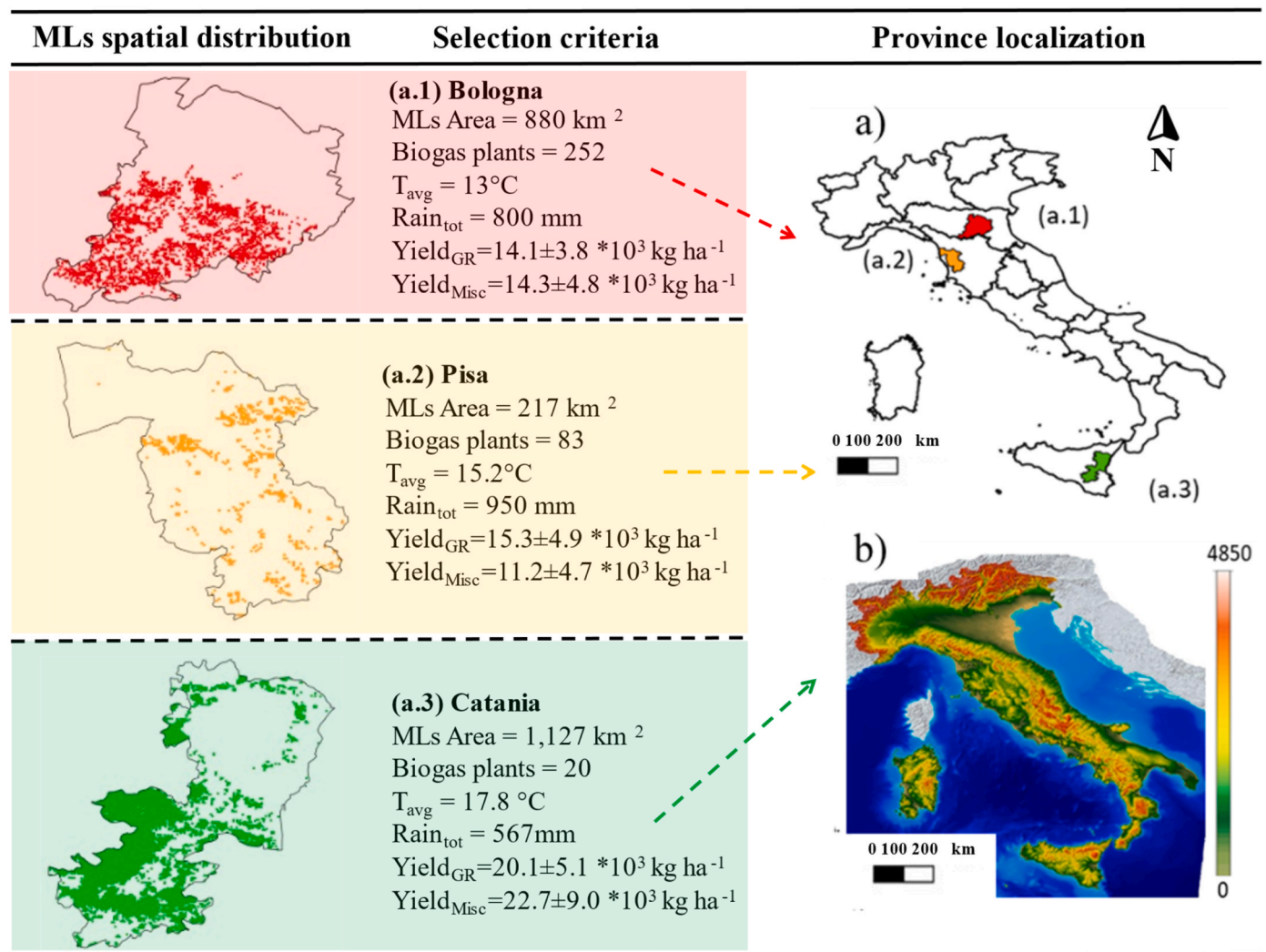


Fig. 1. Distribution of Marginal lands (MLs) of Bologna (a.1, red), Pisa (a.2, orange) and Catania (a.3, green) provinces (a) and elevation (b, m). MLs=marginal lands; T_{avg}=Mean air temperature; Rain_{tot}=Mean cumulative annual rainfall.; Yield_{GR}=Giant reed; Yield_{Misc}=Miscanthus. T_{avg}, Rain_{Tot}, Yield_{GR} and Yield_{Misc}. *NOTE: Data source derived from the national marginality dataset developed by Sallustio et al. [10,11] within the AGROENER project and processed in Cappelli et al. [12] by averaging all grid cells within each selected province. Finally, the extent of marginal land was quantified using QGIS, based on the number of raster cells classified as marginal within each provincial boundary. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cropping system is divided into different domain-specific compartments (e.g., crop, soil, agro-management) and combined into more complex simulation chains targeting specific modelling objectives (Fig. S1 in SM). The ARUNGRO model is a point-scale, process-based crop simulator operating on a daily time step. It simulates phenological development, canopy expansion, soil water balance, and biomass accumulation based on weather, soil, and management inputs. The model can run under water-limited or fully irrigated conditions and accounts for interactions between plant physiology and abiotic constraints. It supports gridded applications and multi-year, multi-site calibration routines across diverse climatic zones, making it suitable for simulations under both current and future climate scenarios. Although ARUNGRO is specifically calibrated for giant reed and Miscanthus, its structure allows adaptation to other perennial non-food crops with similar morpho-physiological characteristics. Full details of model calibration, validation, and gridded deployment are provided in Cappelli et al. [12]. The calibrated model is then connected to a spatially explicit database, with data on i) current climate ii) agronomic practices, iii) soil physics and hydrology, iv) MLs and v) crop suitability to environment and simulations are performed at 500×500 m spatial resolution across Italy (zenodo.org; [12]). Future yield simulations were based on 30-year bias-corrected daily climate series centered on 2030 and 2050, generated using the ETHZ-CLM-HadCM3Q0 regional climate model [14]. The scenario is consistent in magnitude and direction with RCP 8.5 projections for the study area [45,46], assuming $+2$ to $+3$ °C mean air temperature increases and seasonal (April–September) rainfall reductions up to -30% compared to the 1985–2014 baseline.

BO lies within one of the most active and consolidated bioenergy districts in Italy (252 biogas plants in the region), which has been developed over the last 20 years, due to RED [47] and nitrate [48] directives. The province includes a total ML area of 880 km^2 (88,000 ha). The climate is temperate sub-continental, with high temperatures and uniform precipitation during the year. The mean annual temperature is around 13 °C, with a range of $0\text{--}5$ °C in winter, and above 30 °C in the summer. The total amount of annual rainfall is around $700\text{--}900$ mm, with a minimum in summer. Soil types are mostly for clay and silty loam, with relatively high-water holding capacity. The mean productivity of rainfed giant reed and Miscanthus is 14.1 ± 3.8 and $14.3 \pm 4.8 \text{ Mg ha}^{-1}$ respectively [12].

PI has 83 operating biogas plants, with most of them generating less than 1 MWe of electric power, and 217 km^2 (21,700) of MLs. The climate is Mediterranean, characterized by warm dry summers and cool wet winters (mean annual temperature of 15.2 °C). Annual cumulative rainfall is about $900\text{--}1000$ mm, and precipitation events occur mainly from autumn to spring. Soil types include silt loam, clay loam, loam, sandy clay, silt clay, and clay. The average rainfed yield is $20.1 \pm 5.1 \text{ Mg ha}^{-1}$ for giant reed and $22.7 \pm 9 \text{ Mg ha}^{-1}$ for Miscanthus [12].

