D1.5
Report on assessing carbon removal potential and iLUC risks of bio-based solutions

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DISCLAIMER

TABLE OF CONTENTS

LIST OF ACRONYMS

EC: European Commission

EU: European Union

HDPE: High-Density Polyethylene

LDPE: Low-Density Polyethylene

LUC: land use change

iLUC: indirect land use change

dLUC: Direct Land Use Change

GHG: Greenhouse Gas

GWP: Global Warming Potential

IFOAM: International Federation of Organic Agriculture Movements

IPCC: Intergovernmental Panel on Climate Change

LCA: Life Cycle Assessment

NASA: National Aeronautics and Space Administration

PHA: Polyhydroxyalkanoate

PLA: Polylactic Acid

PE: Polyethylene

UN: United Nations

EXECUTIVE SUMMARY

This report examines the environmental sustainability of bio-based products in the textile, packaging and fertiliser sectors. It highlights the dual role of these solutions in mitigating greenhouse gas emissions and promoting carbon neutrality, while addressing potential environmental risks, particularly those related to indirect land use change (iLUC). iLUC occurs when the production of bio-based solutions indirectly leads to the conversion of natural ecosystems into agricultural land, triggering carbon emissions and biodiversity loss. To assess these impacts, the present study uses a comprehensive methodology developed by the European Commission (EC) that considers historical deforestation data, regional land use patterns and crop intensification practices.

The report identifies significant differences in the iLUC impacts of the products analysed. In the textile sector, wool has the highest iLUC emissions due to the significant land requirements for grazing and feed production, while alternative materials such as hemp and polylactic acid (PLA) perform better. In the packaging sector, products containing polyhydroxyalkanoate (PHA) - a polymer derived from crops such as wheat - have higher iLUC due to the significant agricultural inputs required. The study highlights the example of the "beverage brick", a packaging product with a high proportion of PHA, which had one of the highest iLUC values in the project. Fertiliser products, on the other hand, have lower iLUC impacts. Organic fertilisers, for example, reduce greenhouse gas emissions by increasing soil carbon sequestration and reducing reliance on synthetic inputs, thus contributing to a more sustainable agricultural system.

The report stresses the importance of managing both direct and indirect land-use changes to ensure that the environmental benefits of bio-based solutions are not undermined. Strategies such as prioritising cultivation on marginal land and optimising agricultural practices are suggested to reduce competition for land and associated emissions. The study also highlights the need for life cycle assessments (LCA) to assess the full environmental impact of bio-based products, from raw material extraction to end-of-life. This holistic approach is essential to identify trade-offs and guide policy development to achieve carbon neutrality without exacerbating land use pressures.

1. INTRODUCTION

1.1 Global Environmental Context and Land Use Change

Climate change is one of the most urgent global challenges of our time and requires coordinated international efforts to reduce greenhouse gas emissions and limit the rise in global temperatures (UN, 2024). In this context, bio-based solutions such as bioenergy, biofuels, and bioplastics have emerged as promising pathways for reducing greenhouse gas (GHG) emissions and achieving carbon neutrality (Atiwesh et al., 2021; Jeswani et al., 2020; Zuiderveen et al., 2023). These solutions are designed to replace fossil-based products and contribute to the transition towards renewable energy systems. However, their deployment is not without challenges, particularly in relation to Land Use Change (LUC) and, more specifically, to indirect land use change (iLUC).

Land use directly affects the carbon cycle by determining whether carbon is stored in soil and plants or released into the atmosphere as carbon dioxide (CO_2) (NASA Earth Observatory, 2024; Ontl and Schulte, 2012; UN – Climate Action, 2024). Deforestation, intensive agriculture, and the conversion of natural ecosystems to agricultural land are all activities that contribute significantly to global warming by altering the natural carbon balance (Lawrence, 2022).

Land use is therefore a key issue in addressing climate change, and the analysis of how changes in land use can contribute to greenhouse gas emissions is essential to assess the effectiveness of climate policies. In particular, the production of biofuels and bio-based solutions is a sector that has seen growing interest in its potential to reduce carbon emissions, but it also carries risks related to land use change, particularly iLUC. For example, deforestation not only releases carbon previously stored in trees but also reduces the land's ability to act as a carbon sink, thus exacerbating climate change (Houghton & Nassikas, 2017).

Land use changes can occur directly or indirectly and separating these two types of change is important to fully understand the risks and opportunities associated with bioenergy policies. Direct Land Use Change (dLUC) refers to direct and immediate land use changes, such as the conversion of forest land to agricultural land or the construction of infrastructure. These changes are usually planned and measurable, with immediate impacts on biodiversity, soil quality and greenhouse gas emissions. Deforestation to make way for agricultural crops or industrial plantations is a classic example of dLUC (Plevin et al., 2010).

Instead, (iLUC refers to the unintended environmental consequences that arise when the production of bio-based solutions displaces agricultural or other land-based activities to new areas. This displacement often leads to the conversion of natural ecosystems, such as forests, grasslands, or wetlands, into agricultural land, resulting in significant GHG emissions. These emissions stem from the loss of carbon stored in vegetation and soil, as well as the reduced capacity of these ecosystems to act as carbon sinks. Thus, while biofuels and other bio-based solutions are often promoted as tools to mitigate climate change, the iLUC associated with their production can, in some cases, undermine their environmental benefits (Daioglou et al., 2020). Furthermore, unlike dLUC, iLUC is less visible and more difficult to measure, making it a contentious and complex issue in climate policy (Searchinger et al., 2008)

The management of soil and its transformation is crucial to reducing the risks associated with both dLUC and iLUC. Agricultural policies must be geared toward ensuring that bio-based solutions do not contribute to harmful changes in land use.

1.2 The Land Use Change Definition

It is important to note that different definitions are applied to land use change, particularly in the context of dLUC. For example, Marelli et al. (2015) defined a LUC to be direct as occurring when the required crops are grown on previously uncultivated land, as opposed to iLUC, which occurs when crops are grown on already cultivated or used land. Similarly, PAS2050 (BSI, 2011) describes dLUC as *'a change in land use at the production site of the product being assessed'*. In scientific literature, dLUC has also been characterised as "all changes in the above- and below-ground fluxes of carbon, nitrogen and phosphorus at a given site as one land use replaces another" by, for instance, Hamelin et al. (2012) and Tonini et al. (2012). Finally, the amended Renewable Energy Directive (EU, 2009; 2015) defines dLUC as occurring when feedstock production results in *"a change from one of the following IPCC land cover categories: forest, grassland, wetlands, settlements or other land to arable or perennial land"*. This definition is very close to the one proposed by PAS2050 (BSI, 2011).

Indirect land use change occurs when crops of interest are grown on existing agricultural land. In essence, iLUC results from changes in the overall demand for land. The key premise of iLUC is that the global agricultural land area is still expanding (driven by factors such as population growth, gross domestic product growth in certain countries, etc.) and remains finite. For example, if the feedstock for a bio-based case study is grown at the expense of another crop, the demand for the displaced crop - or the service it provides (e.g., protein feed) - will persist on the global market (EC, 2019).

The central assumption behind iLUC is that this relative reduction in supply (e.g., of protein feed) is likely to lead to an increase in agricultural prices, incentivising production expansion elsewhere. This expansion is typically achieved through growth of agricultural land, intensification of production or a combination of both (Bergtold et al., 2017; EC, 2019).

In summary, iLUC occurs when agricultural land, whether cropland or grazing land, is diverted to supply the feedstock of interest. A cascading series of land use changes occurs to compensate for the displaced feedstock. For example, displaced wheat from one country may be replaced by barley from another, which in turn displaces maize from a third country, and so on. This process continues until displacement is no longer possible, either through intensification of production or through conversion of non-agricultural land into agricultural land.

