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Research Article

New Environmental Approach Based on a Combination of Planetary Boundaries and Life Cycle Assessment in the Wood-Based Bioadhesive Market

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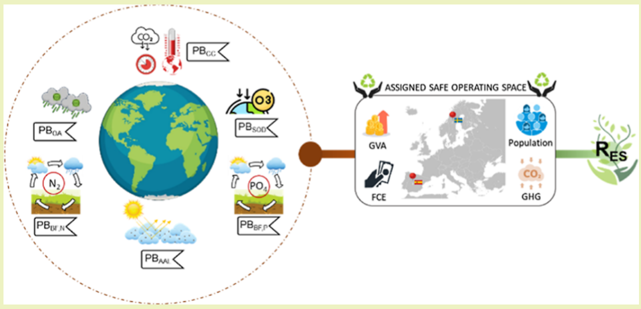

ABSTRACT: The role of the bioeconomy based on the use of renewable resources and also on the valorization of bio-based waste could contribute to a higher degree of sustainability. In this sense, biobased processes and products should exhibit values for indicators that demonstrate and outperform their competing counterparts. To this end, it is essential to apply a methodology to conduct the assessment of environmental impacts and potential damages at a global level. Life cycle assessment (LCA) has proven to be a suitable method to study the environmental profiles and damage scores of products and/or processes within their life cycle. In this regard, LCA impact scores are transformed into planetary boundary (PB) values, for which a threshold has been previously established. This has been the focus of this article, in which the environmental sustainability ratios of different bioadhesive scenarios have been evaluated under the combined framework of PBs and LCA for wood-based bioadhesives following different allocation approaches based on egalitarian, utilitarian, and grandfathering principles. In this way, it has been possible to assess the potential of bioadhesives to replace synthetic resins in the wood-based panel production chain. The results obtained show some variability in the environmental profiles and indicators, but it is possible to conclude that the bioadhesives selected can be considered as sustainable alternatives. However, improvements are required in certain PB categories, such as climate change or biogeochemical flows, as in some cases, the threshold value is exceeded. Future research should focus on two strategic lines: the application of guidelines for the evaluation of environmental sustainability at the planetary level and the optimization of bio-adhesive production to reduce their impact with the aim of achieving a more adequate sustainability ratio.

KEYWORDS: *planetary boundaries, environmental assessment, wood bio-adhesives, life cycle assessment, LCA-PBs*

1. INTRODUCTION

The search for sustainability, the mitigation of the environmental impact of anthropogenic activities, eco-efficiency, and the achievement of sustainable development goals have become the driving force behind the need to modify the current production model.[1,2] The development of new biobased processes in the framework of biorefineries has contributed as a driver of change.[3−5] These focus on the reduction of non-renewable resources, the use of biobased feedstocks, and the proper management of waste, thus converting it into resources, where possible. The focus is on the circular economy concept, where the flow of materials is not based on "use and throw away" but on "use and reuse". However, the use of renewable resources or unusable flows from other productive sectors, such as agriculture or industry, does not always lead to a reduction of environmental impacts.[6] This is often attributed to the lack of optimization of large-scale processes as most new biobased production models are developed on a laboratory or pilot scale. The question arises as to how to determine the environmental impacts associated with production models in order to assess not only the environmental damage but also what improvement strategies should be carried out to reduce the environmental burden. For these assessments, the life cycle assessment (LCA) methodology is considered an essential tool that reports the environmental profile in terms of impact values grouped by categories.[7] It is based on a sequential four-step process: identification of the functional unit of study and system boundaries, development of life cycle inventories, selection of the impact assessment methodology, and interpretation of the results. It is important to mention that in most cases, the data available in the literature for bioadhesive production are at the laboratory level. Therefore, in order to provide comparison

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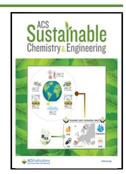

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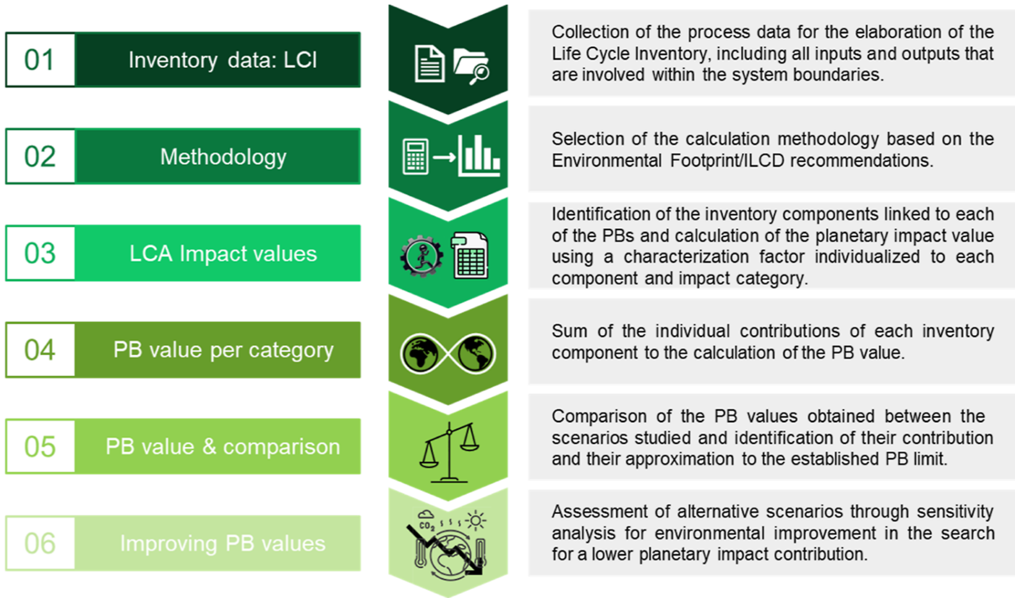

Figure 1. Methodological procedure for assessing the planetary boundaries from the impact values of LCA.

scenarios with synthetic resins, it becomes necessary to upscale the process to an industrial level. To this end, a capacity of 24 ton/day has been used as a base case, similar to that of commercial synthetic resin facilities. In this way, an environmental profile is obtained, in which the main contributors to the overall impact obtained, known as hotspots, can be identified, on which improvement actions should be planned and evaluated in a subsequent sensitivity analysis in order to propose an optimized process scenario. Although the LCA methodology is considered an essential tool, its impact values are usually allocated and quantified within a regional or national approach, not at a planetary level, which entails a "drawback" when pursuing to determine the environmental damage in absolute sustainability (ref 9). In this approach, that is, for the assessment of the globalization of an impact resulting from a production process or a product, it is necessary to combine the concept of planetary boundaries with that of LCA. In this way, an absolute sustainability study is carried out, which makes it possible to define, in a more concrete way, whether a biotechnological biological process alternative can really be considered as environmentally sustainable.[8]

2. METHODOLOGY

The methodology integrating the combined application of LCA and PB_S (planetary boundaries) considers as an initial step the calculation of impacts according to the Environmental Footprint/ILCD guidelines ([7,10,11]). PB_S aims to determine the environmental limits within which a safe and healthy environment for mankind can be maintained. This method is embedded in the concept of developing global sustainability policies, and its framework has been first analyzed by Rockström et al., 2009.[12] Subsequently, it is necessary to apply characterization factors, for which the inventory has to be evaluated once the impact result has been obtained, as only some substances apply for the PB_S results. Subsequently, the results will be extrapolated to a planetary study level, so it is necessary to use allocation approaches and criteria that will be developed later on. Besides, this planetary assessment approach has been applied to analyze the environmental assessment of wood adhesives, both biobased, that is, those based on starch, soya, tannins and lignin, and synthetic ones, being urea formaldehyde (UF), phenol formaldehyde (PF), and melamine urea formaldehyde (MUF).