CT has 20 biogas plants and 1127 km^2 (112,700ha) of MLs. The climate is Mediterranean, with an average annual temperature of 17.8 °C and a dry hot summer (maximum temperature often exceeds $30\text{--}35$ °C). Mean seasonal cumulative precipitation is around $500\text{--}600$ mm, with a maximum in winter. Soil types include sandy loam, loamy sand, sandy clay loam, silty loam, and clay soils. The mean rainfed yield is $15.3 \pm 4.9 \text{ Mg ha}^{-1}$ for giant reed and $11.2 \pm 4.7 \text{ Mg ha}^{-1}$ for Miscanthus [12].

The MLs identified are consistent with the definition and classification from Sallustio et al. [10,11] where MLs are defined as lands that are economically and structurally constrained for conventional agriculture, even though they may not exhibit strong pedological degradation.

Differently from Cappelli et al. [12], this study adopts a more refined aggregation method to model the average yield of giant reed and Miscanthus. Yield data are sourced from the ARUNGRO model, which provides historical series at three time points: t_0 (2024), t_1 (2030), and t_2 (2050). Following Cappelli et al. [12], the total cumulative yield of perennial energy grasses reaches the peak production year in 2030 for all three Italian provinces. Assuming a linear trend in yield

improvement, the annual increase is calculated as the difference between yields at successive time points divided by the number of years between them. This allows for the estimation of annual yields from 2024 to 2044, which are then used to model the total biomass production over the 20-year lifespan of the energy crop in the LCA inventory.

2.2. Goal & scope and system boundary definition

The study aims to assess the environmental impacts of low iLUC perennial energy grasses, i.e., giant reed and Miscanthus, in three MLs of Italian Provinces (BO, PI, CT) to supply ethanol and biomethane production across 20 years until 2044. The results provide an environmental performance of the system for policymakers to support future land use planning strategies for bioenergy sector development.

To reflect the complexity of agricultural systems [49] where land use must balance the provision of ecosystem services with the production of bioenergy feedstocks, two complementary functional units (FU) are chosen to analyse the modelled cropping systems; i) a mass-based FU of 1 Mg of dry-weight biomass of harvested giant reed or Miscanthus to evaluate land use efficiency and biomass yield variability across different pedo-climatic zones. This FU captures how effectively MLs can be converted into productive landscapes while maintaining ecological functions. Second, an energy-based FU of 1 GJ of gross calorific value is applied to the final energy carriers - ethanol (via fermentation) and biomethane (via gasification) - to assess the environmental impacts per unit of useable energy [50]. The dual FU approach enables a more nuanced understanding of the agro-energetic potential of these perennial grasses, aligning with the study's objective to evaluate both agronomic and energy conversion efficiencies.

Fig. 2 shows the system boundary of the analysis, set from the cradle (production of rhizomes and primary inputs) to the gate (energy valorisation routes). All environmental impacts are allocated to functional units, as no waste treatment scenarios and use cases for the generated amount of energy are modelled. The foreground system includes the main processes under the study and refers to primary data by ARUNGRO for the two perennial grasses, feedstocks, and energy yields. The agricultural management practices remain consistent among the two crops, with only the density of the rhizomes varying in application; hence, they are modelled consistently. The background system supports the foreground in terms of inputs and outputs needed for the analysis. The software used is SimaPro v9.6.0.1 [51].

2.3. Life cycle inventory (LCI)

The background data in the inventory are based on the ecoinvent LCA database v3.11 [52]. The perennial energy grasses are rainfed, require no fertilizer input and one pesticide treatment only at the establishment phase [15]. During the planting year, a light soil tillage for land preparation is needed. At this stage, also one application of glyphosate is considered to control weeds and prepare the soil for the rhizomes' propagation. Emission from pesticides application is modelled directly to soil agricultural compartment consistently with the assessment of direct field emissions for inventory of agricultural production systems for ecoinvent database [52].

Giant reed micro-propagated rhizomes are produced and transported in Italy, hence an average distance of 200 km by freight lorry across the three Italian provinces is assumed. Instead, Miscanthus rhizomes are produced and purchased from the Netherlands, so an average distance of 1200 km by freight lorry is included. Miscanthus is a sterile triploid hybrid that does not produce viable seeds and propagates only through rhizomes. This ensures controlled establishment and minimizes ecological risks related to uncontrolled spread. In Italy, the species is not listed among invasive or regulated plants, and no special permits are required for its cultivation. Planting material is generally sourced from within the EU and is subject to standard phytosanitary controls applicable to vegetative propagation materials. The harvesting process

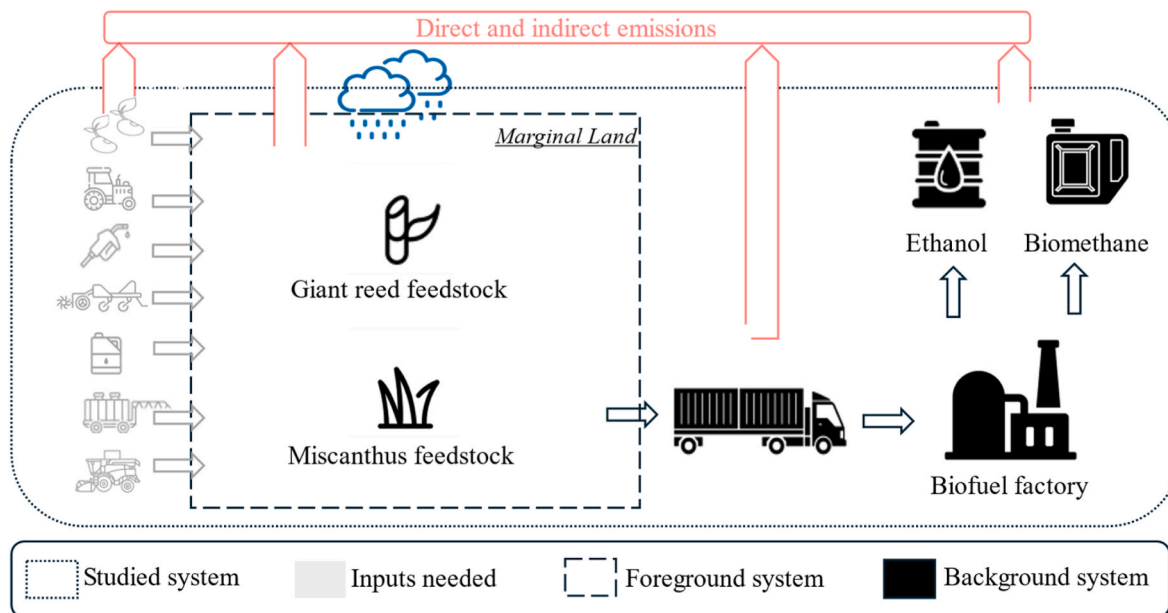


Fig. 2. System boundaries of the analysis.

includes a silage chopper operation used in harvesting giant reed and Miscanthus [43]. However, due to the larger and harder stem of giant reed compared to Miscanthus, an additional 20% of fuel consumption for harvesting Miscanthus is estimated compared to the latter [53]. Emissions from herbicide treatment are modelled at the inventory level, while fertilizer emissions are excluded since they are not used in the

Table 1

Input data derived from Cappelli et al. [12] and used for the LCA analysis. Min and max range of crop and energy yields for giant reed and Miscanthus for the three Italian provinces (BO, PI, CA), filed operations and green water consumption. Energy vectors are calculated by multiplying the biomass by the energy factor coefficients of ethanol and biomethane.