Definitions of iLUC are generally aligned across different sources. In the Renewable Energy Directive (EU, 2009), which focuses on fuels, iLUC is described as follows: *'When pasture or agricultural land previously used for food and feed production is diverted to biofuel production, the displaced demand for food and feed must still be met, either by intensifying existing production or by converting non-agricultural land elsewhere to agricultural use. The latter scenario constitutes indirect land use change [...]'*. Similarly, PAS2050 (BSI, 2011) defined iLUC as *'the change in land use that occurs in locations other than the country where the feedstock of interest is produced'*. Marelli et al. (2015) further elaborate that *'iLUC refers to global land-use changes resulting from the cultivation of the feedstock of interest on existing arable land, displacing production that previously occurred on that land'*.

The importance of treating dLUC and iLUC separately, rather than focusing solely on total LUC, has been questioned several times. In many studies analysing the overall impact of land-use changes like those performed, for instance, by Schmidt et al. (2015) and Tonini et al. (2016), the 'iLUC' impact factor often encompasses the 'dLUC' factor.

In this study, it was decided to carry out the iLUC evaluation based on the methodology developed by the European Commission (EC, 2019) as we believe it is the most comprehensive study currently available. Furthermore, most of the existing studies, methodologies and guidelines are specific to the study and evaluation of biofuels, whereas the European Commission (EC) methodology is more generic and applicable to other realities and processes, such as the bio-based products evaluated in the BIORADAR project. This methodology is explained in Section 2.2.

2. DESCRIPTION OF THE DOCUMENT AND PURSUE

This report presents the results of assessing the indirect land-use change (iLUC) to the products identified by the BIORADAR project.

BIORADAR has a primary focus on three key industry sectors: fertilizers, packaging, and textiles, whose analysed products are shown in Section 2.3 – The application of iLUC Assessment to BIORADAR products.

This deliverable refers to Task 1.5 "Evaluate metrics to assess the carbon removal potential and iLUC risk of bio-based solutions included in WP1 "Identifying and Assessing Sustainability aspects (Environmental, Economic, Social) of Industrial Bio-based Systems and embedding them into BTI Framework".

3. MATERIALS AND METHODS

To bring order to the different methodologies for the assessment of LUC, iLUC and dLUC that exist in the literature, the European Commission undertook an in-depth study to define a methodology and obtain a specific emission factor for the calculation of iLUC. The methodology developed by the European Commission is described in detail in section 3.1; it has not been modified or updated, but the emission factor developed by the European Commission has been used. Section 3.2 explains how the EC developed emission factor was applied and which inventory data were used.

3.1 The iLUC Assessment performed by European Commission

The impacts of iLUC usually are not to be included in the main Life Cycle Assessment (LCA) evaluations. According to PEFCR v.6.3 guidelines (EC, 2018), iLUC is nevertheless estimated and reported separately as a "non-PEF" impact (EC, 2019).

This methodology used a deterministic approach based on historical deforestation data from 2000 to 2010, which is an adaptation/update of the methodology proposed by Tonini et al. (2016). As a result, the method does not predict the impact of future demand for EU bio-based products but rather provides an estimate of the total deforestation and intensification emissions associated with the historical demand for 1 ha of cropland. The underlying assumption is that this estimate can provide valuable insights into the potential scale of such emissions in the future.

Furthermore, due to the methodology used, the generic 'iLUC factor' derived better described as a 'LUC factor', as it represents the average emissions associated with annual deforestation and intensification observed between 2000 and 2010. Consequently, it does not distinguish whether deforestation is a 'direct' or 'indirect' result of additional land demand. As a result, the iLUC factor obtained using this approach should be used independently to reflect the overall impact of LUC and should not be combined with dLUC emissions. Combining the two would lead to an overestimation of land use emissions.

The climate change emission factors from PEFCR v.6.3 were used (EC, 2018). This means that specific land use changes have been created, and the following climate change impacts have been used:

- CO_2 (land use changes), air emission: 1 $kg \cdot kg^{-1}$ CO_2eq (it is 0 for “CO_2, biogenic, air emission”).
- CO (land use changes), air emission: 1.57 $kg \cdot kg^{-1}$ CO_2eq (it is 0 for “CO, biogenic, air emission”).

- CH_4 (land use changes), air emission: 36.75 kg·kg^{-1} CO_2eq (it is 34 for "CO, biogenic, air emission").
- N_2O (land use changes), air emission: 298 kg·kg^{-1} CO_2eq

The EC method assesses the impact of iLUC in terms of modified carbon (CO_2, CH_4) and nitrogen (NO_x, NH_3, N_2O) fluxes (among others) based on the following 6-step methodology (Box 1 - EC, 2019) (see also Figure 1).

Box 1 - 6-Step iLUC Methodology

Step 1: Determine the contribution of expansion and intensification to the iLUC response.

Step 2: Determine the types and amount of land (biomes) that have expanded over the last 10 years of available deforestation data, and their location in the world (region). The result is a "biome x region" land expansion matrix.

Step 3: Determine how much of the observed deforestation from step 2 is due to demand for arable land.

Step 4: Estimate carbon and nitrogen emissions from land expansion using the biome x region matrix from step 2 and the proportion of deforestation due to demand for arable land from step 3.

Step 5: Estimate emissions from intensification

Step 6: Derivation of a generic iLUC factor

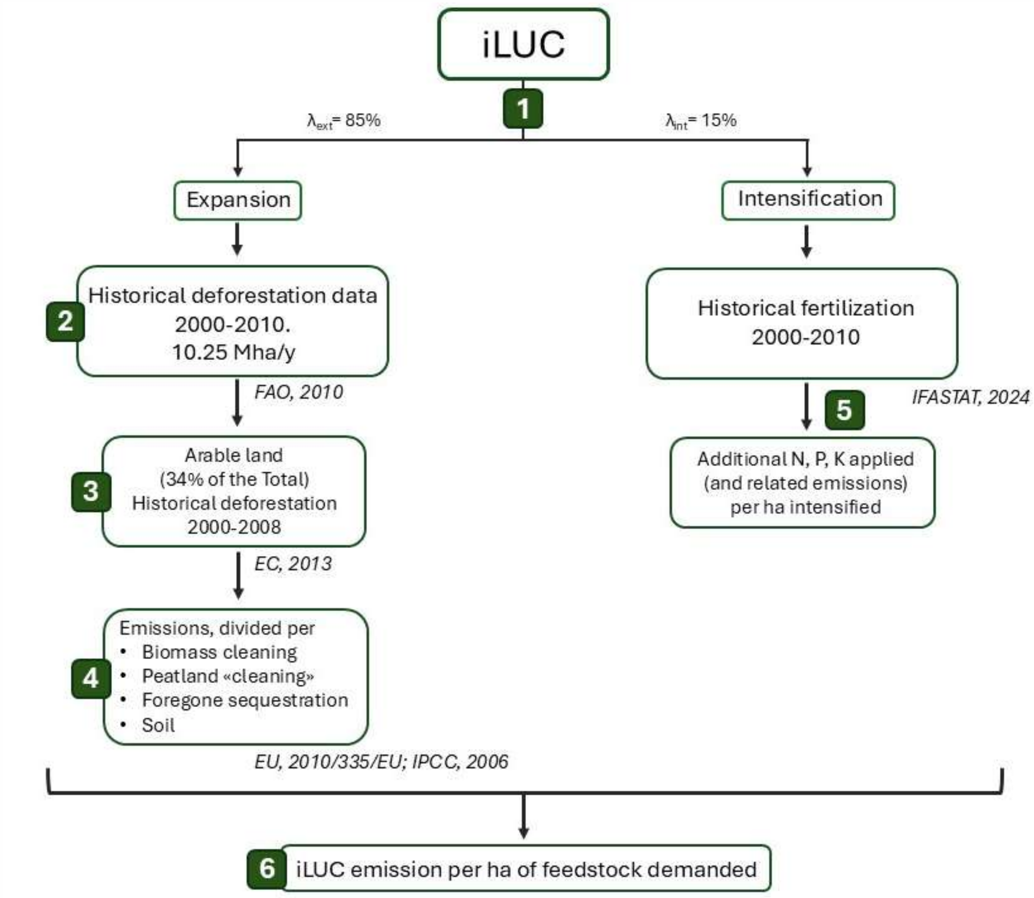

Figure 1 - Explanation of the 6-steps methodology used to assess the impacts of iLUC – Adapted from EC, 2019

3.1.1 Step 1: Share of the response from expansion and intensification

In this step, the share of the iLUC response due to expansion and intensification is determined. These shares are then used in step 6 of the methodology. While expansion is straightforward (conversion of natural land to agricultural land), intensification can be achieved through three main pathways:

- **Input-driven pathway**: This refers to any yield increase achieved through changes in agricultural inputs (e.g., fertilisers, pesticides, irrigation, etc.). Yield increases achieved in this way may, however, be reversible. They are also characterised by 'diminishing returns', which means that for each additional unit of input (e.g., fertiliser) applied, the magnitude of the additional yield becomes smaller and smaller until it is practically negligible.
- **Innovation-driven path**: This refers to yield increases achieved through technological development (e.g., harvesting technologies that allow more biomass to be harvested, plant breeding, etc.), but also to yield increases achieved through the application of additional inputs (e.g., fertiliser).