To allow a better understanding of the procedure followed for the calculation of the PB values, Figure 1 is displayed. These are the ones selected as these are the impact categories for which both PB characterization factors and safe operating space (SoS) scores have been previously developed. As shown, the methodology can be developed in six main steps. The first three are part of the classical LCA methodology, including the collection of the data for the development of the inventories of the proposed scenarios, the selection of the methodology, which will be based on the Environmental Footprint/ILCD recommendations (Table 1), and final environmental loads, grouped in the different impact categories, together with the environmental profiles. Afterward, characterization factors are then applied to the LCA scores to obtain a PB value per impact category. This PB value is going to be assessed under various types of allocation to assess if those are placed under an SoS, which is the threshold for considering a production scenario as sustainable or not.

Table 1. Environmental Impact Categories and Their Corresponding Assessment Methodologies According to the Environmental Footprint/ILCD Recommendations

LCA impact category	unit	recommended method
climate change (CC)	kg CO_2 eq	IPCC 2021 GWP100 V1.00
stratospheric ozone depletion (SOD)	kg CFC11	EDIP 2003 V1.03
eutrophication, freshwater (EF)	kg P eq	ReCiPe 2016 Midpoint (H) V1.06/ World (2010) H
eutrophication, marine (EM)	kg N eq	
photochemical ozone depletion	kg CFC11	

One of the main drawbacks in assessing the planetary boundaries based on the impact results obtained after applying the LCA methodology is based on the variation of the unit of

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measurement as well as the contribution of the same LCA impact category on several planetary boundaries.[13] or example, if the climate change (CC) category is considered, its value in the LCA methodology is expressed in kg CO_2 eq, while for the planetary boundaries, two variables contribute on the CC impact category, with different units of measurement: energy imbalance (W/m^2) and atmospheric CO_2 concentration (ppm). Although the PB value could be obtained directly, the degree of error could be higher as the contributing components are being considered in global terms, rather than specifically for each of the inventory components affecting the PB impact categories. In addition, the fact that all inventory data for bioadhesives and synthetic resins are available in a specific and categorized form allows for a more comprehensive assessment. For this reason, it has been decided to consider conversion factors[14] for each of the compounds affecting the PB impact categories, through which the impact values would be obtained in the corresponding units, that is, W/m_2 and ppm, in the case of the CC impact category in units of kg CO_{2eq}.

On the other hand, to assess the impact of wood adhesive production at the planetary level, global productions of UF, MUF, and PF resins have been considered, which are the result of the global demand for resins to produce wood-based panels as UF, PF, and MUF are the most commonly used resins in wood-based panels. Among them, UF resin is the most widely used resin, with the annual production value amounting to 1.23×10^{10} kg, according to the latest market analysis. Next, PF resin is the most demanded resin, with an average production value of 6109 kg per year, while MUF resin has the lowest annual production value of approximately 2109 kg. Therefore, the overall demand for synthetic-based resins is the sum of the three production values mentioned above, amounting to an overall value of 2.03×10^{10} kg/year. This has been the value considered for the calculation of the planetary boundaries, which is applied to the impact results obtained after applying the LCA methodology. It is worth mentioning that in order to consider the overall impact measured in terms of PB for the synthetic resins, each of the production values of each type of resin has been considered, and the PB associated with synthetic resins has been expressed generically and not for each of them separately.

In step 4, the principles of the planetary boundaries are analyzed on the basis of the LCA outcomes of each component in the corresponding PB units, for which characterization factors[13] and an average annual production volume of wood adhesives are applied, in order to determine the environmental damage on a planetary scale. Table 2 includes the correlation between the LCA and PB values of the categories analyzed in this report. In this way, PB values are obtained for each of the proposed scenarios, which were then compared with each other and evaluated with the established PB limit values. From the results of the analysis, it is possible to identify the critical steps responsible for the impacts and to propose improvement actions and evaluate their consequences in the sensitivity analysis.

2.1. Selection of Planetary Boundaries. The PBs selected for assessment within this article have been included in Table 2; this selection has been based on the bibliographic availability of the characterization factors required for converting the LCA values into PB_S scores. Both atmospheric carbon dioxide concentration and energy imbalance in the upper atmosphere are included in PB_{CC} (planetary boundary: climate change); while the former could be equivalent to carbon footprint, kg CO_{2eq}, the energy imbalance indicator could be considered as a more inclusive and fundamental control variable when assessing the sustainability index of a region. This variable includes how anthropogenic activities lead to variations in radiative forcing, considering not only carbon dioxide emissions but also greenhouse gases (GHGs), nitrogen and sulfur oxides, organic carbon, and ammonia, among others.[15−18] In this sense, it could be assessed how global warming could derive from the influence of human activities rather than just focusing on carbon dioxide emissions. Indeed, in the IPCC report on Climate Change 2021,[15] it could be seen that although CO_2 emissions are the most prominent contributors to global warming, the sum of methane, nitrogen oxides, halogenated gases, and volatile organic compounds leads to a contribution analogous to that of CO_2. This demonstrates the need to include the measurement of the impact of energy imbalance in the upper atmosphere when considering planetary boundaries and sustainability indices.