Inputs			
Item	<i>Giant reed</i>	<i>Miscanthus</i>	<i>Unit</i>
Groundwater	$6.00 \times 10^{+02} - 1.89 \times 10^{+03}$	$6.90 \times 10^{+02} - 1.70 \times 10^{+03}$	m ³ /ha
Rhizomes	$2.78 \times 10^{+4}$	$4.00 \times 10^{+4}$	n/ha
Herbicide	3-5	3-5	kg/ha
Field operations			
Time	<i>Type</i>		
Establishment year	Herbicide treatment Tillage by disk arrow Planting by two-row planter		
Every year	Harvesting by maize chopper		
Outputs			
Item	<i>Giant reed</i>	<i>Miscanthus</i>	<i>Unit</i>
Crop Yields	2024 $1.14 \times 10^{+04} - 1.41 \times 10^{+04}$	$1.00 \times 10^{+04} - 1.75 \times 10^{+04}$	kg/ha
	2030 $1.16 \times 10^{+04} - 1.41 \times 10^{+04}$	$1.21 \times 10^{+04} - 1.75 \times 10^{+04}$	kg/ha
	2044 $1.10 \times 10^{+04} - 1.44 \times 10^{+04}$	$1.11 \times 10^{+04} - 1.62 \times 10^{+04}$	kg/ha
Biomethane Yields	2024 $8.02 \times 10^{+01} - 9.92 \times 10^{+01}$	$6.68 \times 10^{+01} - 1.17 \times 10^{+02}$	m ³ /ha
	2030 $8.16 \times 10^{+01} - 9.92 \times 10^{+01}$	$8.08 \times 10^{+01} - 1.17 \times 10^{+02}$	m ³ /ha
	2044 $7.72 \times 10^{+01} - 1.02 \times 10^{+02}$	$7.40 \times 10^{+01} - 1.08 \times 10^{+02}$	m ³ /ha
Ethanol Yields	2024 $5.24 \times 10^{+01} - 6.48 \times 10^{+01}$	$5.70 \times 10^{+01} - 9.97 \times 10^{+01}$	L/ha
	2030 $5.33 \times 10^{+01} - 6.48 \times 10^{+01}$	$6.89 \times 10^{+01} - 9.97 \times 10^{+01}$	L/ha
	2044 $5.04 \times 10^{+01} - 6.64 \times 10^{+01}$	$6.31 \times 10^{+01} - 9.21 \times 10^{+01}$	L/ha

production system.

Table 1 reports the input data modelled from Cappelli et al. [12]. To define the quantity of biomethane and ethanol that could be obtained from the giant reed and Miscanthus biomasses, the same energy factor coefficients of biomethane (giant reed: 0.276 m³ kg⁻¹; Miscanthus: 0.262 m³ kg⁻¹) and ethanol (giant reed: 0.218 L kg⁻¹; Miscanthus: 0.270 L kg⁻¹) retrieved from Cappelli et al. [12] are employed. The conversion coefficients are derived from an extensive synthesis of experimental studies covering a wide range of biochemical conversion technologies. In total, 21 peer-reviewed publications are considered in Cappelli et al. [12], encompassing different pretreatment strategies, anaerobic digestion configurations, and fermentation schemes for both crops. The resulting coefficients represent literature-based average conversion yields, obtained by aggregating experimental results across heterogeneous process conditions, and are intended to describe attainable, non-optimized performances suitable for spatially explicit and regional-scale LCA assessments rather than specific technological configurations. This choice reflects the fact that highly optimized laboratory-scale or pilot-scale configurations are not yet representative of commercially deployed systems at regional scale.

For bioenergy production, the valorisation routes of ethanol and biomethane are analysed. The transportation of the inedible feedstock to the ethanol valorisation plant is estimated at around 50 km. Beyond that distance, it would be energetically inefficient to transport biomass to production plants [54]. For the biomethane production plant, the transportation is calculated assuming an average distance of 40 km [14] since biogas factories are already widespread in the three Italian Provinces. Two background datasets for the technological transformation activities are selected from the ecoinvent database v3.11 [52]: one for the production of biomethane (process for Switzerland “biogas production from grass – CH”), and one for the production of ethanol (process for Switzerland “ethanol production, without water, in 95% solution state, from fermentation from grass – CH”). These two processes are selected among the others being the more similar energy transformation activities to those of the case study that are available in the ecoinvent database v3.11 [52]. Indeed, they account for anaerobic digestion and a fermentation process which are not as energy intensive as a pyrolysis process system. In both background datasets, the inputs of grass production are replaced by giant reed and Miscanthus production from the MLs of the studied area. Since the output of the ethanol process in ecoinvent is in kg, a conversion factor from litre to kg is employed for

the ARUNGRO ethanol yield output. More detailed information about the inventory (both at field level and for the valorisation processes) are reported in Table S2 of the SM, while information on the difference in crop productivity in the three regions can be retrieved from Cappelli et al. [12]. No credits for avoided fossil fuel use are included in this analysis, as the study is limited to bioenergy production and does not extend the investigation at the consumption phase. Although the bioenergy outputs from the systems could potentially integrate or replace fossil-based energy systems, evaluating such integration or substitution is beyond the scope of this specific research.

2.4. Impact assessment

The Environmental Footprint (EF) 3.1 is selected as a method for the impact assessment [55]. It is recommended for the environmental analysis of products and processes in the European context [55] and well implemented both for the analysis of agricultural and energy systems [56]. It is built on the consensus of the most recognized methods for each of the 16 impact categories (ICs). Within them, 11-ICs are selected for the study based on their relevance and are reported in Table 2.

Table 2

The 11 impact categories selected from EF 3.1 for the study, their units, relevance for the selection, and characterization model applied for their assessment. Adaptation from Zampori & Pant [57].

Impact category	Unit	Relevance for the study	Characterization model
Acidification (AC)	mol H ⁺ eq	fertilizers application and fuel consumption from field operations (NO _x , NH ₃ and SO _x)	Seppälä et al., 2006 [54],
Climate change (CC)	kg CO ₂ eq	climate change mitigation	[1]
Ecotoxicity freshwater (EC)	CTUe	fertilizers and pesticides application	USEtox 2.1, (modified) Fankte et al., 2017
Energy resources, non-renewable (ER)	MJ	relation among fossil energy resources and energy produced	CML 2002, Guinée et al., 2002 Van Oers et al., 2002
Freshwater eutrophication (EU-f)	kg P eq	fertilizers application (nitrogen and phosphorus)	EUTREND, Struijs et al., 2009
Human toxicity, Non-carcinogenic (HT-nc)	CTUh	fertilizers, pesticides and herbicides application, and fuel consumption from field operations	USEtox 2.1, (modified) Fankte et al., 2017
Human toxicity, carcinogenic (HT-c)	CTUh	fertilizers and pesticides application, their heavy metals concentration	USEtox 2.1, (modified) Fankte et al., 2017
Land use (LU)	Dimensionless	land use efficiency of the two low iLUC crops, grown on marginal areas.	Beck et al., 2010 Bos et al., 2016, (modified)
Marine eutrophication (EU-m)	kg N eq	fertilizers application (nitrogen and phosphorus)	EUTREND, Struijs et al., 2009
Photochemical ozone formation, human health (PO)	kg NMVOC eq	fertilizers and pesticides application, and fuel consumption from field operations (VOC, CO, NO _x)	LOTOS-EUROS, Van Zelm et al., 2008
Terrestrial eutrophication (EU-t)	mol N eq	fertilizers application (nitrogen and phosphorus)	Seppälä et al., 2006, Posch et al., 2008

2.5. Sensitivity analysis

A sensitivity analysis on key parameters is carried out to identify relevant variations in the model to investigate further land planning scenarios in MLs after completing the initial feedstock production cycle. A one-at-a-time (OAT) approach [58] is employed, wherein a parameter is varied individually within a predefined range while keeping all other parameters constant.