However, there is likely to be a lag of around 20 years before research and development activities translate into yield increases (Edwards et al., 2010).

- **Multi-cropping**: This is the practice of growing more than one crop on the same hectare of land each year, allowing year-round harvesting in some countries. In 2010, it accounted for about 18% of the world's cropland, and rising crop prices are expected to increase the profitability of this practice (Marelli et al., 2011).

To assess the contribution of intensification and expansion to the iLUC response, historical time series data (2002-2012) retrieved from the FAOSTAT database (FAOSTAT, 2014) were used for crop production, crop yield and cropland area. Total crop production was calculated as the sum of specific crop groups, following the approach proposed by Schmidt et al. (2015). The authors reported that that expansion accounted for 37% of the iLUC response, and intensification for 63%.

In this 6steps methodology, based on Marelli et al. (2011), the minimum) intensification quota (λ_{int}) was increased to 15% of the iLUC response. The expansion rate (λ_{exp}) was then increased to 85%. Furthermore, this study models intensification as 100% input driven (step 4), which may overestimate the impact of increased fertilisation and underestimate the (likely beneficial) impact of multi-cropping (EC, 2019).

3.1.2 Step 2: Geo-quantification of arable land expansion

Existing methodologies in the literature vary widely at this stage. Two main approaches were used: economic equilibrium modelling and causal deterministic modelling (Warner et al., 2013).

The economic equilibrium modelling approach is often used in studies modelling the environmental impacts of iLUC, especially in the context of biofuels (Edwards et al., 2010; Laborde, 2011; Marelli et al., 2011; Searchinger et al., 2008; Valin et al., 2015). This approach is used because of the nature of the iLUC process: changes in land use led to changes in crop supply, which are transmitted through global markets related to commodity substitutability and competition through numerous interactions. To cope with this, sophisticated models of global crop markets are considered essential. Such econometric models are based on partial equilibrium models (representing one sector of the economy) or general equilibrium models (representing the whole economy). They are considered to provide relevant results for the short to medium term (Marelli et al., 2015).

A less complex but more transparent and reliable alternative over time is to use a deterministic causal descriptive model, often referred to as the biophysical approach. This is the approach used in the EC methodology. The aim is to establish a cause-effect relationship between the demand for cropland and the effects of expansion/intensification using historical statistical data on deforestation, loss of natural biomes (e.g., scrubland and grassland), crop yields and fertiliser use. In other words, the aim is to derive a 'generic' emission factor for each initial hectare of cropland required to produce the feedstock.

The starting point is the deforestation that took place between 2000 and 2010 (latest data available), as reported by FAO (2010) by world region.

As a result, an average of 10.25 Mha was converted per year, divided as explained in Table 1.

Table 1 - Deforestation occurred between 2000-2010 - from FAO (2010)

Geographical Area	Percentage (%)
South America (Argentina, Bolivia, Brazil, Chile, Columbia, Ecuador, Falkland Island, French Guyana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela)	40%
Africa	34%
South-East Asia (Brunei, Cambodia, Indonesia, Lao, Malaysia, Myanmar, Philippines, Singapore, Thailand, East Timor, Vietnam) Note: In this case, out of the total, an area of 0.26 Mha y^{-1} has been considered to reflect peatland losses. This is the average annual value for peatland losses in Indonesia & Malaysia in 2000-2010, based on FAO (2012)	12%
Oceania	6.9%
Central America	4.6%
Rest of Asia	2.2%
Eastern Europe (Countries of the former Soviet Union including Russia)	0.2%
Rest of Europe	0.3%
United States and Rest of North America (Bermuda, Canada, Greenland, Saint-Pierre-et-Miquelon)	negligible

Based on IPCC (2006), forest loss has been divided into five biome categories (tropical, subtropical, temperate, boreal and polar). Except for the latter, all have been further subdivided (e.g., tropical rainforest, tropical dry forest, etc.), so that all IPCC (2006a) biomes have been included. To link these biomes to the FAO (2010) deforestation regions (e.g. 'Africa'), it is necessary to distribute the forest loss in each region within each biome in the region. This was done based on the distributions in FAO (2000). In total, 82 combinations of regions x biomes were considered in this step of the 6step methodology (EC, 2019).

3.1.3 Step 3: Attributing deforestation to the demand for arable land

This step consists in understanding how much of the deforestation in the period 2000-2010 was due to demand for arable land, denoted by ξ. This assessment was carried out by DG Environment (EC, 2013). According to this study, 34% of the deforestation that occurred between 2000 and 2008 was due to the demand for arable land, and it is assumed that this value also applies to later periods. The FAO (2010) regional total deforestation values were then adjusted accordingly.

3.1.4 Step 4: Carbon and Nitrogen emissions from expansion

Data on above-ground biomass from the EC (2010) and IPCC (2006) were used to estimate the amount of carbon lost through conversion of natural soils. Two types of emissions were considered: initial emissions from land clearing (above-ground biomass) and emissions from non-sequestration. The latter reflects the CO_2 uptake that would otherwise have occurred.

Emissions from deforestation resulting from possible carbon and nitrogen losses from below-ground biomass and soil carbon were not included. This may underestimate the overall impact of iLUC, as highlighted in some studies (e.g., Gibbs et al., 2008; Müller-Wenk and Brandão, 2010).

Emissions (CO_2-C) from non-sequestration were considered as a loss of ecosystem services over a 20-year period, considering only mature trees (above-ground biomass > 20 years according to IPCC). These emissions are calculated according to Equation 1 (adapted from Equation S17 of Tonini et al., 2016):

Equation 1 - Emissions (CO_2-C) from non-sequestration

$$CEF_{\mathrm{FS,b,r}} = \sum_{b,r=1}^{n} \frac{(1+\mathrm{R})\times \mathrm{AG}_{\mathrm{t>20yb,r}}\times \mathrm{C}\times 44\times SL_r\times LL_r\times \xi}{12}$$

Note:

- $CEF_{FS,b,r}$: carbon dioxide emission for foregone sequestration (t CO_2-C ha^{-1} y^{-1});
- $AGt_{>20}$: above-ground biomass growth for t > 20y (IPCC, 2006a) (t DM ha^{-1}b y^{-1});
- C: carbon content in biomass (47%; IPCC, 2006a) (t C t DM^{-1});
- R: below-ground to above-ground biomass ratio (IPCC, 2006a) (%);
- SL_r: share of land covered by biome b, in region r (%);
- LL_r: land cover loss of biome b, in region r (%);
- ξ: portion of deforestation due to the demand for arable land (34%);
- b,r: indicate biome type and geographic region, respectively.

CO_2, CO, CH_4, N_2O and NO_x emissions from biomass combustion are calculated according to Equation 2, using biomass data reported in (EC, 2010), but IPCC data (IPCC, 2006) were used when no other data were available.