Table 2. Relationship between LCA Impact Categories and PBs, Including the Unit of Measurement and the Acronyms Selected for Each One

LCA impact category	planetary boundary	PB unit	acronym
climate change (CC)	CC-energy imbalance at top-of-atmosphere	W/m^2	$PB_{CC,imb}$
	CC-atmospheric CO_2 concentration	ppm	PB_{CC,CO_2}
	ocean acidification	Ωarag	PB_{OA}
stratospheric ozone depletion (SOD)	stratospheric ozone depletion	DU	PB_{SOD}
freshwater eutrophication (FE)	biogeochemical flows − phosphorus	Tg P	$PB_{BF,P}$
marine eutrophication (ME)	biogeochemical flows − nitrogen	Tg N	$PB_{BF,N}$
photochemical ozone depletion (POD)	atmospheric aerosol loading	AOD	PB_{AAL}

Another approach for assessing CC is through the measurement of ocean acidification (OA). Emissions of nitrogen and sulfur oxides that concentrate in the layers of the atmosphere return to the terrestrial environment in the form of acid rain, leading to acidification of soil and water. One way to measure this environmental impact cycle is through the acidification of the ocean, which leads to an increase in the concentration of H^+ cations at its surface.[19] The presence of these cations directly affects the carbon cycle, specifically the calcium carbonate cycle. It is expressed in aragonites as it is the most soluble form of calcium carbonate and directly affects the development and survival of corals and marine organisms. Its highest reproduction and stability are achieved when the aragonite saturation point is above 3, while when it is reduced to values below 1, stress conditions occur, so the PB_{OA} (planetary boundary: OA) limit is set at this value.[20−22] When assessing CC, the analysis of stratospheric ozone depletion is performed as both concepts are strongly linked and also when assessing the global warming potential by considering the energy imbalance of harmful compounds found in the atmosphere.[23] When assessing the PB_{SOD} (planetary boundary: stratospheric ozone depletion), emissions of GHGs, chlorofluorinated carbonates, CFCs, and halons must be considered as they have a direct impact on the depletion of ozone concentration in the atmosphere. The damage to the ozone layer reported by the European Environment Agency[24] since 1979 has reached almost 25 million km^2 in 2021.

$PB_{BF,P}$ (planetary boundary: biogeochemical flows, phosphorous) and $PB_{BF,N}$ (planetary boundary: biogeochemical flows, nitrogen cycle) represent the planetary boundaries associated with the biogeochemical flows of phosphorus and nitrogen,

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respectively. Biogeochemical cycles are defined as the way N and P flow between the environment and the living organisms.[25,26] In the case of the N_2 cycle, it could be considered as a three-step process: ammonification, nitrification, and denitrification, involving the activity of bacteria for fixation and conversion.[27,28] The alteration of the natural nitrogen cycle has become a critical concern as nitrogen compounds are considered as primary nutrients for microbial growth.[29] The combustion of fossil fuels and the extensive use of fertilizers in agricultural activities contribute to the alteration of the natural nitrogen cycle and, in addition, to an imbalance of nutrients in the soil that can lead to a significant loss of biodiversity.[30] On the other hand, like nitrogen, phosphorus is also considered an essential nutrient for organisms as it plays a role in energy-transfer processes, the structure of the genetic material, and the composition of cell membranes.[31] Human-derived activities, such as agricultural harvesting and fertilization, mining, manure, and animal waste production, have a direct effect on the natural P cycle.[31−33] Given the importance of preserving a proper balance on the concentration of these compounds, due to their involvement in the maintenance of the natural cycles of living organisms, their consideration on the definition and assessment of planetary boundaries becomes essential. The limits established are based on the values of N and P necessary to maintain, at least, a balanced concentration that allows the maintenance of biogeochemical cycles without a significant alteration on the metabolism of living organisms.[34]

The last PB studied in this report is that of atmospheric aerosol loading, PB_{AAL} (planetary boundary: atmospheric aerosol loading). The presence of aerosol compounds and particles in the atmosphere leads to serious damage to human health and also to the Earth's climate. Their interaction with water molecules in the atmospheric layers affects water cycles and atmospheric circulation.[35−37] Aerosols are also strongly linked to global warming, given their impact on the reflection and/or absorption of solar radiation in the atmosphere, thus affecting the increase in global temperature.[38−41] By controlling aerosol emissions, sustainability of both the environment and human health could be achieved.[42]

2.2. Bioadhesive Scenarios to be Evaluated under a Planetary Focus.

2.2.1. Definition of Scenarios. As mentioned in previous sections, the authors have evaluated the environmental profiles of different scenarios of biobased adhesives applied to wood-based panel production using the LCA methodology. While these results provide the potential and degree of sustainability from an attributional scope, they do not show how this new biobased process scenario can affect the environment in a planetary approach. Therefore, it is interesting to extend the LCA values to a global level, that is, to transform from an attributional model to a consequential model, using the principles and knowledge of the planetary boundary concept.

For this purpose, the proposed scenarios for the assessment under a consequential model perspective are represented in Table 3, together with the literature reference, where the description of the production processes and the inventory can be found. It is important to mention that for this study, the Environmental Footprint recommendations[43] have been considered in the selection of the calculation methodologies for each of the impact categories; therefore, the environmental damage values for each of the scenarios have been recalculated based on the inventory data included in the aforementioned bibliographic references.

Table 3. Scenarios Assessed for Reporting the PB Values from the LCA Scores

scenario	definition	ref
KL-NIPU	kraft lignin non-isocyanate polyurethane	44
OSL-NIPU	organosolv lignin non-isocyanate polyurethane	44
SPI-NIPU	soy protein isolate non-isocyanate polyurethane	44
T-NIPU	tannin non-isocyanate polyurethane	44
starch-oil	hydrolyzed starch with bio-oil	45
starch-N	hydrolyzed starch with *N*-methylol acrylamide	45
starch-Fe	oxidized starch with $FeSO_4$ and H_2O_2	45
starch-ECH	oxidized starch with NaClO and epichlorohydrin	45
tannin-Gly	tannin from bark crosslinked with glyoxal	46
tannin-Hexa	tannin from bark crosslinked with hexamine	46
tannin-PF	tannin from bark crosslinked with p-formaldehyde	46
tannin-DMC	tannin from bark crosslinked with $NH_4(OH)$	46
tannin-HDMA	tannin from bark with hexamethylenediamine	46
SF-D	soy flour crosslinked with diacyandiamide	47
SF-WP	soy flour crosslinked with w-polyurethane	47
SF-SE	soy flour crosslinked with SBDS and epoxy resin	47
SP-EP	soy protein crosslinked with polyacrylamide	47
SP-MA	soy protein crosslinked with maleic anhydride	47
SP-TR	soy protein crosslinked with tannin resin	47
synthetics	urea/phenol/melamine urea formaldehyde	48, 49

2.2.2. Brief Description of Basic LCA Concepts. When applying the LCA methodology to assess the environmental profile of the proposed wood-based biobased adhesives, it is necessary to follow the guidelines and instructions available in 14040 and ISO 14044.[7,10] In this regard, the objective of this assessment is to identify the environmental burdens associated with the production of biobased wood adhesives using renewable resources such as tannins, lignin, soybean, and starch, with the aim of studying their potentialities compared to their counterparts, synthetic wood resins (UF, PF, and MUF). To this end, based on laboratory data, a large-scale production process is defined and simulated, with the aim of compiling all the process data (materials, energy requirements, waste flows, etc.) necessary for the development of the life cycle inventories required to obtain the environmental profile. Regarding the system boundaries, a cradle-to-gate approach has been chosen, involving all stages from the extraction of raw materials to the production of the bioadhesive, just before the factory gate. Infrastructure maintenance has not been included within the system boundaries as it has previously been assessed that the environmental burdens arising from the construction, dismantling, and maintenance of equipment are negligible in the environmental profile. Transport activities were not included either for a reason analogous to that stated for the infrastructure processes in addition to the lack of data regarding the location of the industry, so it is considered as a production model applicable to different locations, thus increasing its applicability. On the other hand, all inventory data are shown on the basis of the functional unit of the process, with the production of 1 kg of the bioadhesive as the one selected to perform the LCA methodology.