The sensitivity analysis is specifically focused on the land use transformation processes selected for the crops for two main reasons: first, the final land use destination after the techno-economic assessment of the cropping system remains uncertain; second, existing literature highlights the significant role of the LU indicator in LCA studies related to bioenergy production, making it a key factor in evaluating environmental performance [59].

This analysis aimed to evaluate the robustness of the LU results by exploring how alternative modelling choices in the inventory affect the outcome. Each scenario is modelled independently, and the resulting LU indicator values are compared to the baseline to quantify the range of variation.

3. Results

3.1. Environmental impacts of the agricultural phase

The results of the impact assessment for the agricultural phase in the three Italian provinces are shown in Fig. 3 and presented in Table S3 in SM. The results are presented on the functional unit of 1 Mg of dry-weight harvested biomass for giant reed or Miscanthus and are normalized with the EF 3.1 Global Reference 2010 [55].

Giant reed shows an overall higher impact on the MLs of BO. This is explained by the lower crop productivity of BO (1.13E⁺⁰¹ Mg ha⁻¹ on average) compared to PI (1.40E⁺⁰¹ Mg ha⁻¹ on average) and CT (1.37E⁺⁰¹ Mg ha⁻¹ on average). For Miscanthus, the highest impacts are from BO and CT. Nonetheless, in CT, the slight increase in environmental damage can be explained by the longer distance of transportation needed to bring Miscanthus rhizomes from the Netherlands. As a general trend, both perennial grasses perform better in PI which includes the most productive MLs.

As shown in the contribution analysis of Fig. 4, in terms of environmental damages, major impacts affect the same categories between the performances of the two perennial grasses. This is confirmed by the similarities in agronomic technique and the same inputs and modelling choices at the inventory level. It is worth noticing that most of the impacts considered are recurrent due to the harvesting operations, while the impacts generated in the year of implantation are less than 5% of the overall impact for the cropping system. The main impact contributor to the overall single score is the land use (LU) category which is associated with land transformation and occupation by giant reed and Miscanthus cropping system.

The other relevant impact category is human toxicity (carcinogenic) (HT-c) due to the fuel consumption in field operations, specifically from the annual harvesting with the chopper. For giant reed, the impacts in this category are approximately 20% higher than those of Miscanthus due to the fuel consumed for chopping larger and harder stems. However, in the overall score, across all the relevant impact categories, Miscanthus impacts slightly more on the environment due to the higher number and transport distance of its rhizomes compared to giant reed. Other impacts related to land preparation, and pesticide application (mostly connected with fuel consumption for these field operations) are presented but negligible. Regarding indirect emissions, major contributors are pesticides used for rhizome production and the herbicide treatment occurring in the year of establishment.

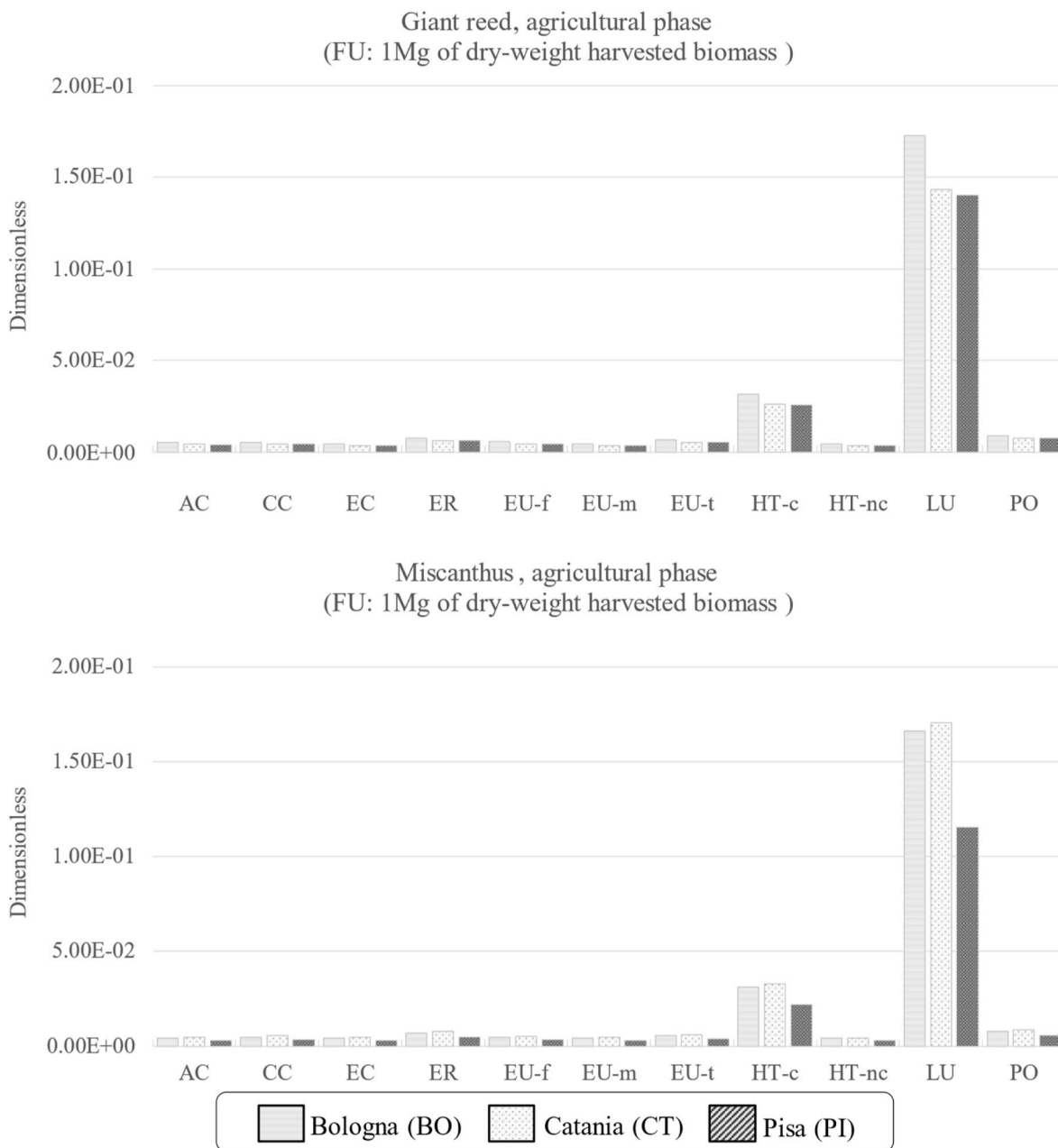


Fig. 3. LCA results per 1 Mg of dry-weight harvested biomass normalized with the EF 3.1 Global Reference 2010 for the agricultural phase of giant reed and Miscanthus for the three Italian provinces; AC= Acidification; CC= Climate change; EC = Ecotoxicity: freshwater; ER = Energy resources: non-renewable; EU-f = Eutrophication: freshwater; EU-m = Eutrophication: marine; EU-t = Eutrophication: terrestrial; HT-c = Human toxicity: carcinogenic; HT-nc = Human toxicity: non-carcinogenic; LU=Land use; PO= Photochemical oxidant formation: human health. No units are reported in the graph as normalisation is dimensionless: environmental results are expressed as a ratio of the absolute environmental impact, and the total annual impact of a global average person in the EU.