Equation 2 - Emissions (CO_2, CO, CH_4, N_2O, NO_x) from biomass combustion

$$CEF_{LC,b,r} = \sum_{b,r=1}^{n} \frac{AG_{b,r} \times EF_{LC,b} \times SL_r \times LL_r \times \xi}{C \times 1000}$$

Note:

- $CEF_{LC,b,r}$: Emission (CO_2, CO, CH_4, N_2O, NO_x) for land clearing (t di emissioni ha^{-1} y^{-1});
- $AG_{b,r}$: above-ground biomass stock (EC, 2010; IPCC, 2006) (t C $ha^{-1}{}_{b,r}$ y^{-1});
- $EF_{LC,\,b}$: Emission factor for biomass burning, for CO_2, CO, CH_4, N_2O, NO_x (IPCC 2006) (g kg^{-1} DM).

Land clearing also includes peatland clearing. This was only considered for the mean annual peatland loss in Malaysia and Indonesia (0.26 Mha y^{-1}; taken from Joosten et al., 2012). The emission factors provided by the IPCC were considered (IPCC, 2013), as shown in Equation 3:

Equation 3 - Emissions from peatland clearing

$$CEF_{PL} = \frac{APL \times EF_{PL} \times \boldsymbol{SPL} \times \xi}{AFL}$$

Note:

- CEF_{PL}: Emission (CO_2-C, CH_4, N_2O-N) from peatland losses (kg o t di emission ha^{-1} y^{-1});
- APL: Average annual peat loss (0.26 Mha y^{-1});
- AFL: Average annual forest loss (10.25 Mha y^{-1});
- EF_{PL}: Emission factor for peatland loss, for CO_2-C, CH_4, N_2O-N (IPCC, 2013) (kg o t ha^{-1} y^{-1});
- SPL: share of peatland covers in South-East Asia (19%).

3.1.5 Step 5: Emissions related to intensification

It is assumed that 100% of the response to intensification is provided by the increase in fertiliser (N, P and K). But how much additional fertiliser is applied per intensified hectare? Emissions from intensification were calculated based on the emission factors presented in Tonini et al. (2016). These are based on statistical data retrieved from the International Fertiliser Association (IFA) database (IFASTAT, 2024) on the annual variation (2000-2010) in the global use of N, P and K fertilisers and on statistics compiled on the annual variation in (fertilised) agricultural land. Accordingly, the following factors were used 166 kg N ha_{int} y^{-1} (considered as urea), 68 kg P_2O_5 ha_{int} y^{-1} (considered as ammonium phosphate), 47 kg K_2O ha_{int} y^{-1} (considered as potassium chloride). Emissions (N_2O, NH_3, NO_x) from urea application were derived from Hamelin et al. (2012), while NO_3 was considered as 20% of applied nitrogen based on Galloway et al. (2004).

3.1.6 Step 6: Step 5: Emissions related to intensification

In the final step the emissions measured per expanded area (from step 4) and per intensified area (from step 5) are aggregated according to their respective iLUC response rates (step 1); the resulting value are summarized in Table 2. The emissions are annualised over 20 years, in line with most LUC calculations used by the Commission (Edwards et al., 2014).

Table 2 - Summary of emission due to indirect land use changes

Expansion/ Intensification	Emission or material input	Value	Unit
Expansion (85%)	$CO_{2,FS}$	0.74	t ha^{-1}_{exp}
	$CO_{2,LC}$	71.6	t ha^{-1}_{exp}
	$CO_{2,PL}$	0.64	t ha^{-1}_{exp}
	$N_2O_{,LC}$	9.08E-3	kg ha^{-1}_{exp}
	$N_2O_{,PL}$	1.24E-4	kg ha^{-1}_{exp}
	$NO_{x,LC}$	0.073	kg ha^{-1}_{exp}
	$CH_{4,LC}$	0.307	kg ha^{-1}_{exp}
	$CH_{4,PL}$	1.60E-4	kg ha^{-1}_{exp}
	CO_{LC}	4.71	kg ha^{-1}_{exp}
Intensification (15%)	N_2O	4.4	kg ha^{-1}_{int}
	NH_3	4	kg ha^{-1}_{int}
	NO_x	6	kg ha^{-1}_{int}
	$NO_{3\text{-}N}$	33	kg ha^{-1}_{int}
	N-fertiliser	166	kg N ha^{-1}_{int}
	P-fertiliser	68	kg P_2O_5 ha^{-1}_{int}
	K-fertiliser	47	kg K_2O ha^{-1}_{int}

Note:
Emission to air except for NO3-N, which is an emission to water.
FS = Foregone sequestration; LC = Land clearing; PL = Peatland losses.

The overall iLUC factor in terms of CO_2eq obtained by the study of the EC is compared with the factors obtained in previous studies (Table 3).

Table 3 - Comparison with other iLUC studies with factors per ha·y^{-1}

Study	Time (y)	iLUC factor ($t\ CO_2eq\ ha^{-1}\ y^{-1}$)	Note
Audsley et al., 2009	/	1.4	General use
Schmidt and Munos, 2014	/	1.7	World average arable land
Tonini et al., 2016	100	4.1	General use
EC, 2019	**20**	**4.0**	**General use**

3.2 The application of iLUC Assessment to BIORADAR products

Table 4 lists the products evaluated in this study. The generic conversion factor developed by the EC in the study described above (EC, 2019) was then used to assess the iLUC for the purposes of the BIORADAR project.

This emission factor, expressed in kg $CO_2eq\ ha^{-1}\ y^{-1}$, was multiplied by the sum of all impact values in terms of land use, whether due to use or conversion (values expressed in m^2a - i.e. annual m^2 - are assimilated to m^2; see e.g., Table 5). The values were converted to hectares (ha) and then multiplied by the emission factor.

For each product evaluated in BIORADAR, the raw material of organic origin from which the product is derived has been considered as the primary input. This information can be found in Table 4 and is described by the LCA based process shown. For example, for the process 'Wool' the input (process) 'Wool' is considered, as provided by the Ecoinvent v3 database within SimaPro.

Table 4 - BIORADAR's target bio-based products.

Products	Data Source	Product Description	Data Process used	Process Database
Textile				
Wool	NTT Data (Prato District)	1 kg of wool fabric	Sheep fleece in the grease {RoW}| sheep production, for wool | Alloc Def, S	Ecoinvent v3
Hemp	Sphera	1 kg of hemp fabric	RER | Hemp fibre fleece [EN15804 A1-A3] and DE | Polyester resin (unsaturated) (UP)	LCA for Experts v10.7.1.28
PLA	Bio4Self Project	1 kg of PLA fabric	Polylactide, granulate {GLO}| market for | Alloc Def, S	Ecoinvent v3
Lyocell	Guo et al., 2021	1 kg of Lyocell fabric	Sulfate pulp {GLO}| market for | Alloc Def, S	Ecoinvent v3
Viscose	Guo et al., 2021	1 kg of Viscose fabric	Sulfate pulp {GLO}| market for | Alloc Def, S	Ecoinvent v3
Packaging				
Folding boxboard/chipboard	SimaPro	1 kg of folding boxboard/chipboard	Folding boxboard/chipboard {GLO}| market for | Alloc Def, S	Ecoinvent v3
Corrugated board box	SimaPro	1 kg of corrugated board box	Corrugated board box {GLO}| market for	Ecoinvent v3

			corrugated board box | Alloc Def, S	
Kraft paper, bleached	SimaPro	1 kg of kraft paper, bleached	Kraft paper, bleached {GLO}| market for | Alloc Def, S	Ecoinvent v3
Kraft paper, unbleached	SimaPro	1 kg of kraft paper, unbleached	Kraft paper, unbleached {GLO}| market for | Alloc Def, S	Ecoinvent v3
Pocket To Go (D1)	PRESERVE Project	Composition: 97% self-reinforced PLA (Sr-PLA) – Inventory data from Maga et al., 2019 Unit: 1 kg	Polylactide, granulate {GLO}| market for | Alloc Def, S	Ecoinvent v3
Snack Flowpack (D2)	PRESERVE Project	Composition: 74% BioLDPE (and to a lesser extent other organic components; everything is assumed to be Bio-LDPE) - Inventory data from Trucillo et al., 2024 Unit: 1 kg	Sugarcane {RoW}| market for | Alloc Def, S	Ecoinvent v3
Beverage Brick (D4)	PRESERVE Project	Paperboard: 80.65% PHA: 19.35% PHA Inventory data from Saavedra del Oso et al., 2023 Unit: 1 kg	Solid unbleached board {GLO}| market for | Alloc Def, S Wheat grain {RoW}| wheat production | Alloc Def, S	Ecoinvent v3
Molded Pulp (D5)	PRESERVE Project	Molded pulp: 87.24% PHA: 12.76% PHA Inventory data from Saavedra del Oso et al., 2023 Unit: 1 kg	Solid unbleached board {GLO}| market for | Alloc Def, S Wheat grain {RoW}| wheat production | Alloc Def, S	Ecoinvent v3