2.2.3. Top-Bottom Approach: Downscaling Planetary Boundaries to Sectoral and National Levels. In a first study of the impact of the wood adhesive production process scenarios in terms of their effect on planetary boundaries, an assessment has been made at the global level, considering the scheme shown in Figure 1. However, once the global scope has been defined, a reduction to lower levels must be made so that the impact can be studied considering the actions. In other words, planetary boundaries provide what is known as "Safe Operating Space", SOS, defined as the "operational budget that an anthropogenic activity must not exceed to ensure maintenance within environmentally sustainable global values". These values are calculated as the difference between the established planetary limit value, for example, 350 ppm in the case of $PB_{CC,imb}$, and the natural background level, which would be the impact value without the incidence of human activities, which in the case of $PB_{CC,imb}$ is set at 278 ppm, resulting in an SOS score that falls to 72 ppm. Therefore, this obtained value is referred to as the "full SoS", which will be denoted as SoS_f. In this regard, Table 4 shows the SOS_f values for each of the planetary boundaries, which have been used to calculate the "share of the total SoS", denoted as aSoS.

Table 4. Planetary Boundary Values and Safe Operating Spaces

PBs	value	SOSf
$PB_{CC,imb}$	1 W/m^2	1 W/m^2
PB_{CC,CO_2}	350 ppm	72 ppm
PB_{OA}	2.75 Ω_{arag}	0.68 Ω_{arag}
PB_{SOD}	275 DU	15 DU
$PB_{BF,P}$	11 Tg P	6.2 Tg P
$PB_{BF,N}$	62 Tg N	62 Tg N
PB_{AAL}	0.25 AOD	0.11 AOD

Although there is no agreement on the type of methodology that should be used to assess the allocation shares for each of the scenarios, there are several methods in the literature that were evaluated throughout this article. The procedure to obtain the sustainability score for the assessed scenario is based on a three-step methodology (Figure 2): calculation of the PB values according to the LCA methodology data by applying a characterization factor to the inventory data; reduction of the LCA-PB scores from the global level to the continental and/or regional level, considering the sharing of environmental burdens, obtaining the assigned SoS, aSOS; and finally, the determination of the degree of sustainability by calculating the ratio between the LCA-PBs scores and the aSOS. These steps are described in the next sections.

The allocation principles discussed in this article were three, which have been identified as the most useful and used in previous environmental studies: egalitarian, utilitarian, and acquired rights.[50−52] The egalitarian principle is based on the premise that environmental burdens should be distributed equitably among the population, whereby the number of inhabitants at the global, European, and national levels will be used as the allocation share factor for calculating aSOS. This principle is also known as the "equal per capita basis", defined as the aSOS allocated on an individual basis in a specific period of time.[53] It is worth mentioning that for the development of the study, data for the year 2021 have been considered. The utilitarian principle considers that it would be ideal to establish the necessary guidelines to maximize the welfare of the population,[54] which is why this principle uses the economic parameters of gross value added (GVA) and final consumption expenditure (FCE) as they represent the economic value generated by producers in an economic area, in this case the timber sector, and the level of economic expenditure of consumers, respectively.

Finally, the principle of allocation of acquired rights is based on the grandfathering approach,[55] which argues that the aSOS should be assessed according to the degree of environmental impact derived from timber sector productions, in this particular scenario, for a given production year. To assess the damage factor, GHG emissions were considered as this is one of the most widely used indicators to assess impacts at industrial and sectoral levels as well as having an extensive database available.[56] The equations included in Table 5 were used to calculate the aSoS values for each of the allocation principles.

The allocation shares considered in the development of this study were initially focused at the European level, given the potential of the timber sector in Europe and the availability of

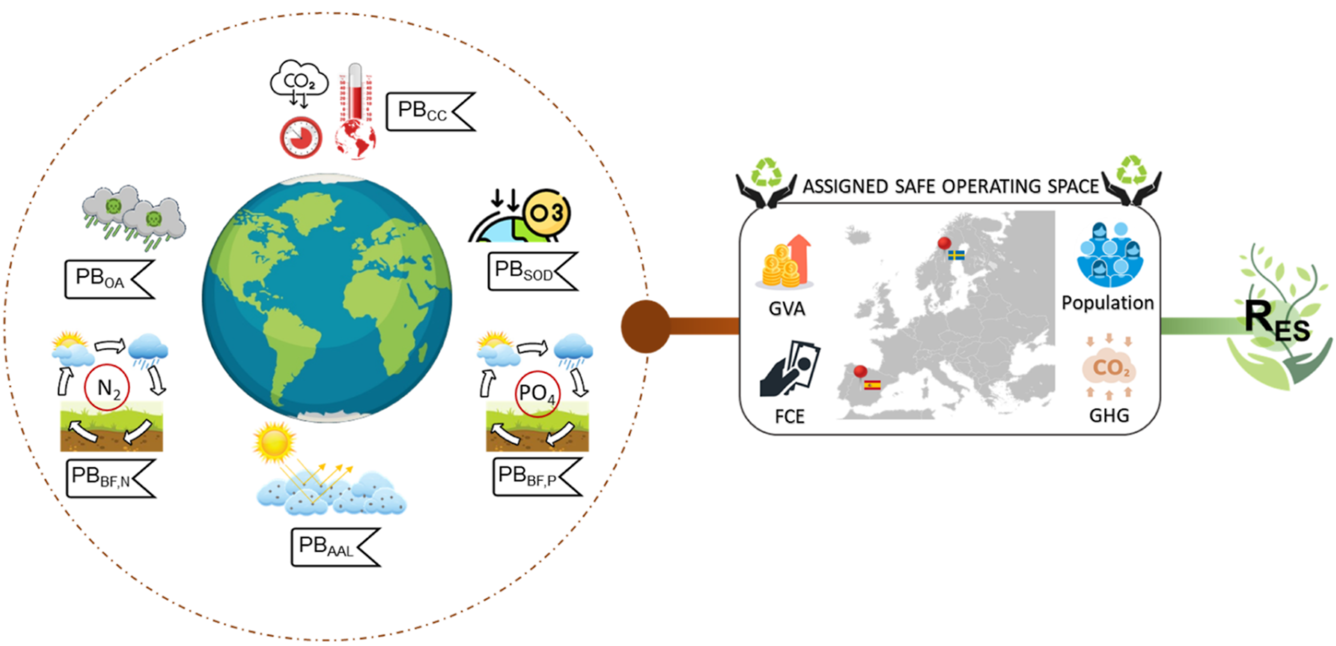

Figure 2. Methodology for performing the allocation approaches.

