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The global energy challenge: second-generation feedstocks on marginal lands for a sustainable biofuel production

Claudio Russo[1], Valerio Cirillo[1*], Nausicaa Pollaro[1], Fabio Terribile[1,2], Andrea Chiodini[3] and Albino Maggio[1]

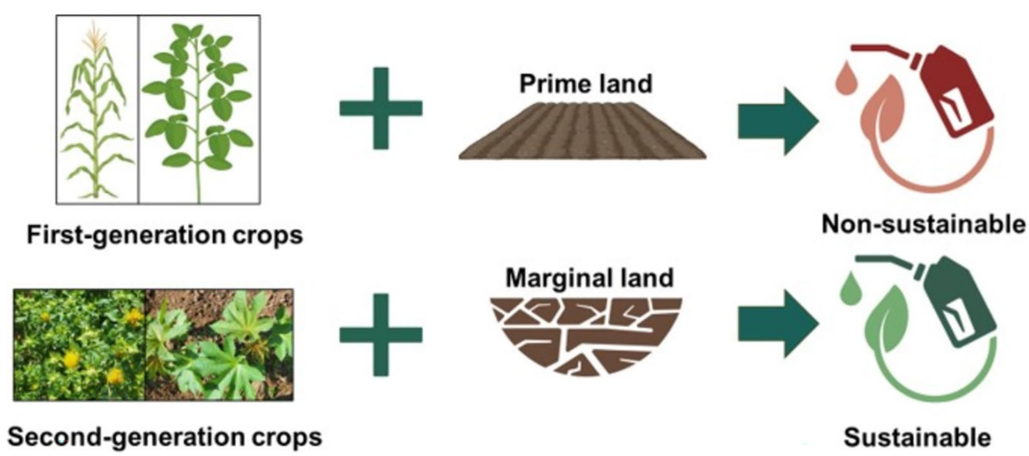
Abstract

As the global population continues to grow, so does the demand for energy resources. As a consequence, using renewable energy sources as an alternative to fossil fuels has become mandatory to reduce the environmental footprint of the energy sector. Biofuels represent a renewable source of energy, but their production has raised concerns regarding their possible impacts on food security. Indeed, the current biofuel production primarily relies on food crops and arable lands. That is in conflict with the need to produce more food for an increasing world population. To overcome this incongruence, it is proposed to cultivate second-generation biofuel crops on marginal lands, since this option could bring benefits in terms of food security and sustainability. Based on the scientific literature, we addressed the following critical points: (i) whether marginal land worldwide can be considered a reasonable alternative to arable lands for biofuel production; (ii) evaluate the sustainability of biofuel production with respect to unintended negative consequences of crop cultivation such as indirect land use change, social insecurity and loss of biodiversity. It was concluded that the amount of land for growing plants can possibly sustain both food and biofuel production if marginal land are included. In this context, it becomes a priority to select biofuel crops with high productivity on marginal lands and pronounced resilience and adaptability traits. Underutilized crops such as *Carthamus tinctorius*, *Ricinus communis*, *Brassica carinata*, *Camelina sativa* etc. may fit the purpose and may represent a valuable alternative to first-generation feedstock because they require minimal agronomical input. Using underutilized crops on marginal lands can also provide important ecological services, including improving soil fertility and water regulation, increasing biodiversity and reducing soil erosion. To fully exploit this option, it will be critical to calibrate plant growth models to estimate the potential biofuel production on marginal land from second-generation feedstock and to create tools for a more rational management of this land.

Keywords *Ricinus communis*, *Carthamus tinctorius*, Food-fuel debate, Life cycle assessment, GHG

*Correspondence:
Valerio Cirillo
valerio.cirillo@unina.it
Full list of author information is available at the end of the article