Blow Molded Bottle (D8)	PRESERVE Project	Bio r-HDPE: 30.00% Bio r-LDPE: 57.50% Inventory data from Trucillo et al., 2024 Unit: 1 kg	Sugarcane {RoW}| market for | Alloc Def, S	Ecoinvent v3
Fertilizer				
Compost - South	FER-PLAY project	Food and green waste compost is produced in Mediterranean Europe.	Own inventory	Ecoinvent v3.9.1
Compost - Central	FER-PLAY project	Food and green waste compost produced in central Europe.	Own inventory	Ecoinvent v3.9.1
Compost - North	FER-PLAY project	Food and green waste compost produced in northern Europe.	Own inventory	Ecoinvent v3.9.1
Feather Meal - Case 1	FER-PLAY project	Without the background processes linked to WWT	Own inventory	Ecoinvent v3.9.1
Feather Meal - Case 2	FER-PLAY project	With the background processes linked to WWT	Own inventory	Ecoinvent v3.9.1
Feather Meal - Case 3	Fer-Play project Hasler, 2017	Animal's feather unspecified. Hydrolyzing compound H_2O_2.Water content in hydrolysed feather, 40% and N content 12%	Own inventory	LCA for Experts v10.7.1.28

Feather Meal - Case 4	FER-PLAY project Hasler, 2017 Fitriyanto et al., 2022 Vavrova et al., 2022	The feather source was goose feathers. The ratio hydrolysed feather/raw feather was modified as well as the water content in hydrolysed feather (65%) nitrogen content (15.3%) and the hydrolysing compound (NaOH instead of H_2O_2)	Own inventory	LCA for Experts v10.7.1.28
Feather Meal - Case 5	FER-PLAY project Hasler 2017 Sobucki et al., 2019 Fitriyanto et al., 2022	The feather source was layer chicken feather. The ratio hydrolysed feather/raw feather was modified (0.788) as well as the nitrogen content (11.9%), water content of the hydrolysed feather (40% instead of 65%) and the hydrolysing compound (NaOH instead of H_2O_2)	Own inventory	LCA for Experts v10.7.1.28
Wood Vinegar - Case 1	Brassard et al., 2019 Brassard et al., 2021	Without valorisation of the byproducts. Wood biomass unspecified. Water content 29.9%. Volatile matter 80%. Lower heating value 17.8 MJ/kg	Own inventory	LCA for Experts v10.7.1.28
Wood Vinegar - Case 2	Brassard et al., 2019 Brassard et al., 2021	Valorising the byproducts of CASE 1	Own inventory	LCA for Experts v10.7.1.28
Wood Vinegar - Case 3	Pérez Riesgo, 2016 Gholizadeh et al., 2019	Poplar residues. Water content 7.4%. Volatile matter 79.3%. Lower heating value 18.4 MJ/kg	Own inventory	LCA for Experts v10.7.1.28

Wood Vinegar - Case 4	Amutio et al., 2015 Velázquez Martí et al., 2023	Eucaliptus residues. Water content 9.5%. Volatile matter 87.4%. Lower heating value 15.4 MJ/kg	Own inventory	LCA for Experts v10.7.1.28
Wood Vinegar - Case 5	Cuesta Astorga, 2019 Velázquez Martí et al., 2023 Gholizadeh et al., 2019 Theapparat et al., 2018	Cotton stalk. Water content 2.1%. Volatile matter 80.6%. Lower heating value 17.1 MJ/kg	Own inventory	LCA for Experts v10.7.1.28
Algae - Case 1	Castro et al., 2023	Microalgae from wastewater with CO_2 injection	Own inventory	LCA for Experts v10.7.1.28
Algae - Case 2	LIFE PROJECT – Confidential industry data	Microalgae from wastewater with CO_2 and polyelectrolyte addition	Own inventory	LCA for Experts v10.7.1.28
Algae - Case 3	Arashiro et al., 2018	Microalgae from wastewater with organic flocculant	Own inventory	LCA for Experts v10.7.1.28
Algae - Case 4	HE PROJECT – Confidential industry data	Microalgae fed with biowaste	Own inventory	LCA for Experts v10.7.1.28

Table 5 - Inventory data for evaluation of Occupation and Transformation of land - Example for Wool

Sheep fleece in the grease {RoW}| sheep production, for wool | Alloc Def, S			
Unit: kg 1			
Impact	**System**	**Unit**	**Value**
Occupation, arable, non-irrigated	land	m^2a	1.48E-05
Occupation, construction site	land	m^2a	4.01E-02
Occupation, dump site	land	m^2a	1.62E-02
Occupation, forest, intensive	land	m^2a	2.05E+00
Occupation, industrial area	land	m^2a	1.78E-01
Occupation, mineral extraction site	land	m^2a	6.29E-03
Occupation, pasture and meadow, extensive	land	m^2a	4.72E-06
Occupation, pasture and meadow, intensive	land	m^2a	1.62E-04
Occupation, shrub land, sclerophyllous	land	m^2a	6.43E-04
Occupation, traffic area, rail network	land	m^2a	3.41E-03
Occupation, traffic area, road network	land	m^2a	3.58E-02
Occupation, urban, discontinuously built	land	m^2a	2.71E-01
Occupation, water bodies, artificial	land	m^2a	1.61E-02
Transformation, from arable	land	m^2	2.34E+01
Transformation, from arable, non-irrigated	land	m^2	1.92E-03
Transformation, from dump site, inert material landfill	land	m^2	5.62E-05
Transformation, from dump site, residual material landfill	land	m^2	5.88E-05
Transformation, from dump site, sanitary landfill	land	m^2	1.10E-05
Transformation, from dump site, slag compartment	land	m^2	2.56E-06
Transformation, from forest	land	m^2	1.02E-03
Transformation, from forest, extensive	land	m^2	5.01E-04
Transformation, from industrial area	land	m^2	2.06E-05
Transformation, from mineral extraction site	land	m^2	2.01E-04
Transformation, from pasture and meadow	land	m^2	1.11E+02
Transformation, from pasture and meadow, extensive	land	m^2	9.43E-08
Transformation, from pasture and meadow, intensive	land	m^2	7.76E-05
Transformation, from sea and ocean	land	m^2	1.28E-04
Transformation, from shrub land, sclerophyllous	land	m^2	8.77E-02
Transformation, from unknown	land	m^2	7.25E-04
Transformation, to arable	land	m^2	6.20E+00
Transformation, to arable, non-irrigated	land	m^2	3.95E-05
Transformation, to dump site	land	m^2	1.11E-04