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Table 5. Allocation Approaches Considered for Calculating the aSOS Scores

allocation principle	allocation	acronym	upscale	equation
combined egalitarian with utilitarian principles	GVA	$aSOS_{GVA}$	R/C[a]	$\frac{POP_{R/C}}{POP_{World}} \cdot \frac{GVA_{WS}}{GVA_{R/C}}$
	FCE	$aSOS_{FCE,\ ind+POP}$	WS[a]+ POP[a]	$\frac{POP_{R/C}}{POP_{World}} \cdot \frac{FCE_{WS}}{FCE_{R/C}}$
		$aSOS_{FCE,\ ind+POP+VC}$	WS[a]+ POP[a]+ VC[a,b]	$aSOS_{FCE_{ind+POP}} \cdot \frac{VC_{WPP\ R/C}}{VC_{WS}}$
Grandfathering	GHG	$aSOS_{GF}$	R/C[a]	$\frac{POP_{R/C}}{POP_{World}} \cdot \frac{GHG_{WS,\ R/C}}{GHG_{R/C}}$

[a]The acronym POP refers to the population value at global, regional, or country levels. R/C refers to the regional or country level, WS refers to the wood sector, and VC refers to the value chain. [b]The term value chain (VC) represents the contribution of the production volume of wood panels or the region or country in the wood sector, within the same location. For instance, to its calculation, the wood sector database has been considered. To calculate the VC, WPP, and R/C, the production volume of wood panels for each region has been compiled, including fiberboards, plywood, OSB, and MDF/HDF, among others. On the other hand, to assess the VC of the wood sector, denoted by VCWS, the global production volume of wood products has been considered, that is, saw wood, wood logs, pulpwood, wood for fuels, wood chips and residues, printing and writing papers, newsprint, etc.

Table 6. PB Scores for Each Adhesive Scenario: Climate Change Energy Imbalance, Atmospheric CO_2 Concentration, and Ocean Acidification

adhesive	$PB_{CC,imb}$ W/m^2	PB_{CC,CO_2} ppm	PB_{OA} Ω_{arag}	adhesive	$PB_{CC,imb}$ W/m^2	PB_{CC,CO_2} ppm	PB_{OA} Ω_{arag}
KL-NIPU	8.36×10^{-4}	2.12×10^{-2}	1.73×10^{-5}	tannin-PF	9.78×10^{-4}	2.17×10^{-2}	1.00×10^{-5}
OSL-NIPU	3.30×10^{-4}	1.05×10^{-2}	1.61×10^{-5}	tannin-DMC	2.43×10^{-3}	0.13	3.48×10^{-4}
SPI-NIPU	7.81×10^{-4}	1.77	8.73×10^{-6}	tannin-HDMA	1.01×10^{-3}	4.65×10^{-2}	1.13×10^{-4}
T-NIPU	1.00×10^{-3}	4.07×10^{-2}	2.47×10^{-5}	SF-D	1.50×10^{-4}	1.36	2.66×10^{-6}
starch-oil	7.83×10^{-4}	0.62	1.14×10^{-4}	SF-WP	2.24×10^{-4}	0.83	2.43×10^{-6}
starch-N	3.25×10^{-4}	0.59	2.46×10^{-6}	SF-SE	3.81×10^{-3}	2.19	6.49×10^{-6}
starch-Fe	1.65×10^{-4}	3.86×10^{-3}	2.62×10^{-6}	SP-EP	4.79×10^{-4}	1.30	6.54×10^{-6}
starch-ECH	3.24×10^{-4}	1.32×10^{-2}	5.70×10^{-6}	SP-MA	2.17×10^{-4}	1.97	5.92×10^{-6}
tannin-Gly	9.96×10^{-4}	2.21×10^{-2}	1.03×10^{-5}	SP-TR	2.47×10^{-4}	0.93	2.39×10^{-6}
tannin-hexa	1.00×10^{-3}	2.23×10^{-2}	1.05×10^{-5}				
synthetics	3.35×10^{-4}	4.47×10^{-2}	7.09×10^{-5}	synthetics	3.35×10^{-4}	4.47	7.09×10^{-5}
PB limit	1	350	2.75	PB limit	1	350	2.75

data at both continental and sectoral levels in terms of production, imports, exports, and economic statistics (GVA and FCE) and GHG emissions. On the other hand, after assessing sectoral data, provided from FAO,[57] The World Bank,[58] and EDGAR[59] (Emission Database for Global Atmospheric Research) databases, it was identified that Sweden has one of the highest GVA values in Europe, while standing out for its low GHG emissions, so this nation has been chosen to assess the results of the allocation shares at a lower level. Furthermore, in order to provide an intermediate allocation value, Spain has been chosen as another study scenario because it has an intermediate GVA value but, compared to Sweden, higher annual GHG emission values. In this way, a compendium of impact results and various environmental sustainability ratios is presented, which provides a comprehensive and global view of the potential degrees of sustainability of each of the allocation factors considered.

2.3. Assessing the Values of the aSOS within the Sustainability Concept.

2.3.1. Assessment of aSOS Values within the Sustainability Concept. One of the main objectives in the calculation of environmental shares using the allocation principles is to determine the degree of environmental sustainability of the proposed production scenarios, denoted as R_{ES}. It is measured as the ratio between the PB-LCA value calculated for each of the planetary boundaries and the proposed adhesive production scenarios, and the $aSOS_{pp}$, where pp is the type of allocation and the principle used for its calculation.[53] The value of this ratio will be indicative of the degree of sustainability of the production scenario. Thus, if the R_{ES} score is equal to or less than 1, then the scenario is considered environmentally sustainable, while if it is greater than 1, it means that the scenario is unsustainable as the environmental load exceeds the established PB limit and therefore requires optimization and improvement.[60,61]

Therefore, the lower the R_{ES} score, the gross difference between the actual PB-LCA value and the allocated SoS, the higher the absolute environmental sustainability potential of the scenario under assessment. Therefore, in this sense, the scenarios with the lowest R_{ES} scores are the ones that are classified as the best production strategies under the PB approach. Thus, all scenarios proposed in Table 3 will be analyzed considering the allocation principles considered, expressing their environmental damage using the R_{ES} approach.

In this section, it is important to note that the proposed bioadhesive scenarios are based on large-scale process simulation performed on the basis of laboratory data available in the literature. In contrast, the synthetic resin scenarios, which are widely used in the wood-based panel production sector, are evaluated using data obtained from large-scale production processes, whose production parameters are fully optimized.