3.2. Environmental performance of the energy valorisation routes

Overall, perennial energy grasses, as a source of inedible feedstock produced in MLs in the three considered provinces would provide a total ethanol production of $1.33E^{+05}$ kg ha⁻¹ from giant reed or $1.70E^{+05}$ kg ha⁻¹ from Miscanthus, while for biomethane of $2.15E^{+05}$ m3 ha⁻¹ from giant reed or $2.11E^{+05}$ m3 ha⁻¹ from Miscanthus for the three considered Italian provinces across the 20 years.

Fig. 5 highlights the overall environmental assessment including the valorisation routes. The results are presented on the functional unit of 1 GJ of energy content and are normalized with the EF 3.1 single score Global Reference 2010. Results are shown also for particulate matter formation (PM) IC, not relevant in the agricultural phase, but

particularly important for the energy production process. The complete results can be consulted in Table S4 and Table S5 in the SM.

Ethanol production shows major impacts on ER, HT-c, PM, and PO categories. The damage on ER and PO mainly derived from the diesel consumption of the chopper machine in the harvesting operation and feedstock transportation, while the rest of the impacts is from the electricity and heat required by the system. For HT-c major indirect impacts derived from the coke used to produce chopper and lorry machinery, with the remaining part from the electricity and heat construction system. Finally, the impact on PM is an indirect impact generated by the upstream process of wood chips (as feedstock) combustion in the furnace for generating heat production itself.

For biomethane production, the relevant hotspots are ER, HT-c, and



Fig. 4. Contribution analysis of the agricultural phase.

PO categories. For ER, and PO impacts derived from the diesel consumption of the chopper machine in the harvesting operation and transportation of feedstock to the biogas plant. In addition, a small contribution derived from the heat of the biogas process itself. For HT-c major damage was derived from the coke production used to produce chopper and lorry machinery. In this case, impacts on PM are less relevant because there is not a distillation process for biomethane production.

Results of the energy valorisation routes show the same trend of damage for all IC of the agricultural phase. For the overall score, across all the relevant impact categories, the contribution of the transplanting operation results in a slightly higher value for Miscanthus, in spite of a major productivity, because of the greater transport distance and greater number of rhizomes compared to giant reed.

The analysis of the biofuel's energy unit (GJ) shows a better performance (lower impacts per GJ) for biomethane, due to the higher energy conversion efficiency.

Table 3 highlights the contribution analysis in relation to productivity of the Italian regions in terms of agricultural phase activities and

energy yields for biomethane and ethanol production and the environmental impacts reported normalized per single EF 3.1 score. Results are also presented graphically in Fig. 6 for an easier interpretation. PI represents the best region to produce both biomethane and ethanol due to its high performance in feedstock production, regardless of the type of energy crop. BO incurred major environmental damage from giant reed production due to biomass and energy productions with the lowest productivity in terms of feedstock. Finally, CT shows higher environmental impacts in Miscanthus production.

These results match the diverse pedo-climatic conditions experienced by the two crops across the three study areas. Giant reed and Miscanthus are macrothermal species that require optimal growth temperatures in the range of 20–35 °C [60] and are poorly adapted to heavy clay soils prone to compaction and poor drainage [61]. In BO, the coldest of the three provinces, the productivity of both crops is primarily constrained by suboptimal average daily temperatures for photosynthesis and, to a lesser extent, by soil texture that hampers root deepening, functionality, and growth because of the high clay content.

In CT, while temperatures are closer to the optimal range for both

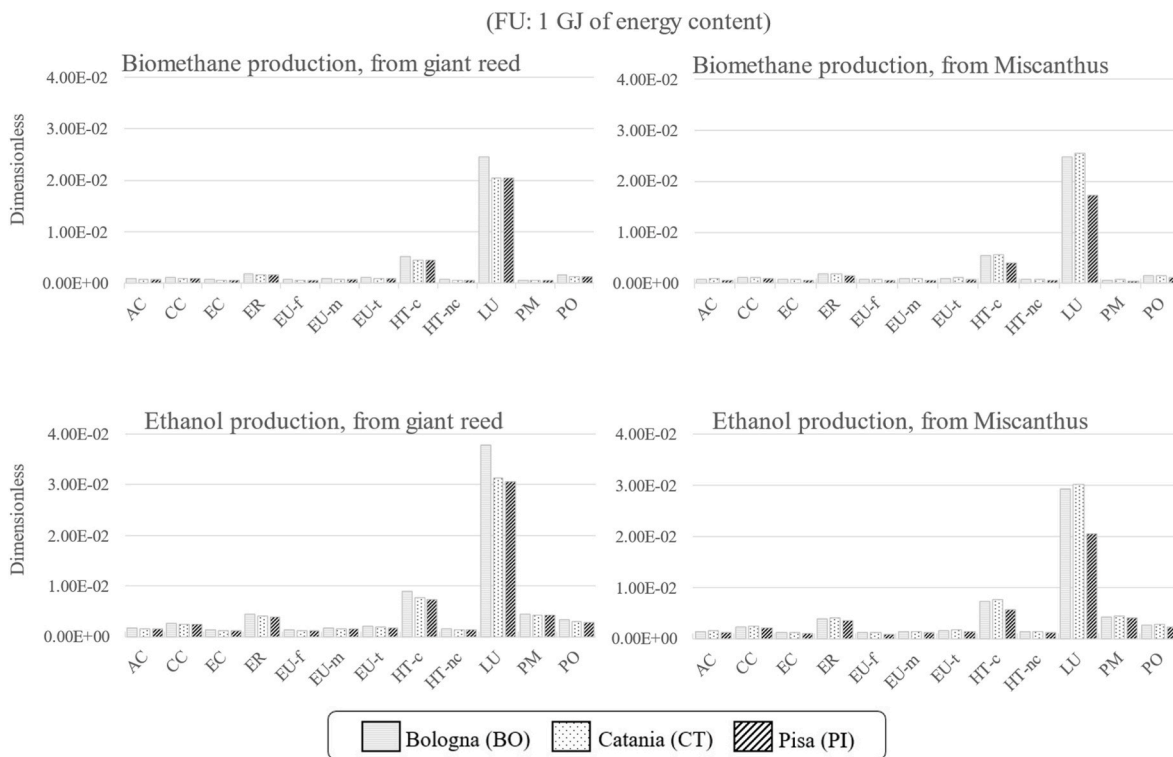


Fig. 5. LCA results per 1 GJ of energy content normalized with the EF 3.1 Global Reference 2010 for energy vectors in the three Italian provinces; AC= Acidification; CC= Climate change; EC = Ecotoxicity: freshwater; ER = Energy resources: non-renewable; EU-f = Eutrophication: freshwater; EU-m = Eutrophication: marine; EU-t = Eutrophication: terrestrial; HT-c = Human toxicity: carcinogenic; HT-nc = Human toxicity: non-carcinogenic; LU=Land use; PM = particulate matter formation; PO= Photochemical oxidant formation: human health. No units are reported in the graph as normalisation is dimensionless: environmental results are expressed as a ratio of the absolute environmental impact, and the total annual impact of a global average person in the EU.