Graphical abstract



Introduction

Fossil fuels are the most reliable source of energy used worldwide for different purposes. However, they are not renewable, they pollute the environment and can be dangerous if irresponsibly used. The energy sector has the highest environmental impact compared to other sectors contributing with 73.2% to total carbon dioxide emission, of which transport accounts for 16% [1]. Considering that carbon dioxide, mostly derived from fossil-fuel-related emissions, is one of the most critical determinants of global warming, our reliance on fossil fuels must be reduced [2, 3]. The search for new energy sources as an alternative to fossil fuels has been a longstanding priority of most governments worldwide (Directive (EU) 2018/2001, 2018) and biofuels have been playing an important role in this scenario [4–10]. Nowadays, ethanol and vegetable fuel oil produced from different crops, can be used for powering engines and they account for 5.4% of the global fuel consumption [11]. However, as the interest in biofuel has increased, the debate on the competition between biofuel production and food security has become increasingly heated [12]. The focus of the debate is simple: with a need for more food to satisfy the Sustainable Development Goals (SDGs) 2.1 (end hunger) and 2.2 (end all forms of malnutrition) by 2030, biofuels will compete with land [13], water [14] and fertilizers, which are the same critical resources necessary to feed the world [15]. The competition for cropland has a major drawback for the food-fuel debate, regarding the increase of food prices [16], and the negative consequences on food security [17, 18] which make the production of biofuels not a viable option to reduce the use of fossil fuels. This was the conclusion after years of biofuels production based on first-generation feedstock crops, such as corn, wheat and sugarcane for ethanol, and soyabean, rapeseed and sunflower for vegetable oil [16, 19]. It is worth pointing out that these were the conclusions based on a limited number of scientific papers available in the literature, but a complete evaluation of this aspect is not currently available. From another point of view, the increase of fossil fuel cost has been identified as the major cause of food prices increases [20]. Therefore, substituting biofuels with fossil fuels could limit food price increase since their use could reduce the price for energy. To the best of our knowledge, these opposite views (increase vs. decrease in food price) have never been addressed thoroughly thus deserving further comparative studies. Although the possibility that first-generation crops could not be ideal for biofuel production they are still today the main biofuel crops with a covered arable land of 6% [21–23]. The production of first-generation biofuel crops is also misaligned with other SDGs, including SDG2 (responsible consumption and production) [24], SDG15 (life on land) [25] and SDG6 (life below water and clean water sanitation) [26] which makes it even more conflictual. Therefore, to consider biofuels crops as a reliable energy source, these inconsistencies must be solved [27]. Using marginal lands in combination with highly resilient crops, a common trait of second-generation crops, could cope with this conflict since most often marginal land would be unsuitable for food production and therefore would not compete with it. In addition, cultivation of marginal land could provide important ecosystem services that would bring additional value to the overall biofuel production process [25, 28]. Marginal land, if properly cultivated, could contribute to carbon immobilization and storage [29], biodiversity conservation [30] and reducing soil erosion [31, 32]. The definition of marginal land and how it evolved over time has been largely debated [33, 34] From an agronomical point of view, a marginal land can be defined as a land with low agricultural value, where food production as well as biofuel production from first-generation crops is not cost-effective due to biophysical constrains [35–37], socio-economic factors [38–40] or a mix of them [41]. Nevertheless, these lands may still host crops with modest cultural requirements, which can be used for nonfood purposes. Minor and/or underutilized crops may be profitably cultivated as second-generation feedstocks on marginal lands to produce biofuel with minimal or no impact on food supply, leading to several environmental [42–44], economic, and social benefits [16, 45, 46]. Here we will present the main aspects of biofuel production based on the underutilized crops-marginal land combination by addressing current estimates of marginal land occurrence worldwide, their potential for biofuel production, and the environmental benefits of using second versus first generation feedstocks to increase the sustainability of biofuels production.