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This implies that the degree of improvement of bioadhesive scenarios is extensive and much more significant than in the case of synthetic resins, where the degree of optimization is very low or almost non-existent. Therefore, those biobased adhesive scenarios that have a lower R_{ES} value than synthetic resins propose a production scenario with a much higher degree of sustainability, given their wide feasibility of improvement.

3. RESULTS AND DISCUSSIONS

This section of the report shows the planetary boundary values for each of the adhesive scenarios under evaluation using the methodological scheme presented in Figure 1. Then, to evaluate the shares of SoSs, applied at European and regional levels, the results obtained by developing the procedure illustrated in Figure 2 and defined in Section 2.1 are also included.

3.1. Planetary Boundaries of Wood Adhesives: A Global Approach. When considering the assessment of the process scenarios in global terms, the planetary values are expected to be considerably low compared to the established PB limit values. That is why, these scores have been used to evaluate the scenarios comparatively, that is, between biobased adhesives and synthetic resins. In this sense, the potential benefits of biobased adhesives have been established from the point of view of environmental sustainability and impact reduction. In this methodological approach, the numerical results of the planetary boundary values are included in Tables 6 and 7. Furthermore, comparative graphs showing the impact values on a scale between 0 and 1 are included, applying the value of 1 to the adhesive alternative, both biobased and synthetic, with the highest impact value, for each of the planetary boundaries under assessment categories.

Table 7. PB Scores for Each Adhesive Scenario: Atmospheric Aerosol Loading, Stratospheric Ozone Depletion, and Biogeochemical Flows

adhesive	PB_{AAL} AOE	PB_{SOD} DU	$PB_{BF,N}$ Tg N/year	$PB_{BF,P}$ Tg P/year
KL-NIPU	2.78×10^{-5}	6.64×10^{-5}	0.05	5.29×10^{-4}
OSL-NIPU	1.24×10^{-5}	5.04×10^{-5}	0.03	4.77×10^{-4}
SPI-NIPU	2.80×10^{-5}	7.05×10^{-5}	0.05	0.17
T-NIPU	2.90×10^{-4}	1.35×10^{-4}	0.16	2.75×10^{-3}
starch-oil	7.10×10^{-6}	1.05×10^{-5}	0.03	6.27×10^{-2}
starch-N	7.80×10^{-6}	1.11×10^{-5}	0.04	1.11×10^{-2}
starch-Fe	9.34×10^{-6}	2.13×10^{-4}	0.02	1.67×10^{-3}
starch-ECH	1.69×10^{-5}	3.92×10^{-5}	0.04	5.60×10^{-3}
tannin-Gly	3.01×10^{-5}	3.10×10^{-5}	0.05	8.80×10^{-5}
tannin-hexa	3.09×10^{-5}	4.02×10^{-5}	0.05	1.17×10^{-4}
tannin-PF	2.97×10^{-5}	3.24×10^{-5}	0.05	4.37×10^{-4}
tannin-DMC	2.94×10^{-5}	7.03×10^{-5}	0.05	3.97×10^{-3}
tannin-HDMA	2.66×10^{-5}	5.36×10^{-5}	0.05	1.37×10^{-3}
SF-D	5.15×10^{-5}	2.14×10^{-5}	0.01	3.23×10^{-2}
SF-WP	7.24×10^{-5}	4.08×10^{-6}	0.01	7.75×10^{-2}
SF-SE	1.02×10^{-5}	1.12×10^{-5}	0.02	5.17×10^{-2}
SP-EP	1.76×10^{-5}	5.11×10^{-5}	0.03	0.12
SP-MA	6.87×10^{-6}	7.57×10^{-6}	0.01	4.85×10^{-2}
SP-TR	7.31×10^{-6}	4.47×10^{-6}	0.01	8.70×10^{-2}
synthetics	2.05×10^{-5}	5.49×10^{-5}	0.07	2.85×10^{-3}
PB limit	0.25	275	62	11

Figure SM1 shows the planetary impact scores for isocyanate-free bioadhesives produced using lignin, both Kraft and Organosolv, tannins, and soy as renewable-based raw materials and their respective comparison with synthetic resins. It is worth mentioning that the value of formaldehyde-based resins has been calculated individually for UF, PF, and MUF adhesives as they are the most prominent in panelboards, and then, taking into account their overall production value, a single planetary limit value for non-renewable based resins is obtained. As can be seen, the environmental implication is diverse among the PBs under discussion; the contribution values of the synthetic-based resins are those represented in red, while those of the biobased resins are in green. For all NIPU bioadhesive alternatives, the contribution on the $PB_{CC,imb}$ is significant, being higher than 50% compared to the synthetic resins, with the exception of the OSL-NIPU bioadhesive, where its impact value is analogous to that of the formaldehyde-based resins. In contrast, in the planetary categories of OA and biogeochemical flows, in both nitrogen ($PB_{BF,N}$) and phosphorous ($PB_{BF,P}$) cycles, the environmental damage resulting from the production of NIPU bioadhesives is significantly lower compared to that of formaldehyde resins. Only one exception is the contribution of SPI-NIPU resin production in $PB_{BF,P}$, where it is 20% higher compared to synthetic resins. In the other PBs, the variability of the damage depends on the type of bioadhesive. However, in seeking to establish which of the alternatives is the most beneficial option from an environmental sustainability point of view, that is, the one that results in a lower degree of impact and therefore contributes to keeping environmental loads below the established planetary boundaries, the preferred alternative would be OSL-NIPU. KL-NIPU could also be considered as a suitable option, but its implication on the $PB_{CC,imb}$ planetary boundary is considerably higher compared to that of the OSL-NIPU bioadhesive scenario.

Starch-based bioadhesives are another type of bioadhesives that have been studied for the replacement of formaldehyde-based resins. Their potential is high due to the mechanical and thermogravimetric properties derived from the use of starch polymers, characterized by the ability to provide adequate bonding forces to produce wood-based panels, ensuring an adhesive-board bond that meets the standards and criteria requirements for consumer use.[62] However, in the approach to studying their cost-effectiveness, it is also important to consider their degree of sustainability and environmental suitability. Figure SM2 shows the PB values obtained for these bioadhesives. A significant impact of bioadhesives in the $PB_{CC,imb}$ category compared to the environmental burden of synthetic resins is observed, being significantly higher for the starch-oil and starch-Fe scenarios but quite similar in the cases of starch-N and starch-ECH, which shows their potential. On the other hand, it is observed that the alternatives requiring starch oxidation for the bioadhesive formulation, that is, the starch-Fe and starch-EOH scenarios, result in a higher environmental burden in the stratospheric ozone depletion impact category associated with the PB_{SOD} planetary boundary, being much more significant for the starch-Fe scenario. However, a holistic assessment of the proposed bioadhesive scenarios shows that their implication on the planetary boundaries is lower than that of synthetic resins in most of the analyzed categories and, when compared to the previous bioadhesive category, a higher potential of starch-based bioadhesives is observed, given their lower contribution to the environmental burdens of the respective planetary boundaries. On the other hand, looking for the identification of the best scenario for this second category of bioadhesives, it is established that the starch-Fe bioadhesive is

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the best alternative, although some improvement would be required to reduce its contribution to the PB_{SOD}.