Table 3

Contribution analysis of yields of the agricultural phase, energy productions for biomethane and ethanol, and environmental impacts for the three Italian regions per ha for 20 years.

Prov.	Giant reed				Miscanthus			
	Yield	FU	Process	Single score	Yield	FU	Process	Single score
BO	$2.27 \times 10^{+02}$	Mg ha ⁻¹	Agri phase	1.71×10^{-02}	$2.36 \times 10^{+02}$	Mg ha ⁻¹	Agri phase	1.64×10^{-02}
CT	$2.73 \times 10^{+02}$	Mg ha ⁻¹	Agri phase	1.42×10^{-02}	$2.30 \times 10^{+02}$	Mg ha ⁻¹	Agri phase	1.71×10^{-02}
PI	$2.80 \times 10^{+02}$	Mg ha ⁻¹	Agri phase	1.39×10^{-02}	$3.40 \times 10^{+02}$	Mg ha ⁻¹	Agri phase	1.14×10^{-02}
BO	$1.60 \times 10^{+03}$	GJ ha ⁻¹	Bio methane	2.70×10^{-03}	$1.58 \times 10^{+03}$	GJ ha ⁻¹	Bio methane	2.73×10^{-03}
CT	$1.92 \times 10^{+03}$	GJ ha ⁻¹	Bio methane	2.29×10^{-03}	$1.54 \times 10^{+03}$	GJ ha ⁻¹	Bio methane	2.86×10^{-03}
PI	$1.92 \times 10^{+03}$	GJ ha ⁻¹	Bio methane	2.30×10^{-03}	$2.27 \times 10^{+03}$	GJ ha ⁻¹	Bio methane	1.99×10^{-03}
BO	$1.04 \times 10^{+03}$	GJ ha ⁻¹	Ethanol	4.99×10^{-03}	$1.35 \times 10^{+03}$	GJ ha ⁻¹	Ethanol	4.07×10^{-03}
CT	$1.26 \times 10^{+03}$	GJ ha ⁻¹	Ethanol	4.32×10^{-03}	$1.31 \times 10^{+03}$	GJ ha ⁻¹	Ethanol	4.20×10^{-03}
PI	$1.29 \times 10^{+03}$	GJ ha ⁻¹	Ethanol	4.21×10^{-03}	$1.94 \times 10^{+03}$	GJ ha ⁻¹	Ethanol	3.20×10^{-03}

species, the limited rainfall during the growing season negatively affects Miscanthus production due to its higher sensitivity to water stress compared to giant reed [61] and the lower water-holding capacity of the local soils. In contrast to the other two provinces, PI shows thermo-pluviometric conditions and soil properties that are closer to the optimum for both crops, leading to top yield even in unfertilized rainfed systems grown on MLs.

3.3. Sensitivity analysis on land use category

As evidenced by the results of the environmental assessment of the agricultural phase, land use emerges as the most impactful category within the analysed system. This is primarily attributed to the inclusion of the generic “transformation, to unspecified, IT” process during the modelling phase. Although the characterization factor is regionally adapted for Italy, the results carry significant uncertainty because of the

lack of specific data on post-cultivation land use scenarios, which limits the accuracy of impact attribution. To address this uncertainty, a sensitivity analysis is conducted on this critical parameter by exploring alternative “transformation, to” scenarios.

The sensitivity analysis is limited to a single scenario—giant reed cultivation in Bologna (BO)—with the objective of providing an indicative estimate of the potential reduction in environmental impact, rather than a comprehensive evaluation of all possible land conversion pathways following biomass cultivation. The characterization factor for this technosphere flow is region-specific and corresponds to the Italian context.

Replacing the “transformation, to unspecified, IT” process with either “transformation to annual, IT” or “transformation to perennial, IT” results in an approximate maximum reduction range of 65% in LU-related impacts. The 65% reduction is calculated using a min-max normalisation approach, where the difference between the worst-case

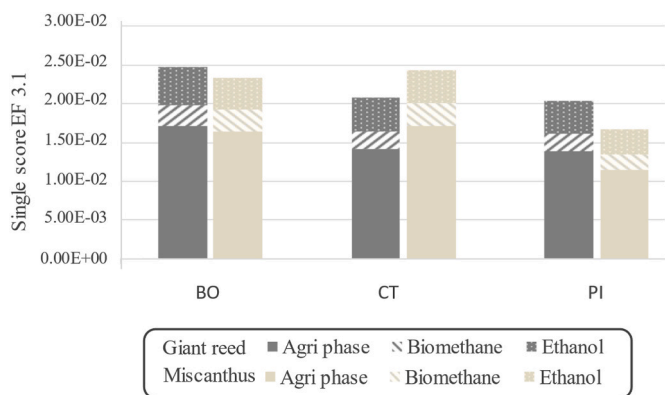


Fig. 6. Environmental impacts' normalized per single EF 3.1 score for the three Italian regions per ha for 20 years. No units are reported in the graph as normalisation is dimensionless: environmental results are expressed as a ratio of the absolute environmental impact, and the total annual impact of a global average person in the EU.

(transformation from grassland to unspecified: 27.70) and the best-case (transformation from grassland to permanent or annual: 2.07) land transformation scenarios is expressed relative to the LU impact score of the current scenario (agricultural phase, giant reed, BO: 39.20 points). Notably, no distinction is observed between the “annual” and “perennial” alternatives, as both are assigned identical characterization factors under the Environmental Footprint method. Nevertheless, perennial crops may offer additional agronomic and ecological benefits on MLs, such as enhanced soil organic matter retention and improved erosion control.

4. Discussion

4.1. Modelling choice and limitations

The work relies on the integration of ARUNGRO [12] outputs in LCA. ARUNGRO provides agronomic simulated inputs for giant reed and Miscanthus production to support LCA analysis and build inventory data for environmental assessment. However, some modelling choices and limitations are reported for future development to move ahead in the research field.

Data of Cappelli et al. [12] from ARUNGRO model neither simulate a precise rise or water content above field capacity nor consider water infiltration or groundwater contributions, even if, especially in the provinces of BO and PI, crops do draw from the water table, which is quite shallow. Hence, these flows are not accounted for both LCA inventory level or at the impact assessment phase. To close this gap at the inventory level, other Agro-Hydrological Models like AquaCrop can be used to obtain background LCA data to simulate water flows, including infiltration and percolation. While most existing water impact assessment methods, including EF 3.1, do not characterize green water withdrawal, the AWARE methodology can provide a more comprehensive approach by accounting for both blue and green water use in assessing water scarcity [62]. Both energy crops rely significantly on water for biomass production, which may affect results for other methods characterizing for other types of water withdrawal beyond tap water (WU). Estimation of water uptake values for both crops is calculated considering only net rainfall as input water able to infiltrate the soil since no irrigation is applied to the crops in the MLs of interest.

Other modelling parameters of ARUNGRO are reflected in the LCA inventory and their results: i) the absence of nitrogen fertilization (e.g., timing, type of product, and application method) and of irrigation (e.g., timing, number of applications, and volumes), both during establishment and across the crop cycle and ii) the lack of a model response function to rising atmospheric CO₂ concentrations under future climate

scenarios. The first two aspects are directly related to the adopted definition of MLs since the exclusion of irrigation reflects structural constraints in the selected areas, where water infrastructure is unavailable or impractical; the absence of fertilization is linked to logistical barriers, limited soil accessibility, and additional costs that may not be offset by corresponding yield increases. In this context, the selection of giant reed and Miscanthus is particularly appropriate, as both crops are known for their high productivity under low-input conditions—even on nutrient-poor and drought-soils, provided they are not prone to water-logging [61].