Marginal lands for biofuels production

The shortcomings of first-generation feedstock for large-scale biofuels production have been discussed [47–49]. The rise of food prices in the 2006–2008 period has been associated with a confluence of factors such as export bans on grain from different countries, production losses due to weather-related event, speculative activity on the market, increase of energy costs causing an overprice for fertilizer production, as well as, the increased use of grains (corn, wheat) and oilseeds (soybean, rapeseed) for the production of biofuel [16, 50–52]. According to Graham and Rowe [12], it looks like biofuels crops should not be grown on cropland but on land that cannot be used for food production, i.e. marginal land with serious land degradation problems, leaving the prime land for food crops [12]. Most estimates to classify marginal land have been based on the Geographically Information System (GIS), which allowed us to cross different datasets and therefore describe main parameters or characteristics useful to define marginal lands. Campbell et al. [53] and Nijsen et al. [54] have obtained different estimates of marginal land availability by using datasets with the same resolution of ~ 10 km^2. This was likely due to a different definition of marginal land used by these authors. Nijsen et al. [54] presented a *scale* of marginality depending on several factors, including soil erosion, water availability and the presence of toxic elements. Based on this set of parameters estimates varied from 247 million hectares to 1248 million hectares of land affected by marginality worldwide, potentially supplying 5–10% of the global energy demand [54]. In contrast, Campbell et al. [53] by using historical land use data, satellite-derived land cover data and global ecosystem modelling estimated that the global marginal land, defined as abandoned agricultural land, accounted for 470 million hectares. Similarly, Cai et al. [55] and Wicke [28] utilized datasets with the same resolution of ~ 1 km^2 but once again, the definition of marginal area diversified their estimates. Cai et al. [55] defined marginal areas as abandoned land, degraded or with a minimal agricultural production, while Wicke [28] considered only salinized soils, most of which affected by moderate salinity (< 5 dS m^{-1}) and therefore potentially used for cultivation. For the United States, Jiang et al. [56] have utilized a dataset with high resolution (~ 100 m^2) to define the profitability of land cultivated for food crops. In this way, marginal lands were defined as those with low to zero profitability, with a high risk of abandonment and therefore potentially available for biofuels production. By crossing datasets of historical and recent land use, Zumkehr and Campbell [57] have also classified marginal lands as abandoned croplands that account for a total of 68 million hectares, with a capacity to supply from 4 to 30% of United States liquid fuel demand. For Europe, main estimates were based on biophysical constraints build on the concept of *less favorable area*s (e.g. presence of coarse fragments, steep slope, limited rooting depth) described by the Joint Research Center (JRC) [58]. By using this methodology, a total of marginal lands between 20 and 50 million hectares was identified [59]. Elbersen et al. [35] defined the marginal areas according to the different parameters indicated by the JRC and they further validated them by verifying, from Goole Earth and Street View photos, several points to check/confirm the actual use and/or possible changes/improvements of these areas over-time. By using this approach, it was possible to fine-tune the JRC data and narrow them down to 29% (approx. 10 million hectares). Other ranking systems [60] have looked at combinations of different indicators elaborated on the criteria proposed by Mueller [61], such as topsoil structure, rooting depth, and hazard-like components (*e.g.,* salinization, drought, and steep slope) to finally estimate a total of 52 million hectares of marginal lands in Europe. Sallustio [62] crossed land slope and economic value to assess the economic marginality of agricultural land in Italy. The economic value was derived from land-use classes provided by the Corine Land Cover dataset, which enabled the identification of areas where the economic value was below the average agricultural land value. In this way, lands with steep slope (> 30°) and lower economical value than the average value were classified as marginal. The study estimates that the 39% of Italy's agricultural land can be considered marginal at different levels (from low to high). By utilizing only the high marginal lands for the cultivation of lignocellulosic crops, up to 7.8% of the Italian fuel consumption could be satisfied; by using all marginal lands up to 69% of the fuel consumption could be reached [63]. Estimates of marginal lands for other regions of the world are limited (Table 1). It is essential to account for the temporal range of the various estimates and acknowledge the limitations of the classification approaches discussed above. For instance, soil information is typically rather coarse (e.g. FAO Harmonised World Soil Database) [64, 65] in terms of quantity (spatial resolution) and data quality (e.g. lack of good hydrological information). Nevertheless, considering all diverse figures given above and the large supporting scientific literature [54, 55, 66–68] it can be reasonably stated that there is globally a substantial amount of underutilized or agronomically marginal land that can be considered to mitigate the competition between food and fuel production. While theoretical estimates on the potential of marginal lands for biofuels production are promising, it is worth mentioning that most estimates on the actual plant biomass that can be harvested on marginal land are inferred from the published literature on first-generation crops and do not rely on ad hoc experiments on second-generation crops [28, 55, 68, 69], with a few exceptions. Campbell et al. [53] used available plants growth models to conclude that it is possible to produce up to 2.1 Gt for year of dry matter on the available marginal land. With similar approach Milbrandt and Overend, [66] provided a more conservative simulation for a total of 1.6 Gt of dry matter equal to 260 Mt of gasoline. Cai et al. [55] managed to calculate the net energy gain from second-generation crops, which turned out to be 55% of global fuel needs. A summary of estimates of available marginal land and the respective potential for biofuel production is reported in Table 1.

Biofuel sustainability and second-generation feedstocks

Second-generation feedstocks have therefore been proposed to solve the sustainability concerns of biofuel production at large. Fischer et al. [19] have clearly stated that biofuel from first-generation feedstocks (grain, corn, sugarcane) is unsustainable and unethical because transforms food into energy in a world where one sixth of population is affected by chronic hunger, whereas second-generation feedstocks (non-food crop and/or underutilized crop) are suitable for an environmentally cleaner, economically competitive and socially accepted biofuel production. Doornbosch and Steenblik, [70] highlighted the positive effects of second-generation feedstocks such as their contribution to GHG reduction, valorization of poor-quality soils, conservation of biodiversity and more. Those benefits are also listed as specific indicators in the European Biofuels Framework (Directive (EU) 2018/2001). The "Renewable Energy Directive" (RED) established stringent criteria for defining sustainable biofuel production. Among those, it is indicated that biofuels must emit a maximum of 35% of the greenhouse gas (GHG) emissions released by fossil fuels to be considered environmentally sustainable (Directive (EU) 2018/2001). The GHG emissions of biofuel production from seeds to

Table 1 Estimates of marginal land availability and relative potential production of bioenergy/biofuel

Area of interest	Marginal land (Mha)	Potential production		Methods to estimate potential production	Authors
		(Dry matter Gt/year)	(J/year)		
World	470	1.6–2.1	–	Plant growth model	[53]
Asia-America	400	1.3	–	Plant growth model	[66]
China	130	0.65	–	Review scientific literature	[68]
Africa	907	–	2.39×10^{10}	Review scientific literature	[69]
Asia	696	–	1.55×10^{11}	Review scientific literature	[69]
Latin America and Caribbean	448	–	2.3×10^{11}	Review scientific literature	[69]
Brazil	37	–	–	–	[124]
World	247	–	32×10^{18}	Review scientific literature	[54]
World	1128	–	42×10^{18}	Review scientific literature	[28]
Europe	53	–	5.2×10^{18}	Review scientific literature	[59]
World	320–720	–	9.5×10^{10}	Review scientific literature	[55]
United States	61–126	–	–	–	[125]
United States	25	–	–	–	[56]
Europe	52	–	–	–	[60]
Italy	2	0.09	–	Land suitability	[63]
Europe	10.8	–	–	–	[67]

final products have been calculated via Life Cycle Assessment (LCA) for both first- and second-generation crops (Table 2).