Research on tannin bioadhesives has increased in recent years; its driving force derives from three main factors: first, its wide availability and renewable nature; second, its easy handling in bioadhesive formulation as it does not require as intensive an activation process as in the case of lignin; and third, perhaps the most relevant, the superior performance of the final panel on which it is applied as it provides highly competitive properties with those provided by formaldehyde-based resins.[63,64]

When assessing their environmental performance at the planetary level, it is observed that while some alternatives appear to be suitable for reducing damage contributions in LOS PB values, given their lower scores obtained compared to those of synthetic resins, others lead to increased impacts, resulting in a lower potential for sustainability. This is the case for dimethyl carbonate (DMC) and hexamethylene diamine (HDMA) crosslinked tannin bioadhesives, as shown in Figure SM3. Even their involvement in PBs associated with biogeochemical nitrogen and phosphorus fluxes is almost zero; in the remaining categories, their score is significantly higher compared to that of formaldehyde-based adhesives. In contrast, the potential of the other alternatives for tannin bioadhesives is high, although some optimization would be required to try to decrease the impact on the $PB_{CC,imb}$ and PB_{AAL} categories. The main reason for the high impact value obtained in the PB_{AAL} is the background activities required for the manufacture of condensed tannins, including not only the extraction stage but also the activities associated with forestry operations and waste stream management.

The last alternative bioadhesives are soy-based ones. The viability and adaptability of this renewable resource, together with its low cost and abundance, make it a suitable source for bioadhesive production. The PB values obtained also support the suitability of soy resources (Figure SM4), with the exception of soy protein crosslinked with epoxy resin and polyacrylamide.

The environmental loads of this bioadhesive were assessed by Arias et al. (2020), in which it has been reported that the main hotspot is the soy protein.[47] Its impact is based on two main causes: the energy requirements needed for soy protein extraction and the secondary activities associated with agricultural cultivation and harvesting. On the other hand, the contribution in the categories associated with CC, that is, $PB_{CC,imb}$ and PB_{CC,CO_2}, is also significant and higher than for formaldehyde-based resins in most of the proposed scenarios. In the case of $PB_{CC,imb}$, all soy bioadhesive alternatives have a contribution that far exceeds that of synthetic resins. The main reason for this high environmental burden probably stems from the electricity consumption and heat requirements, mostly obtained from fossil resources, as well as the lack of optimization and energy efficiency of the soy protein extraction and adhesive production processes. Furthermore, for $PB_{CC,imb}$, it is also observed that formaldehyde-based resins have a lower damage score, which leads to consider them as more suitable options from a sustainability point of view. However, when assessing the categories of biogeochemical flows and the impact over the stratospheric ozone depletion planetary boundary, the selection of biobased adhesives is preferable as their damage burden is almost zero compared to that of synthetic ones. Considering that preserving the natural cycling of nitrogen and phosphorus compounds is essential for crop development, for the survival of organisms given their involvement in the food value chain, for the productivity of ecosystems, and to avoid the accumulation of harmful toxic compounds in soil, air, and water, the development of wood adhesive alternatives that contribute to maintaining the natural cycling of these nutrients is essential.[65,66] As shown in Figure SM4, the contribution of soy bioadhesives in these PBs is negligible compared to that of formaldehyde adhesives, thus making them suitable options. However, to avoid potential damage to the remaining PBs, their optimization and process improvement are required, which are possible because their production alternatives are at an earlier stage of development compared to UF, MUF, and PF resins, whose processes are fully developed and optimized.

3.2. Downscaling Planetary Boundaries of Wood Adhesives: GVA Allocation. When assessing the total economy of the nation, one of the fundamental aspects to consider is the value of the gross domestic product (GDP) as it expresses the size of the economy and how it performs. It is commonly used as a parameter to assess the overall "health" of the economy: the higher the GDP, the higher the performance of the economy develops, indicating the economic sustainability of a nation/country.[67] To this end, in calculating this score, three main approaches could be considered: production, income, and expenditure approaches.[68] The most common is the production approach, the income approach, and the expenditure approach. The most common is the production approach using GVA, which is measured as the difference between the production values of the industry and the intermediate inputs needed in the production process.[69] In this case, the industrial sector being assessed is the wood sector, specifically the one in charge of producing wood-based panels. In order to determine the sustainability index according to the GVA allocation approach, it is first necessary to calculate the allocated safe operating space (aSOS) for the communities of Europe, Sweden, and Spain based on the industrial and population scope (POP), $aSOS_{FCE, ind+POP}$. For this purpose, GVA and POP values were taken from the available database, with FAO (Food and Agriculture Organization of the United Nations),[57] UNECE (United Nations Economic Commission for Europe),[70] and World Bank Group − International Development, Poverty, and Sustainability.[58] The data collected for the estimation of $aSOS_{GVA}$ are shown in Table 8 for the territories of Europe, Sweden, and Spain.

Table 8. GVA and aSOS Values at the European, Sweden, and Spanish Levels

			
GVA_{WS}	$1.64 \cdot 10^5$	$4.09 \cdot 10^3$	$1.11 \cdot 10^3$
$GVA_{R/C}$	$1.13 \cdot 10^7$	$3.82 \cdot 10^5$	$9.97 \cdot 10^5$
$POP_{R/C}$	$7.48 \cdot 10^8$	$1.02 \cdot 10^8$	$4.67 \cdot 10^8$
$aSOS_{GVA, ind+POP}$	$1.40 \cdot 10^{-3}$	$1.24 \cdot 10^{-4}$	$6.76 \cdot 10^{-5}$

As can be seen in Table 8, the GVA value in the wood sector in Sweden is 4 times higher compared to that of Spain, but when it comes to country, Spain becomes the leader, with a value that is 6.15×10^5 times higher. Using these data, the allocated GVA SoS, $aSOS_{GVA}$, is estimated for the territories of Europe, Sweden, and Spain, acquiring the lowest value for Spain and the highest for Europe, as expected. These values will directly affect the environmental sustainability ratio, R_{ES}, of the assessed wood bioadhesives. As it is calculated by dividing the PB value, according to the impact scores obtained using the LCA methodology, by the $aSOS_{GVA}$, the lower the assigned score, the higher the R_{ES} as it is inversely proportional.