As for the lack of CO₂ enrichment response, its significance varies depending on the crop's photosynthetic pathway. In giant reed (C₃), this limitation could lead to an underestimation of future yields, especially under dry or sandy conditions, where increased CO₂ may enhance water-use efficiency [63]. For Miscanthus (C₄), however, the physiological response to elevated CO₂ is expected to be negligible [64], making this limitation less critical.

From the LCA perspective, for the agricultural phase, giant reed or Miscanthus should include a mechanical operation for plant removal at the end of the cropping system. In such a case, the plots require deep tillage and around 300 L ha⁻¹ (5 kg ha⁻¹) of glyphosate to successfully remove the crops [65]. However, because the production is on MLs, the perennial energy grasses are assumed to be left on the field after the end of the economic analysis timeframe considered in this study. The rationale for this assumption is that it would be economically unfavourable to perform a full removal of the cropping system, because of the cost of plant removal operation, and not to offset the beneficial ecosystem services provided by the two species in the medium-long term.

At the inventory level, the transplanting process is slightly different between the two crops, as the giant reed rhizomes are bigger and require different tillage operations. This could bring a small variation in fuel consumption and environmental damage. In addition, the Miscanthus rhizome dataset is applied to both crops as the two crops are sufficiently alike, and no better background data are available in the ecoinvent database.

Finally, one potential downside of the implementation of perennial energy grasses in MLs is the impact on biodiversity due to the LUC from the conversion of native grassland in the MLs with perennial arable crops like giant reed and Miscanthus. However according to Dauber et al. [66], the cultivation of perennial grasses on grassland systems generally results in lower biodiversity impacts compared to their cultivation on arable land. This is because grassland-based systems tend to maintain more ecological features and habitat continuity than intensively managed arable systems. However, biodiversity impacts could not be characterized due to the lack of standardised biodiversity impact categories within PEF (Fontanier et al., 2025). Chaudhary et al. [67] already develop a method for land use impacts on biodiversity using country-level characterization factors, however MLs are not part of the method as land use classes.

4.2. Comparison with previous literature

The findings for giant reed and Miscanthus on Italian MLs align with previous LCAs conducted in Southern Europe, where land occupation/land transformation and machinery related field operations typically dominate agricultural burdens [36,38,39]. However, unlike many Mediterranean LCAs that include irrigation and nitrogen fertilization as key yield and impact drivers [36,37,43], this study considers rainfed, unfertilized cultivation on MLs, making harvesting the most impactful field operation. Land use emerges as the primary contributor (often >50% of the agricultural single score), with HTc mainly driven by diesel use and machinery production—patterns that reflect the recognized influence and uncertainty of land use modelling in bioenergy LCAs [11, 42]. A key methodological advancement of this study is the adoption of EF 3.1 as the impact assessment method, released by the European

Commission after 2021; earlier assessments generally predate and therefore do not apply a standardised European LCIA framework.

The explicit coupling of MLs' dataset with ARUNGRO-based crop simulations further distinguishes this work from earlier LCAs that often rely on fixed yield assumptions [37,31]. Across conversion pathways, biomethane systematically outperforms ethanol per unit of energy delivered, owing to higher conversion efficiency and the absence of distillation, consistent with comparative analyses of lignocellulosic routes [31]. The cumulative biomethane ($2.1\text{--}2.2 \text{ E}^{+05} \text{ m}^3 \text{ ha}^{-1}$ over 20 years) and ethanol ($1.3\text{--}1.9 \text{ E}^{+05} \text{ kg ha}^{-1}$) yields fall within literature ranges but remain below laboratory optimized pretreatment results for Miscanthus/common reed [19–21], as expected when applying averaged regional conversion coefficients [12]. The limited crop level variation in methane potential is consistent with the role of harvest timing and ensiling—rather than genotype—as the dominant drivers of methane yield [18].

4.3. Modularity and scalability between LCA and ARUNGRO

This work stands on the same methodological approach, model calibration, and georeferenced input database adopted in Cappelli et al. [12] which include crop parameterization for giant reed and Miscanthus, marginality and suitability maps from Sallustio et al. [11], management calendars and soil parameters, and conversion coefficients from dry biomass to bioethanol and biomethane energy output. However, there are some methodological differences concerning the aggregation data process and the climatic scenario. These refinements are not only methodological but also directly support the objectives of the study, as they link dynamic crop modelling with spatially explicit LCA to evaluate bioenergy options under realistic marginal land constraints.

Such methodological improvements address a well-documented limitation of earlier LCAs, which often relied on static yields or single-route assessments of giant reed and Miscanthus [38,43]. Only a few studies have compared multiple pathways consistently [30,50,68], and integrated crop model–LCA applications remain rare for perennial crops on marginal land [14]. Recent efforts to couple modelling and LCA under climate change are promising but seldom target lignocellulosic species or land heterogeneity. By contrast, this study links process-based simulations with marginality layers to assess ethanol and biomethane production under harmonized assumptions. By replacing generic averages with dynamic, site-specific simulations, this framework overcomes the limited comparability of earlier studies and generates results that are directly relevant for both regional planning and international assessments. Unlike Cappelli et al. [12], who explored multiple realizations and focused on long-term horizons (2055 and 2085), this study applied a single realization focusing on 2030 and 2050. These near-term horizons are more relevant to current policymaking and agricultural planning, given the uncertainty associated with more distant projections. This is because investment decisions and corporate strategies are often influenced by short-term factors, such as market prices, production costs, agricultural policies, and environmental regulations, which may shift rapidly and unpredictably. This distinction highlights how the present work complements previous studies by targeting more immediate planning needs, while maintaining methodological consistency. By contrast, Cappelli et al. [12] simulated markedly projected temperature increase ranged between +3 and 5 C and even stronger rainfall reductions, especially for the 2085 horizon.

The structure of the simulation and assessment workflow in this study is based on a modular architecture in which components are independent but also interoperable units. This structure enables targeted substitution or updating of single elements (e.g., crop, location, management practice) without altering the integrity of the overall simulation system. Hence, the modularity enables adaptations in a systematic and traceable way, consistent with established modelling principles [69]. The context-aware yield and input data of ARUNGRO solve the availability issue of site-specific primary data for agriculture at the

inventory level in LCA, which is always demanding in terms of extensive input data related to agricultural activities in a specific geographical area. In addition, it improves the internal coherence and credibility of the modelled results.