Based on the results from the literature summarized in Table 2, that the GHG emissions from second-generation biofuels obtained from ethanol and vegetable oil are 50% lower than first-generation biofuels and below the ideal sustainable emission threshold of 32.9 g CO_2 MJ^{-1} established by the RED II Directive (EU) 2018/2001 (Fig. 1a). A more detailed prospect on GHG emissions from first- and second-generation crops are displayed in Fig. 1b.

Among first-generation crops considered in this analysis, only sugarcane presents a lower GHG emissions compared to the RED II threshold (−3.3%). In contrast, the second-generation crops considered in this analysis are more efficient compared to first-generation crops with respect to GHG (Fig. 1a, b). Safflower (*Carthamus tinctorius*) was the most sustainable crop (47% below the RED II threshold), followed by switchgrass (*Panicum virgatum*) 36% below the threshold, castor bean (*Ricinus communis*) and *Miscanthus spp* both 14% below the threshold, false flax (*Camelina sativa*) and pennycress (*Thlaspi arvensis*) both 5% below the threshold. Among the second-generation crops, only the Ethiopian mustard (*Brassica carinata*) showed higher emission with respect to the RED II threshold (+3%). The cultivation of these crops on marginal lands would add an additional benefit in terms of GHG emissions due to low indirect land use change (I-LUC)(Directive (EU) 2018/2001). Low I-LUC biofuels are those obtained by feedstock listed in the Annex IX of Directive (EU) 2018/2001 or crop cultivated on unused, degraded land with low carbon stock and may provide an income increase for small farms [71]. Moreover, low I-LUC crops can offer an opportunity to farmers to diversify their cropping systems, improve soil and agricultural practices while producing feedstocks for biofuels [71]. The technical limits to integrate new crops in well-established farming systems, the higher cost of the final products and the consequent possible exposure to commercial risks should not be underestimated, however [72, 73]. Most second-generation feedstocks fall within the low I-LUC biofuels category. It is important to point out that not all the GHG emissions displayed in Fig. 1b include the I-LUC component and associated emissions, which explains the variability observed for some crops such as soybean (*Glicine max*), sunflower (*Helianthus annuus*), and rapeseed (*Brassica napus*) (Table 2). Moreover, the data used in this analysis have been produced over 17 years, a time span that may have introduced some uncertainty in the interpretation of the results. Additionally, for some second-generation crops like *Carthamus tinctorius* and *Ricinus communis* there are limited LCA studies in the scientific literature (Table 2). To overcome

Table 2 LCA outcome for first- and second-generation crops. Emissions are reported as grams (g) CO_2 equivalent for MJ of biofuel produced

Biofuel source	g CO_2 equivalent for MJ of biofuel	Land use change	References
Brassica carinata	53	Considered	[126]
Brassica carinata	38	Considered	[127]
Brassica carinata	21	Not considered	[128]
Brassica carinata	43	Considered	[129]
Camelina sativa	60	Not considered	[130]
Camelina sativa	20	Considered	[128]
Camelina sativa	27	Considered	[131]
Camelina sativa	40	Considered	[132]
Camelina sativa	31	Considered	[133]
Camelina sativa	37	Considered	[134]
Carthamus tinctorius	16	Not considered	[135]
Carthamus tinctorius	15	Not considered	[135]
Carthamus tinctorius	21	Not considered	[136]
Ricinus communis	26	Considered	[137]
Ricinus communis	30	Considered	[138]
Ricinus communis	34	Considered	[139]
Ricinus communis	23	Considered	[140]
Zea mays	62	Considered	[141]
Zea mays	73	Considered	[142]
Zea mays	40	Considered	[143]
Zea mays	104	Not considered	[144]
Zea mays	55	Not considered	[145]
Zea mays	60	Considered	[146]
Zea mays	45	Considered	[147]
Brassica napus	24	Not considered	[128]
Brassica napus	45	Considered	[131]
Brassica napus	121	Considered	[132]
Brassica napus	70	Considered	[148]
Brassica napus	37	Considered	[149]
Brassica napus	53	Considered	[150]
Brassica napus	46	Not considered	[151]
Brassica napus	33	Considered	[152]
Brassica napus	67	Considered	[152]
Glycine max	23	Not considered	[153]
Glycine max	50	Considered	[131]
Glycine max	164	Considered	[132]
Glycine max	41	Considered	[154]
Glycine max	48	Considered	[149]
Glycine max	100	Considered	[150]
Glycine max	140	Considered	[150]
Glycine max	100	Not considered	[155]
Glycine max	32	Not considered	[156]
Helianthus annuus	22	Not considered	[128]
Helianthus annuus	94	Considered	[132]
Helianthus annuus	43	Considered	[150]

Table 2 (continued)