Transformation, to dump site, inert material landfill	land	m^2	5.62E-05
Transformation, to dump site, residual material landfill	land	m^2	5.88E-05
Transformation, to dump site, sanitary landfill	land	m^2	1.10E-05
Transformation, to dump site, slag compartment	land	m^2	2.56E-06
Transformation, to forest	land	m^2	1.86E-04
Transformation, to forest, intensive	land	m^2	2.56E-02
Transformation, to heterogeneous, agricultural	land	m^2	3.14E-05
Transformation, to industrial area	land	m^2	3.36E-04
Transformation, to mineral extraction site	land	m^2	1.20E-03
Transformation, to pasture and meadow	land	m^2	1.11E+02
Transformation, to pasture and meadow, extensive	land	m^2	4.90E-06
Transformation, to pasture and meadow, intensive	land	m^2	2.30E-05
Transformation, to shrub land, sclerophyllous	land	m^2	1.29E-04
Transformation, to traffic area, rail network	land	m^2	7.89E-06
Transformation, to traffic area, road network	land	m^2	1.42E-04
Transformation, to unknown	land	m^2	3.50E-05
Transformation, to urban, discontinuously built	land	m^2	5.39E-03
Transformation, to water bodies, artificial	land	m^2	1.52E-04
Occupation, arable	land	m^2a	5.70E+00
Occupation, forest, extensive	land	m^2a	3.13E-03
Occupation, pasture and meadow	land	m^2a	1.11E+02
Occupation, permanent crop	land	m^2a	8.95E-04
Transformation, from forest, intensive	land	m^2	2.52E-02
Transformation, from heterogeneous, agricultural	land	m^2	5.99E-08
Transformation, from permanent crop	land	m^2	2.19E-05
Transformation, from traffic area, road network	land	m^2	3.65E-08
Transformation, to forest, extensive	land	m^2	2.41E-05
Transformation, to permanent crop	land	m^2	4.48E-05
Transformation, to urban/industrial fallow	land	m^2	9.08E-09
Transformation, to permanent crops, non-irrigated, intensive	land	m^2	1.59E-07
Transformation, to permanent crops, non-irrigated	land	m^2	4.30E-08
Transformation, to permanent crops, irrigated, intensive	land	m^2	1.64E-06
Transformation, to arable, non-irrigated, intensive	land	m^2	1.92E+01
Transformation, to arable, non-irrigated, extensive	land	m^2	3.04E-03
Transformation, to arable, irrigated, intensive	land	m^2	1.85E-04
Transformation, to arable, fallow	land	m^2	2.52E-06
Transformation, from permanent crops, non-irrigated, intensive	land	m^2	1.59E-07

Transformation, from grassland, not used	land	m^2	2.89E-07
Transformation, from forest, primary	land	m^2	1.99E-02
Transformation, from arable, non-irrigated, intensive	land	m^2	1.95E+00
Transformation, from arable, non-irrigated, extensive	land	m^2	3.02E-03
Occupation, urban/industrial fallow	land	m^2a	6.81E-07
Occupation, grassland, not used	land	m^2a	3.21E-04
Occupation, arable, non-irrigated, intensive	land	m^2a	9.68E+00
Occupation, arable, non-irrigated, extensive	land	m^2a	1.67E-03
Occupation, arable, irrigated, intensive	land	m^2a	2.24E-04
Occupation, arable, irrigated	land	m^2a	2.15E+00
Transformation, to traffic area, rail/road embankment	land	m^2	1.52E-04
Occupation, traffic area, rail/road embankment	land	m^2a	1.99E-02
Occupation, seabed, drilling and mining	land	m^2a	1.28E-04
Occupation, seabed, infrastructure	land	m^2a	1.45E-06
Transformation, from cropland fallow (non-use)	land	m^2	8.44E-07
Transformation, from seabed, infrastructure	land	m^2	3.49E-09
Transformation, from wetland, inland (non-use)	land	m^2	7.58E-07
Transformation, to seabed, drilling and mining	land	m^2	1.28E-04
Transformation, to seabed, infrastructure	land	m^2	5.05E-07
Transformation, to seabed, unspecified	land	m^2	3.49E-09
Transformation, from traffic area, rail/road embankment	land	m^2	1.06E-04
Transformation, to forest, secondary (non-use)	land	m^2	4.30E-08
Transformation, to wetland, inland (non-use)	land	m^2	1.36E-07
Total Occupation		m^2	**1.31E+02**
Total Transformation		m^2	**2.72E+02**
Total		m^2	**4.03E+02**

4. RESULTS AND DISCUSSION

Table 6 and Figures 2-4 show the results of the iLUC evaluation for the products belonging to the textile, packaging and fertiliser sectors considered in the BIORADAR project.

As can be seen from Table 6, the results vary widely, from -0.36 kg CO_2eq for compost (the 'North' case) to 182.32 kg CO_2eq for wool. It is not scientifically meaningful to compare the different products with each other, as they are completely different products with very different functions. However, it is possible to identify some general factors that underlie some of the results. For example, wool seems to be the product with the greatest impact in terms of iLUC (even between products with the same 'kg of fabric' function), because the results include land conversion for grazing, feed production, hay production for bedding, etc. In the context of wool products, iLUC might be considered if the production of wool leads to changes in land use that indirectly cause environmental harm. For example, if grazing land for sheep is expanded into previously untouched natural areas, this could contribute to iLUC. The iLUC in wool production refers to the environmental impacts that occur when land use is altered indirectly due to the demand for wool. This can happen when land previously used for other purposes, such as forests or grasslands, is converted to grazing land for sheep. This conversion can lead to increased carbon emissions and loss of biodiversity. For example, if the demand for wool increases, it might lead to more land being used for sheep farming. This can displace other agricultural activities or natural habitats, causing indirect environmental impacts.

In the textile sector, the use of natural fibres such as cotton, wool, flax and hemp play a crucial role in reducing CO_2 emissions. Plants such as cotton and hemp absorb CO_2 from the atmosphere as they grow through the process of photosynthesis, effectively storing carbon in their structures. This makes their cultivation not only a source of raw materials but also a natural carbon sink. In addition, some of these crops, such as hemp and flax, are known for their fast growth rates and minimal need for synthetic fertilisers or pesticides, further enhancing their environmental benefits (Liu et al., 2023).

The use of bio-based materials also offers a significant advantage by reducing dependence on petroleum-based synthetic fibres such as polyester and nylon, which are derived from fossil fuels and have a high carbon footprint throughout their production processes. Synthetic fibres not only contribute to greenhouse gas emissions during their manufacture but also release microplastics into ecosystems during their use and disposal phases, compounding their environmental impact (Gonzalez et al., 2023; Liu et al., 2023).

In addition, natural fibres are often biodegradable, meaning they break down more easily in the environment than synthetic fibres, minimising long-term waste.

Efforts to increase the uptake of bio-based textiles are in line with circular economic principles, emphasising renewable inputs and reducing end-of-life waste. Recent advances in sustainable agriculture and fibre processing technologies also increase the feasibility of scaling up the use of these natural materials in the textile industry (Seile et al., 2022). Overall, the integration of natural fibres and bio-based alternatives into the textile sector can significantly contribute to reducing the industry's carbon footprint while addressing broader environmental challenges, including resource depletion and waste management.

Other products with high iLUC values are packaging products, which (if wool is excluded) have the highest average values of all products evaluated. In particular, the value for the product 'Beverage Brick (D4)' is particularly high, mainly due to the high proportion of PHA in its formulation (32%). As reported by Saavedra del Oso et al. (2023), PHA is derived from cereal crops and 105.7 kg of wheat is required to produce 1 kg of finished product. In general, iLUC in the production of PHA, involves the unintended environmental impacts that occur when land use is altered indirectly due to the demand for PHA feedstocks. Polyhydroxyalkanoates are typically produced from renewable resources like sugar or vegetable oils, which can lead to changes in land use patterns. For instance, if the demand for PHA increases, it might lead to more agricultural land being dedicated to growing the necessary feedstocks.

The large impact of PHA is also evident from the fact that the second packaging product with the highest iLUC result is 'Molded pulp (D5)', which contains 12.8% PHA. In this respect, the production of bio-PE (and bio-HDPE and bio-LDPE, which are assimilated to it) also has a non-negligible impact, since, according to Trucillo et al. (2024), 40.62 kg of sugar cane are needed to produce 1 kg of finished product (PE).

The introduction of bio-based packaging materials, such as bioplastics made from renewable resources such as corn starch, sugar cane or cellulose, offers a promising and sustainable alternative to traditional fossil-based plastic packaging. Unlike traditional plastics, which are derived from petroleum and contribute significantly to greenhouse gas emissions during production, bio-based packaging materials often have a lower carbon footprint. These materials are made from biomass that absorbs CO_2 as it grows, offsetting some of the emissions generated during production (Rosenboom et al., 2022; Shen, 2022).