Thanks to this integration, the LCA inventories reflect the real pedoclimatic constraints and yield potential of each marginal area. Environmental impacts per MJ of energy (e.g., GHG emissions, land occupation, acidification potential) are directly linked to simulated performance. For instance, Bologna and Pisa exhibit better environmental profiles due to higher biomass productivity and more favourable soils, while Catania shows higher impact intensities, reflecting both lower yields and more fragmented land availability. The combined model–LCA framework also enables the assessment of territorial trade-offs. In high-yield areas, biogas production may benefit from scale efficiencies and simpler logistics. In lower-yield or fragmented areas, achieving acceptable biogas output might require technological intensification, such as pretreatment or co-digestion, which implies higher capital and operational costs. This highlights that environmental and economic scalability are deeply interrelated and must be evaluated concerning local constraints and opportunities. In future developments, the modular framework could be extended to include cost modelling, infrastructure availability, and financial risk analysis, enabling a fully integrated techno-environmental evaluation of sustainable bioenergy systems. Although this study is focused on three representative provinces, the simulation–assessment framework can be generalized to regions with comparable pedo-climatic and structural conditions—such as areas characterized by limited irrigation infrastructure, low land profitability, and similar temperature and rainfall regimes. This generalizability is supported by the gridded spatial structure of the input data and the harmonized LCA integration. Moreover, the modelling approach is transferable to other perennial lignocellulosic crops that share key morpho-physiological traits—such as rhizomatous propagation, multi-year growth cycles, high water use efficiency, and tolerance to nutrient-poor soils. Suitable examples include switchgrass (*Panicum virgatum*), reed canary grass (*Phalaris arundinacea*), and cardoon (*Cynara cardunculus*), which are widely recognized as low-input bioenergy crops. With updated species-specific parameters and management calendars, the same framework can be applied without modifying its core architecture. The integration of spatial marginality layers, dynamic crop modelling, and cradle-to-gate LCA enables rapid generation of alternative scenarios and evaluation of sustainability trade-offs. In particular, the use of process-based yield simulations improves internal coherence and reliability, especially under uncertain climate conditions. This flexibility also makes the framework suitable for policy-relevant scenario analysis, supporting agricultural and energy planning under diverse marginal land contexts.

4.4. Integration of LCA findings into bioenergy policy contexts

The Italian National Bioeconomy Strategy (SNB, [70]) and its Implementation Action Plan (BIT II, [71]) do encourage and, in some cases, require environmental assessments such as LCA for bioenergy production from biomass, especially when using MLs. The LCA conducted in this study shows its relevance in providing critical environmental insights into the sustainability performance of perennial lignocellulosic crops in MLs for bioenergy production. The normalized single score highlights the importance of the LU impact category. This is consistent with concerns raised in EU and national policy frameworks regarding land use change and ecosystem integrity. However, as shown by the sensitivity analysis in chapter 3.3, the uncertainty derived from the knowledge of the current land transformation of these areas (short and long vision) generates a wide variability in the environmental score of the LU impact category. This score range derives from the characterization factors assigned by the environmental assessment methods for the different types of land transformation processes selected for the analysis. The climate change impact category shows a relatively low

contribution to the total impact. The environmental footprint of biomass-based energy reflects the positive carbon balance of these crops, supporting their role in low-emission bioenergy pathways. These findings align with the sustainability criteria outlined in the EU Renewable Energy Directive (RED II/III) and also in the SNB.

In terms of production market, bioenergy in Italy, which encompasses both modern and traditional biomass sources as well as municipal waste combustion, represents the primary source of domestic energy production, totalling $4.95E^{+05}$ TJ (terajoules) in 2023 [3] (see Table S6 in SM). By considering the average annual energy yield of giant reed and Miscanthus cultivated on MLs (see Table S7 in SM), it is possible to estimate the potential yearly increase in biofuel-derived energy within Italy's overall domestic production. As shown in Table 4, if all MLs in three selected Italian provinces are allocated for biomethane production, the total marginal increase in domestic energy production is approximately 4.15%. In a more conservative scenario, where ethanol is produced from giant reed on the same MLs, the potential increase would be around 2.60%. These bioenergy productions could support the national feed demand of energy for Italy providing an additional source to maintain current biofuel shares and further develop their sustainable market potential in Europe.

However, from an economic point of view, literature can show the downside of their implementation, highlighting especially their high operation costs [72]. Even if there is a willingness to grow perennial energy crops in MLs rather than in arable farmland, the uncertainty from a revenue perspective remains relevant. The economic risks are due to on the high starting cost of the investment, plus the variability of the market price that discourages farmers from adopting this business model. To support farmers, mechanisms for encouraging the adoption of permanent energy crops in MLs should be put in place based on the EU policy, for example, the Common Agricultural Policy (CAP) could include specific targets and measures for lignocellulosic crops within its framework or a de-taxation of renewable energy producers. Such discussion is strengthened if the environmental impacts are contextualized at the global scale. Finally, in recent decades, research on bioenergy systems has primarily focused on improving the agronomic performance of energy crops to maximize biomass yields. However, under marginal land conditions and future climate scenarios, the scope for further yield improvements through crop management is inherently limited and partly beyond direct human control. In contrast, substantial opportunities remain for improving overall system performance through advances in biomass-to-energy conversion technologies, which determine how much useable energy can be obtained from a given amount of biomass. Several studies have shown that targeted pretreatments and process optimization can markedly enhance methane and ethanol yields from lignocellulosic feedstocks, including perennial grasses. Within this context, robust and spatially explicit estimates of biomass supply represent a prerequisite for evaluating the real potential and environmental implications of technological improvements at regional scale—particularly on MLs under climate uncertainty.

5. Conclusion

The research evaluates the environmental impacts of low iLUC perennial energy grasses, namely giant reed and Miscanthus, on marginal lands (MLs) in three Italian provinces to support ethanol and biomethane production over a 20-year period. Results reveal that land use and human toxicity (carcinogenic) are the two most impacted categories, jointly accounting for approximately 75% of the total environmental burden, while climate change and other impacts are negligible. Harvesting activity, driven by annual chopping operations, emerged as the main contributor to environmental damage. When assessing biofuel production on an energy source (GJ), biomethane exhibited higher environmental performance due to its energy conversion efficiency. Regional differences are noted, with the best environmental performance observed in the province of PI, where optimal soil

Table 4

Marginal increase of the domestic yearly energy production from biomethane and ethanol production derived from giant reed and Miscanthus in the MLs of Bologna (BO), Pisa (PI), Catania (CT). This table reports only the incremental contribution of cultivation activities on marginal lands, while infrastructure construction, processing, and distribution stages are intentionally excluded from this comparison because they fall outside the defined system boundaries of the present study. These values are therefore not to be interpreted as a full life-cycle energy balance but as marginal gains in domestic bioenergy potential under the specific land-availability scenarios considered.

Geographical representation	Process	Total annual average energy yield from Giant reed	Total annual average energy yield from Miscanthus	Unit
BO + CT + PI	Biomethane production	$2.00 \times 10^{+04}$	$2.14 \times 10^{+04}$	TJ
BO + CT + PI	Ethanol production	$1.32 \times 10^{+04}$	$1.83 \times 10^{+04}$	TJ
Italy	Domestic energy production, Italy, from biofuel and waste [3]	$4.95 \times 10^{+04}$	$4.95 \times 10^{+04}$	TJ
BO + CT + PI	Marginal increase of the domestic energy production from biomethane	3.88	4.15	%
BO + CT + PI	Marginal increase of the domestic energy production from ethanol	2.60	3.57	%

properties and favourable thermo-pluviometric conditions supported higher yields. In terms of potential contributions to domestic energy production, if all MLs in the three evaluated NUTS-3 provinces are devoted to biomethane production from Miscanthus, there could be an increase of 4.15% in Italy's total energy supply, whereas the worst-case scenario in the current study, involving ethanol production from giant reed, would reach a 2.60% increase. To provide a more comprehensive understanding of the role of MLs in supporting a sustainable energy transition, future research should account for dynamic climate scenarios, expanding the site analysis to all MLs in Italy and comparing other energy crops. In addition, an economic assessment is also essential to evaluate the financial feasibility of scaling up this bioenergy strategy.

CRedit authorship contribution statement

Francesco Cirone: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simone Amadori:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giovanni Cappelli:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Enrico Ceotto:** Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Andrea Monti:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Matteo Vittuari:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biombioe.2026.109079>.

Data availability

Data will be made available on request.

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