Biofuel source	g CO_2 equivalent for MJ of biofuel	Land use change	References
Helianthus annuus	52	Not considered	[157]
Helianthus annuus	52.8	Not considered	[157]
Helianthus annuus	79	Not considered	[157]
Helianthus annuus	72	Not considered	[157]
Thlapsi arvense	41	Considered	[158]
Thlapsi arvense	26	Not considered	[159]
Thlapsi arvense	40	Considered	[160]
Thlapsi arvense	30	Not considered	[161]
Triticum spp	99	Considered	[132]
Triticum spp	68	Considered	[141]
Triticum spp	50	Considered	[162]
Triticum spp	76	Considered	[148]
Triticum spp	65	Considered	[143]
Triticum spp	74	Considered	[146]
Saccharum officinarum	92	Considered	[163]
Saccharum officinarum	30.5	Considered	[164]
Saccharum officinarum	38.4	Considered	[165]
Saccharum officinarum	51	Not considered	[166]
Saccharum officinarum	20.5	Not considered	[167]
Saccharum officinarum	19	Not considered	[167]
Saccharum officinarum	13	Not considered	[167]
Saccharum officinarum	27.5	Considered	[165]
Saccharum officinarum	36.8	Not considered	[166]
Saccharum officinarum	21.3	Not considered	[168]
Saccharum officinarum	48	Not considered	[169]
Saccharum officinarum	42	Not considered	[169]
Saccharum officinarum	36	Not considered	[169]
Miscanthus spp	30.1	Not considered	[170]
Miscanthus spp	40.7	Not considered	[170]
Miscanthus spp	49.2	Not considered	[170]
Miscanthus spp	60.9	Not considered	[170]
Miscanthus spp	28.7	Not considered	[170]
Miscanthus spp	38	Not considered	[170]
Miscanthus spp	20.2	Not considered	[171]
Miscanthus spp	23	Not considered	[172]
Miscanthus spp	9	Considered	[173]
Miscanthus spp	12	Considered	[173]
Miscanthus spp	14	Considered	[173]
Miscanthus spp	19	Considered	[173]

Table 2 (continued)

Biofuel source	g CO_2 equivalent for MJ of biofuel	Land use change	References
Miscanthus spp	32	Considered	[174]
Miscanthus spp	19	Not considered	[175]
Panicum virgatum	10	Considered	[173]
Panicum virgatum	15	Considered	[173]
Panicum virgatum	14	Considered	[173]
Panicum virgatum	20	Considered	[173]
Panicum virgatum	36	Considered	[174]
Panicum virgatum	19	Not considered	[175]
Panicum virgatum	2	Not considered	[176]
Panicum virgatum	17	Not considered	[177]
Panicum virgatum	24	Not considered	[178]
Panicum virgatum	32.9	Not considered	[179]
Arundo donax	40	Not considered	[180]
Arundo donax	25	Not considered	[169]
Arundo donax	10.1	Not considered	[181]
Arundo donax	40	Not considered	[182]

this limitation, process-based models can be a proxy tools not only for assessing the potential yield of crops, but also for gaining a deeper understanding of their sustainability [74]. These models rely on diverse data inputs, such as weather conditions, soil characteristics, and crop management practices, to simulate chemical, biological, and physical processes underlying crop growth [75–77]. Models like ARMOSA, STICS, and SALUS are useful to estimate crop productivity as well as critical aspects of soil health, including changes in soil organic matter and nitrate leaching that are also important for environmental sustainability [75–77]. Furthermore, these models can be used to assess different management strategies, the effects of various crop rotation systems, and the potential impacts of climate change on crop performance [78–80]. However, to fully leverage this approach, comprehensive empirical data on crop phenology, management practices, and biometric measurements are essential for accurate parameterization. Since data on second generation crops are currently limited compared to first-generation crops, this could explain the slow progress in this field (Fig. 2).

Overall, second-generation crops, which are generally "underutilized crops", are ideal for biofuel production on marginal areas and/or land with low agricultural value since those crops are physiologically adapted to survive in extreme environments and can better cope with seasonal environmental constrains and growth limitations [27, 81–84]. For example, *Camelina sativa* only requires 26 kg *per* hectare of nitrogen for an economically convenient production [85]. In a similar