Furthermore, bio-based packaging materials can be designed to be compostable or biodegradable, offering an additional advantage in reducing the accumulation of persistent plastic waste in the environment. Compostable bioplastics, for example, break down into natural elements under specific conditions, reducing waste in landfills and curbing microplastic pollution. Some types of bio-based packaging, such as those derived from agricultural residues or forestry by-products, also make use of otherwise wasted resources, enhancing their overall environmental performance (Yadav & Nikalje, 2024). In addition to their ecological benefits, bio-based packaging materials align with the principles of a circular economy. By transitioning from finite fossil-based resources to renewable feedstocks, these materials support a regenerative approach to production and consumption. They also encourage the development of closed-loop systems, where materials are continuously reused, recycled, or returned to the earth (Rosenboom et al., 2022).

However, challenges remain in scaling up the use of bio-based materials. These include the need for efficient production processes, infrastructure for composting and recycling, and potential competition for arable land between biomass production and food crops. Despite these barriers, the continued development of bio-based technologies and supportive policy frameworks can accelerate the adoption of these sustainable alternatives. Overall, the transition to bio-based products in packaging and other sectors is critical to reducing greenhouse gas emissions, addressing the plastic waste crisis and promoting a more circular and sustainable economy. It is an important step towards achieving global climate and environmental goals (de Souza et al., 2024).

Both dLUC and iLUC can have a significant impact on environmental performance, especially when considering the increased future demand for bio-based products (Schulte et al., 2021). For example, a study evaluating different agricultural substrates for biogas production showed that dLUC can reduce the total Global Warming Potential (GWP) by up to 50%, while iLUC can increase it by about 16% to 31% (Lask et al., 2020). To minimise the negative impacts of dLUC and iLUC, cultivation should be prioritised on marginal land where little or no competition with food crops is expected (Lewandowski et al., 2016; Schulte et al., 2021).

Table 6 - iLUC Results for BIORADAR products

Sector	Product	iLUC kg CO_2eq
Textile	Wool	182.32
	Hemp	1.58
	PLA	2.00
	Lyocell	1.94
	Viscose	1.94
Packaging	Folding boxboard/chipboard	0.73
	Corrugated board box	0.56
	Kraft paper, bleached	1.99

	Kraft paper, unbleached	2.95
	Pocket To Go (D1)	6.77
	Snack Flowpack (D2)	7.34
	Beverage Brick (D4)	126.06
	Molded Pulp (D5)	50.86
	Blow Molded Bottle (D8)	6.55
Fertilizer	Compost - South	0.44
	Compost - Central	0.16
	Compost - North	-0.36
	Feather Meal - Case 1	0.003
	Feather Meal - Case 2	0.004
	Feather Meal - Case 3	0.004
	Feather Meal - Case 4	0.021
	Feather Meal - Case 5	0.020
	Wood Vinegar - Case 1	0.0235
	Wood Vinegar - Case 2	0.024
	Wood Vinegar - Case 3	0.03
	Wood Vinegar - Case 4	0.03
	Wood Vinegar - Case 5	0.03
	Algae - Case 1	0.00
	Algae - Case 2	0.02
	Algae - Case 3	0.03
	Algae - Case 4	0.01