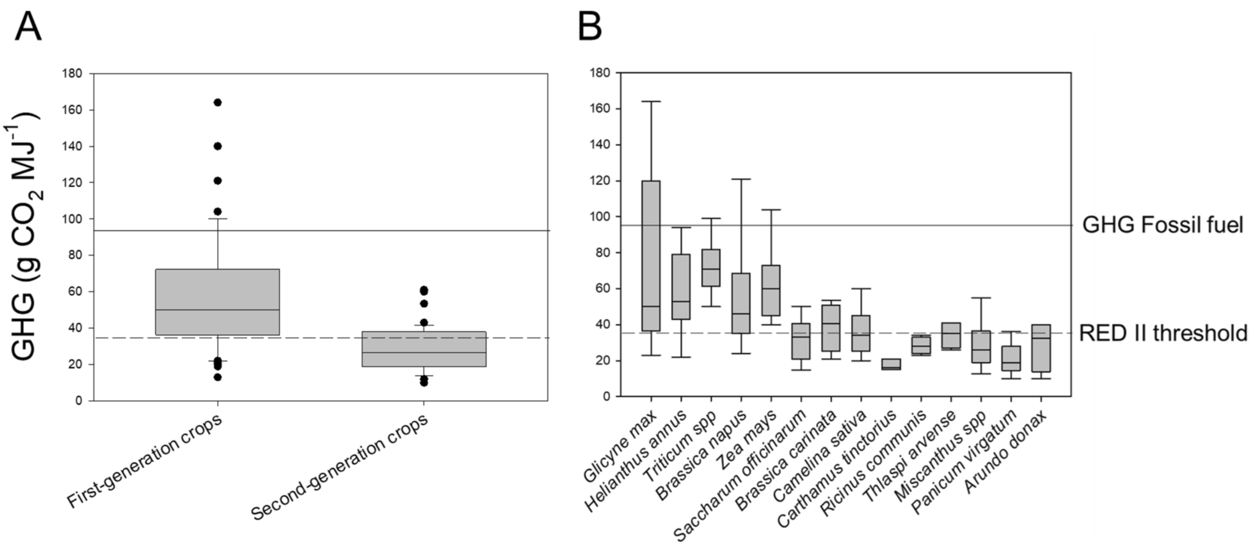


Fig. 1 Average GHG emissions from first- and second-generation crop **A** and average GHG emissions from all specific crops **B**. First-generation crops (*Zea mays, Brassica napus, Glicyne max, Helianthus annus, Triticum spp and Saccharum officinarum*) and second-generation crops (*Brassica carinata, Camelina sativa, Ricinus communis, Thlaspi arvensis, Miscanthus spp, Panicum virgatum and Arundo donax*). GHG emission of fossil fuel according to RED II (94 g CO_2 MJ^{-1}, continuous line and RED threshold for sustainable biofuel (32.9 g CO_2 MJ^{-1}, dashed line). Data utilized for the graphs can be found in Table 2

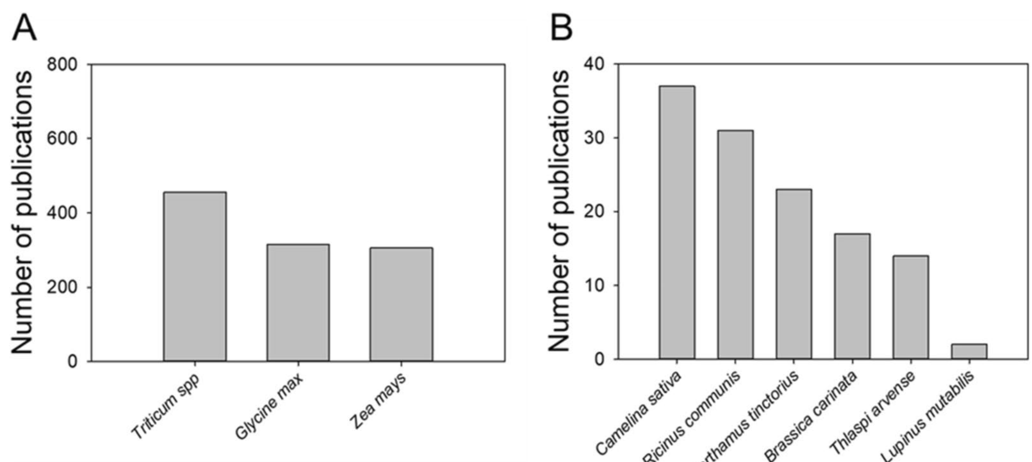


Fig. 2 Number of publications in Scopus database for "crop name" AND "phenology" AND "biofuels" as key of search for **A** first generation (*Triticum* spp, *Glycine max*, *Zea mays*) and **B** second generation (*Camelina sativa*, *Ricinus communis*, *Carthamus tinctorius*, *Brassica carinata*, *Thlaspi arvense* and *Lupinus mutabilis*)

way, the fertilization need for *Brassica carinata* can range from 47 up to 93 kg of nitrogen [86]. In contrast, first-generation crops generally require significantly higher nitrogen fertilization. The optimal nitrogen application ranges from 206 to 315 kg of nitrogen *per* hectare in corn [87–89], from 56 up to 225 kg of nitrogen *per* hectare in wheat [90, 91] and from 120 to 200 kg of nitrogen *per* hectare in sugarcane [92–94]. *Ricinus communis* and *Carthamus tinctorius* show high drought stress tolerance with small yield losses under water limited cultivation thanks to specific physiological tolerance to drought stress [95–98]. Similarly, *Ricinus communis* shows high tolerance to salt stress [99] and heavy metal soil contamination [100], both of which represent typical constraints to crop productivity on marginal lands [101].