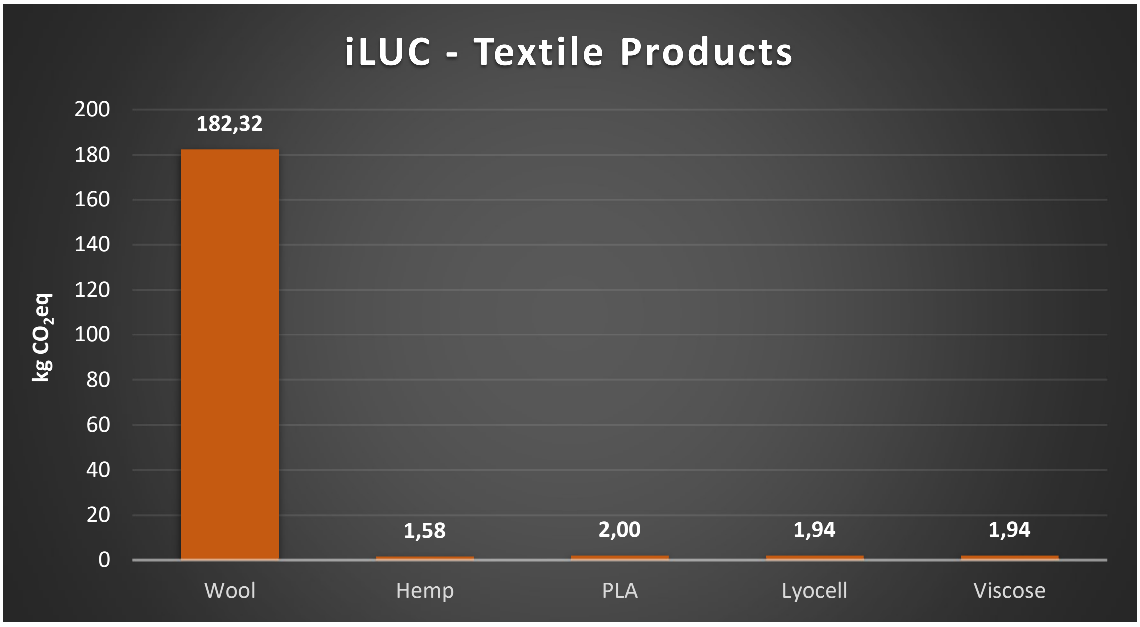

Figure 2 - iLUC results for textile products

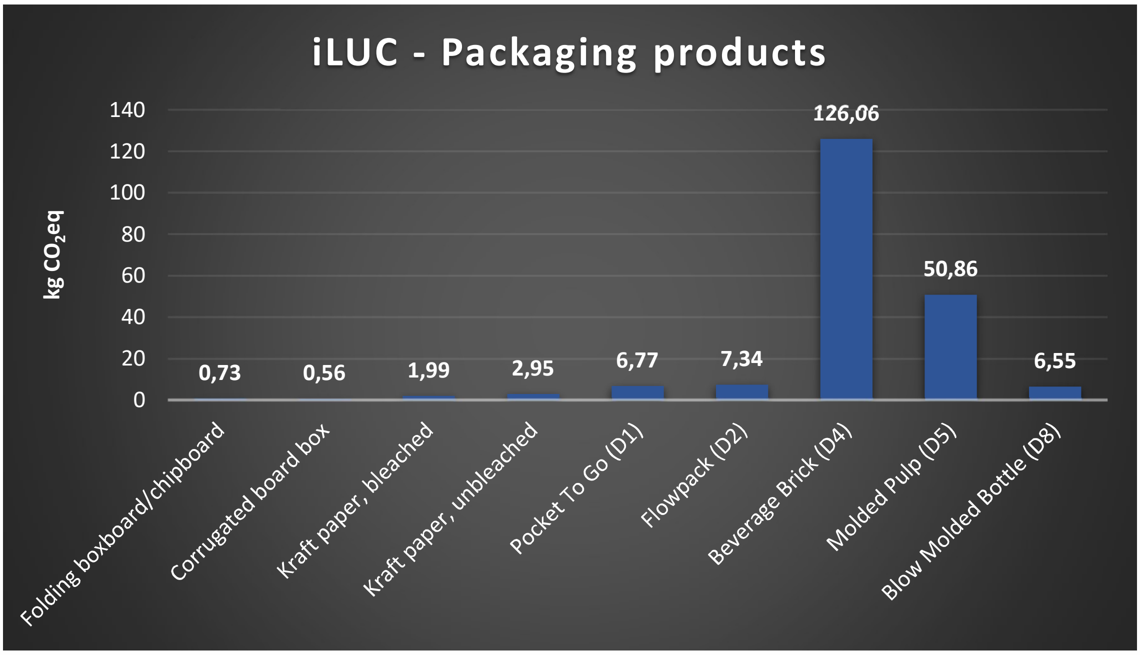

Figure 3 - iLUC results for packaging products

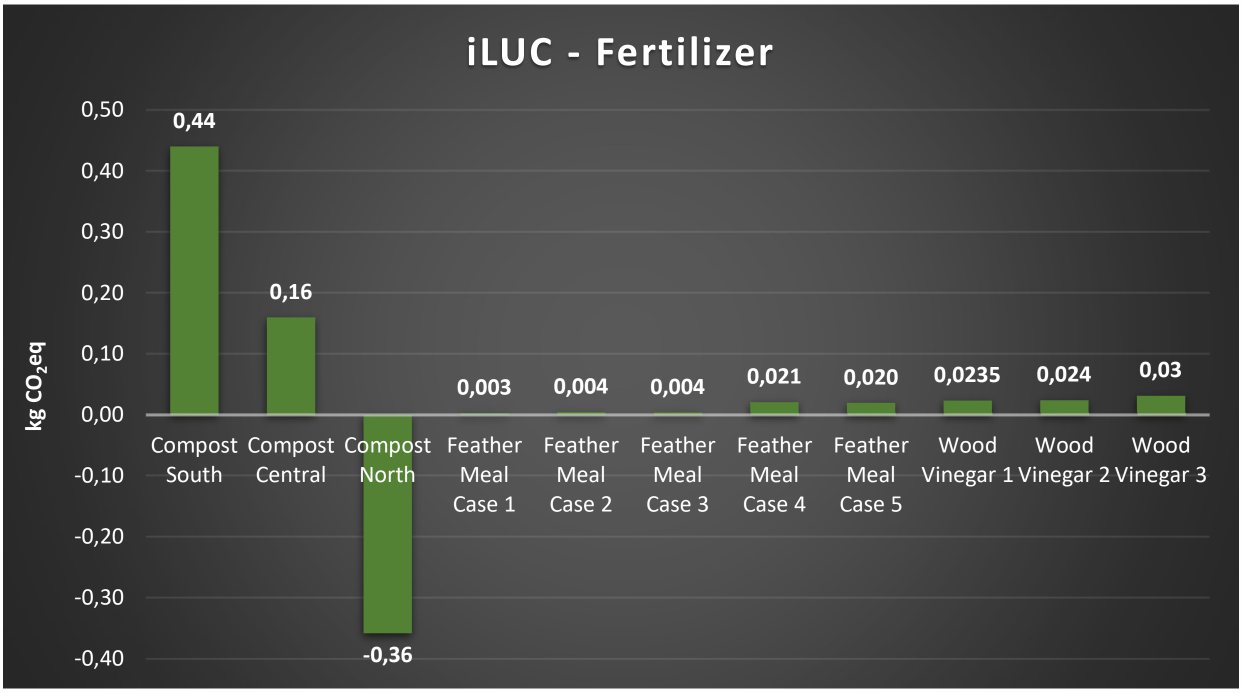

Figure 4 - iLUC results for fertilizer products

About iLUC values for fertilizers, the results showed lower values compared to the textile and packaging sectors due to the following reasons (IFOAM, 2009; Khan et al., 2024):

1) Reduced Chemical Inputs: organic fertilizers reduce the need for synthetic chemicals, which are often associated with higher greenhouse gas emissions and energy use in their production and application.
2) Improved Soil Health: by enhancing soil structure and fertility, organic fertilizers can increase crop yields on existing agricultural land, reducing the pressure to convert natural ecosystems into farmland.
3) Carbon Sequestration: organic farming practices, including the use of organic fertilizers, can enhance soil carbon sequestration, which helps mitigate climate change and reduces the need for land conversion.
4) Biodiversity Conservation: organic farming often integrates practices like crop rotation and cover cropping, which support biodiversity and ecosystem services, further reducing the need for land-use change.

The use of organic fertilisers derived from biomass, such as compost or digestate from biogas plants, offers a sustainable alternative to synthetic fertilisers while providing multiple environmental benefits. Organic fertilisers provide plants with essential nutrients, including nitrogen, phosphorus, and potassium, in forms that are released gradually into the soil, reducing the risk of nutrient leaching and water pollution. Unlike synthetic fertilisers, which are energy-intensive to produce and often contribute to greenhouse gas emissions, organic fertilisers use waste biomass, transforming it into a valuable resource and promoting a circular approach to agricultural systems (Chew et al., 2019).

In addition to providing nutrients, these fertilisers contribute to the accumulation of organic matter in the soil, which is essential for carbon sequestration. As organic matter decomposes, it forms humus, a stable soil component that can store carbon for decades or even centuries. This process not only helps mitigate climate change by capturing and storing atmospheric CO_2 but also improves soil health. Increased levels of organic matter promote better water retention, reduce soil erosion, and support the development of beneficial microbial communities that further enhance soil fertility and resilience. In addition, the use of organic fertilisers can play a key role in regenerative farming practices that prioritise soil health and aim to reverse land degradation. By improving soil structure, organic fertilisers help increase the soil's ability to absorb and retain water, making it more resilient to drought. They also reduce dependence on fossil fuel-based inputs, aligning agricultural practices with global climate goals (Leifeld & Fuhrer, 2010; Zheng et al., 2024).

However, challenges remain in scaling up the use of organic fertilisers. These include logistical issues such as transport and storage of bulky materials, variability in nutrient content, and potential contamination if inputs are not effectively managed. Despite these challenges, advances in bioprocessing technologies and better waste management systems can help overcome these barriers and enable wider adoption of organic fertilisers as a sustainable solution for modern agriculture. Overall, the integration of organic fertilisers into farming practices not only supports the health and productivity of agricultural systems but also makes a significant contribution to global efforts to sequester carbon and combat climate change (Zheng et al., 2024).

5. CONCLUSIONS

Climate change demands urgent global action to reduce greenhouse gas emissions and limit temperature rise. Bio-based solutions such as bioenergy, biofuels, and bioplastics show promise in mitigating emissions and supporting carbon neutrality. However, their implementation faces challenges, particularly regarding land use changes. Direct land use change (dLUC), such as deforestation for agriculture, and indirect land use change (iLUC), where bio-based solution production displaces agricultural activities, both contribute to significant carbon emissions. While biofuels can help reduce emissions, iLUC may counteract these benefits by disrupting ecosystems and releasing stored carbon. Understanding and managing both dLUC and iLUC is crucial for evaluating the effectiveness of bio-based solutions in climate policy. Agricultural practices and policies must be aligned to minimize these risks and ensure that bio-based solutions truly contribute to a sustainable, carbon-neutral future.

One aspect to consider is the carbon sequestration potential of bio-based products. This refers to the ability of these products to sequester or reduce carbon dioxide (CO_2) emissions throughout their life cycle. The use of bio-based materials in the textile, fertiliser and packaging sectors can make a significant contribution to mitigating climate change (Borchers et al., 2024).

While bio-based production offers a significant reduction in carbon footprint compared to fossil-based alternatives, it is important to note that these materials are often derived from annual crops or herbaceous plants. As a result, the carbon absorption and storage associated with these products is temporary, representing biogenic carbon rather than long-term sequestration. The carbon captured during plant growth is eventually released back into the atmosphere through degradation, combustion, or biodegradation of the bio-based products. This cyclical nature highlights the importance of considering the full life cycle of bio-based materials when assessing their carbon removal potential (Jansson et al., 2010; Matuštík & Kočí, 2022; Textile Exchange, 2024).

This aspect can be emphasised with a comparative LCA of biobased products and classical fossil-based products, allowing for a clearer understanding of the environmental impacts associated with each. By assessing the entire life cycle - from raw material extraction to production, use, and disposal - this comparison highlights key differences in sustainability, such as reduced carbon footprints, lower resource depletion, and improved end-of-life options for biobased alternatives. Furthermore, such an analysis can inform decision-making processes for industries looking to transition towards more sustainable practices while weighing the trade-offs between performance, cost, and environmental benefits.

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