Second-generation feedstocks provide also environmental and social services

First-generation feedstocks have significant environmental impacts, also. Soybean and corn for biodiesel production in the United States will still cause the highest land use change, and potential biodiversity loss in 2030 [102–104]. Moreover, similar effects on biodiversity from sugarcane expansion have been reported also in Africa [105, 106]. In contrast, the use of second-generation crops for bioenergy and biofuel production can provide additional environmental benefits that are maximized if cultivated on marginal lands. *Panicum virgatum*, *Mischantus spp*., and *Agave spp*. can improve soil fertility, water use efficiency and biodiversity [42, 43] and the agroecological/environmental value of the overall farmers revenues [44] which are becoming increasingly important in modern agriculture [107, 108]. Crops like *Camelina sativa* and *Thlaspi arvense* represent potential sources of food for pollinators and other insect species [109]. Similarly, *Lupinus mutabilis*, a leguminous species whose seeds can be used both for oil and protein extractions can be a source of nectar for wild pollinators such as *Bombus spp*, *Xilocopa spp* and *Anthophora spp* [110]. Moreover, low input crops respond well to minimum tillage, which contributes preserving the soil quality by reducing soil erosion, promoting soil water absorption capacity and preserving the soil carbon stock [111, 112]. *Brassica carinata*, grows well under minimum tillage and copes well with weeds and nutrients scarcity, which would lead to reduced herbicide and fertilizer use [82, 113]. Tudge et al. [114] found first-generation crops reduced species richness and abundance by 37% and 49% respectively compared to previous natural vegetation. Second-generation crops also have an impact on species richness (−19%) and abundance (−25%), yet smaller compared to first-generation crops. With respect to socio-economic benefits, both first- and second-generation biofuel crops can contribute to rural development through an increase of employment and income [105, 115]. It has been estimated that the cultivation of *Ricinus communis* in Ethiopia may increase household food security by 25% [45]. Subramaniam et al. [46] have demonstrated that second-generation feedstock could improve environmental sustainability and food security in 51 developing countries, with a positive impact on food production and environmental quality. Overall, second-generation feedstocks may have lower impact on biodiversity, additional environmental services and socio-economics benefits in contrast to first-generation feedstocks [42–44, 46, 82, 107–114].

The production cost of biofuel from second-generation feedstocks

In addition to environmental and social services associated with the implementation of second-generation feedstocks, the economic sustainability of biofuel production should also be considered. In this respect, the Life Cycle Cost (LCC) is an adequate methodology for the assessment of the final price of a feedstock. Several studies have evaluated the economic cost of biofuel production. As in the case of the CO_2 footprint, the data on first-generation crops are more accurate than second-generation ones (Table 3).

Based on the data of Table 3, the production costs of second-generation feedstocks can vary from 17 US$ to 35 US$/Megajoule, which is −23% to +56% compared to fossil fuel costs, respectively. For first-generation biofuel crops, the cost varies from 9 US$ to 34 US$/Megajoule, which is −59% to +48% of the fossil fuels costs, respectively (Fig. 3).

The higher costs to produce biofuel from second-generation feedstocks can be associated with crop yield, conversion costs and labor costs [116]. Second-generation feedstocks show indeed lower yield than first-generation, and thus higher labor cost per unit of product. Finally, second-generation feedstocks have low conversion efficiency than first-generation, and thus they can require additional pre-treatment operations to produce biofuel [117–119]. Another relevant aspect of producing these feedstocks on marginal lands is transportation cost. Gouzaye et al. [120] highlighted that transportation costs play an important role in the biofuel industry. For low-energy–density feedstock, it may be more economical to utilize highly productive lands located near biorefineries rather than relying on less productive (marginal) lands scattered across a country. Therefore, key factors to lower the production costs of biofuel production from second-generation crops should focus on the breeding for highly productive varieties, the improvement of agronomical management, the energy densification early in the chain and the optimization of the conversion processes [91, 94–98]. For the latter, Hamelinck et al. [123] found a possible cost reduction of 23% thanks to an increasing scale of the biofuel facility and combined fuel and power production for a traditional method of energy conversion (Fischer–Tropsch). Similarly, for the production of ethanol from second-generation feedstocks it has been estimated a reduction of 52% of the current cost thanks to improved pre-treatment methods, reactor integration and decreased costs of cellulase enzymes. Sims et al. [72] identified several aspects that can be improved to reduce costs associated with biofuel production. For the biochemical route, the use of dilute and concentrate acid may improve the pre-treatment quality to maximize the

Table 3 LCC outcome for first- and second-generation feedstocks

Crops	Crop-generation	Biofuel production method	Cost Biofuel (Dollar GJ^{-1})	References
Triticum spp	First	–	8.5	[183]
Triticum spp	First	Fischer–Tropsch	9.05	[184]
Zea mays	First	Fischer–Tropsch	9.05	[184]
Brassica napus	First	–	10	[183]
Helianthus annuus	First	–	10	[183]
Helianthus annuus	First	Fischer–Tropsch	10.3	[184]
Brassica napus	First	Fischer–Tropsch	10.3	[184]
Glycine max	First	Transesterification	16	[185]
Glycine max	First	Transesterification	18.01	[116]
Brassica napus	First	Transesterification	19.5	[186]
Brassica napus	First	Transesterification	20	[187]
Glycine max	First	Transesterification	30	[188]
Zea mays	First	Hydrolysis and fermentation	30	[188]
Zea mays	First	Hydrolysis and fermentation	31.2	[117]
Zea mays	First	Hydrolysis and fermentation	36	[185]
Glycine max	First	Transesterification	37.5	[117]
Brassica napus	First	Transesterification	39	[189]
Brassica napus	First	Transesterification	45.6	[117]
Ligno-cellulosic	Second	Fast Pyrolysis	12.2	[190]
Ligno-cellulosic	Second	Hydrothermal liquefaction	18	[191]
Brassica carinata	Second	Transesterification	20	[127]
Ricinus communis	Second	Transesterification	21	[192]
Camelina sativa	Second	Transesterification	24	[187]
Ricinus communis	Second	Transesterification	27	[193]
Camelina sativa	Second	Transesterification	29	[194]
Brassica carinata	Second	Transesterification	31	[195]
Brassica carinata	Second	Catalytic hydrothermolysis	32	[196]
Camelina sativa	Second	Transesterification	34	[195]
Camelina sativa	Second	Transesterification-hydroprocessing	46	[197]
Fossil fuel	–	–	23	[184]

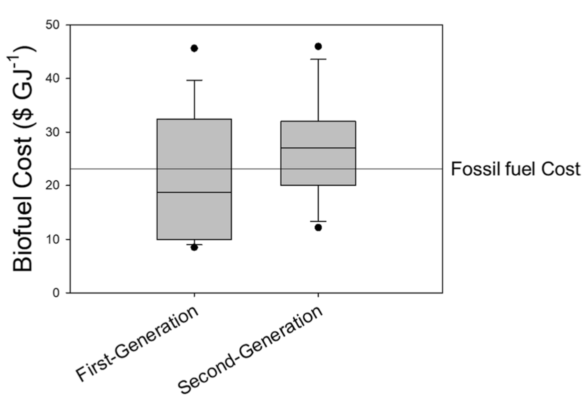


Fig. 3 Biofuel cost from first- and second-generation feedstock. First-generation crops (*Zea mays*, *Brassica napus*, *Glicyne max*, *Helianthus annus* and *Triticum spp*) and second-generation crops (*Brassica carinata*, *Camelina sativa*, *Ricinus communis*). The continuous line represents the diesel cost according to Wit et al. (2010)

subsequent hydrolysis. For the Fischer–Tropsch process, exploring catalysts with longer lifetime and lower susceptibility to impurities may also improve the overall efficiency of the system [72]. Lowering the cost of biofuel production from second-generation feedstocks is a pivotal aspect to maximize the benefits of their use compared to first-generation ones.

Conclusions

The challenge of energy supply for an ever-growing world population is highly debated. While concerns persist regarding the use of agricultural crops for bioenergy production, following clear and stringent guidelines for their cultivation could render this strategy promising. The combination of marginal land and second-generation feedstock can indeed overcome two of the major concerns regarding biofuel production, that is the food-fuel land competition and the high environmental footprint of first-generation feedstocks. Indeed, second-generation crops are generally associated with lower impact on biodiversity, additional environmental services, lower land use changes and economic benefits in areas where the cultivation of first-generation crops cannot be economically convenient. These aspects are the basis for a sustainable production of biofuel (*i.e.,* with minimal inputs on low productive fields for food production) which, in principle, could not impact food production and food prices. As other renewable energy sources, biofuels are not the silver bullet to solve the ongoing global energy challenge as indicated by the estimates of several authors, but could contribute to reducing the environmental impact of fossil fuels and human activities. Marginal lands could play a crucial role in developing sustainable biofuels since they would contribute to minimizing the competition between food and biofuel production. The value of ecosystem services could give a boost for a sustainable transition to biofuels production if they become a concrete and significant component of the farmer revenues. Moreover, breeding for highly productive varieties and optimization of conversion processes can also reduce the biofuel production cost from second-generation feedstocks. However, better soil databases (in terms of both quality and quantity of soil information) are required to map land suitability of second-generation biofuel crops at detailed scale. Indeed, the uncertainty on the amount of marginal land worldwide may misestimate the potential biofuel production, thus making impossible a fruitful comparison with other renewable energy sources. In addition, reliable ecosystem services assessments/quantifications based also on plant growth models are needed to help valuing the factual provision of ecosystem services and performing cost–benefit analyses for biofuel production with second-generation feedstocks on marginal lands. Finally, by crossing climatic, soil and crop data as input for process-based models it will be possible to simulate not only the productivity of biofuel crops and/or rotation between biofuel and food crops but also their impact on agronomic/environmental parameter such as soil organic matter accumulation and nitrogen leaching. This approach can be valuable to support policy decisions for a rationale planning of sustainable land use worldwide.

Author contributions

CR wrote the first draft of the manuscript, VC, NP, AM, FT and AC contributed to the revision and the final version. All authors read and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Agriculture, University of Naples Federico II, P.zza Carlo di Borbone, 80055 Portici, Italy. [2]CRISP Research Center, University of Napoli Federico II, P.zza Carlo di Borbone, 80055 Portici, Naples, Italy. [3]Eni S.P.A. Renewable, New Energies and Material Science Research Center (DE-R&D), Via Fauser, 4 – 28100, Novara, NO, Italy.

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