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Seeking to assess the scenarios within the three allocation approaches, Figure SM5 is shown. At the European level, most of the sticker scenarios are below the threshold value for environmental sustainability, although there are some exceptions for certain PB categories. Those where the threshold value is exceeded for several bioadhesive alternatives are $PB_{CC,ppm}$ and $PB_{BBF,P}$. This is particularly the case for SPI-NIPU bioadhesives, starch-oil, and starch-Fe, and as far as bioadhesives formulated from soy are concerned, none of them are below the threshold value in the above-mentioned PBs. Therefore, in this first analysis, considering an allocation by GVA, it could be determined that soy-based adhesives should be formulated with another formulation method, or their production processes require significant optimization focusing on their main hotspots, which were identified by Arias et al.[47] In this aforementioned article, it was concluded that the main contributors to environmental burdens are the raw material itself, that is, soybean, derived from agricultural activities (cultivation, fertilization, harvesting, etc.) and also the use of certain crosslinking agents (such as DMC or HDMA). On the other hand, when soy protein is used, thus requiring pre-processing of its extraction, it was identified that electricity consumption is also responsible for a significant impact on the environmental profile obtained. As for SPI-NIPU bioadhesives, their lower environmental sustainability compared to their counterparts stems from the same reasons as those stated for soy-based adhesives — background agricultural activities together with the use of HMDA as crosslinking agents[44] — although some contribution of power requirements, necessary for reactor agitation, is also observable in the environmental profile of this alternative.

Finally, in the case of starch, the bioadhesive formulated with bio-oil requires an acid-hydrolysis pre-treatment of the starch, while the bioadhesive formulated with iron sulfate, starch-Fe, is obtained with a starch oxidation pre-treatment. Regarding the environmental profile of the starch-oil bioadhesive, the agricultural activities of cultivation and harvesting, together with the energy requirements and emissions associated with the production process, mainly ammonium sulfate and ammonium chloride, are the cause of its environmental score. In contrast, for the starch-Fe scenario, the chemical agents required for polymerization and formulation of the bioadhesive structure, butyl acrylate, and vinyl acetate are the inventory items that have resulted in a higher impact value.[45]

On the other hand, when the allocation is done at the national level, for both Sweden and Spain, most bioadhesives, and even synthetic resins, exceed what is considered to be the environmental sustainability threshold value, with a single exception, the category of PB_{SOD}, in which all remain within the environmental threshold values. However, certain exceptions of sustainable bioadhesive scenarios are noted in some of the PBs under assessment: PB_{OA}, $PB_{BF,P}$, and PB_{AEL}. It is important to note that most of the bioadhesive alternatives that are below the R_{ES} limit are also below that of synthetic resins, making them potential replacement options. In general, the largest number of bioadhesives that meet the R_{ES} in these PBs are those formulated from soybean, although given their high involvement on PBs associated with CC,ppm and BBF,P, starch and tannin bioadhesives are the ones that provide R_{ES} scores closest to the limit value of this parameter, with those formulated from starch having the highest potential to be considered as environmentally sustainable, as the scores obtained are generally lower than the characteristics of biobinders formulated from tannins.

The scores obtained considering the allocation in Spain are higher than those obtained for Sweden, which was expected given the aSOS value obtained for this nation. However, despite this, some analogy can be observed in some scenarios with respect to the R_{ES} values obtained for Sweden. The potential of starch and tannin bioadhesives for the substitution of synthetic resins is maintained as, although their values exceed the sustainability limit, they are still below those of formaldehyde-based resins. The most notable difference is observed in soy-based bioadhesives, where proportions exceeding what is considered sustainable by up to 100 points are achieved, thus contributing more significantly to the environmental damage of PBs.

3.3. Downscaling Planetary Boundaries of Wood Adhesives: FCE Allocation.

The FCE allocation approach has been used as the combined egalitarian and utilitarian principle to downscale the planetary boundaries to the continental and regional scales[71,72] to Europe, Sweden, and Spain, respectively.

The reasons for the selection of these territories have been discussed above but are based on its prominence in the timber sector. FCE is an indicator of the expenditures of the community of a territory, including both households and industry, which are used to increase the regional/national economic value where they are consumed and to respond to the individual and collective demands of the citizens. The relationship between FCE and PBs is close since the consumption pattern and the demands of the population result in the need to produce goods and services, which requires the consumption of resources (fossil and natural) and energy and leads to emissions and waste streams that need to be managed. In this way, it directly affects the BPs and is a source of contribution to them.

To assess the sustainability index of wood-based adhesives analyzed, it is first necessary to calculate the aSOS for the communities of Europe, Sweden, and Spain. Two approaches have been considered: the allocation based on industrial and population (POP) scope, $aSOS_{FCE,\ ind+POP}$, and the allocation considering industrial, population and VC scope, $aSOS_{FCE,\ ind+POP+VC}$. To this end, FCE, POP, and VC values are taken from the available database, with FAO (Food and Agriculture Organization of the United Nations), UNECE (United Nations Economic Commission for Europe), MITECO (Spanish Ministry for Ecological Transition and Demographic Challenge),[73] and World Bank Group — International Development, Poverty, and Sustainability. The data collected for estimating the $aSOS_{FCE}$ are shown in Table 9 for Europe, Sweden, and Spain territories. The main difference observed compared to the previous approach considered, where the

Table 9. FCE and aSOS Values at the European, Sweden, and Spanish Levels

			
FCE_{WS}	$3.71 \cdot 10^{7}$	$9.97 \cdot 10^{8}$	$1.36 \cdot 10^{9}$
$FCE_{R/C}$	$1.13 \cdot 10^{7}$	$3.82 \cdot 10^{5}$	$9.97 \cdot 10^{5}$
$POP_{R/C}$	$7.48 \cdot 10^{8}$	$1.02 \cdot 10^{8}$	$4.67 \cdot 10^{8}$
$VC_{WPP\ R/C}$	$8.96 \cdot 10^{7}$	$6.53 \cdot 10^{5}$	$3.73 \cdot 10^{6}$
VC_{WS}	$9.00 \cdot 10^{8}$	$1.45 \cdot 10^{8}$	$4.17 \cdot 10^{7}$
$aSOS_{FCE,\ ind+POP}$	0.32	3.41	8.24
$aSOS_{FCE,\ ind+POP+VC}$	$3.16 \cdot 10^{-2}$	$1.54 \cdot 10^{-2}$	0.74

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Figure 3. R_{ES} scores for both bioadhesives and synthetic resins obtained, considering $aSOS_{GVA}$.

allocation score for the Spanish region is the lowest within the three territories, is based on the fact that by downscaling within the FCE approach, the lowest allocated values are obtained for Sweden, in the case of $aSOS_{FCE,\ ind+POP}$, and for Europe, when the value chain is considered for allocation, $aSOS_{FCE,\ ind+POP+VC}$.

Once the aSOS score is calculated, it is used to downscale the PBs for the wood adhesive alternatives and to determine the ratio of environmental sustainability, R_{ES}, of the alternative wood adhesives scenarios, which must be less than 1 to consider the scenario as sustainable. For this, the previously obtained LCA values, following the recommendations of the Environmental Footprint report in the selection of the impact calculation methodology, will be divided by the SOS for human activities (SOS_f, Table 4).

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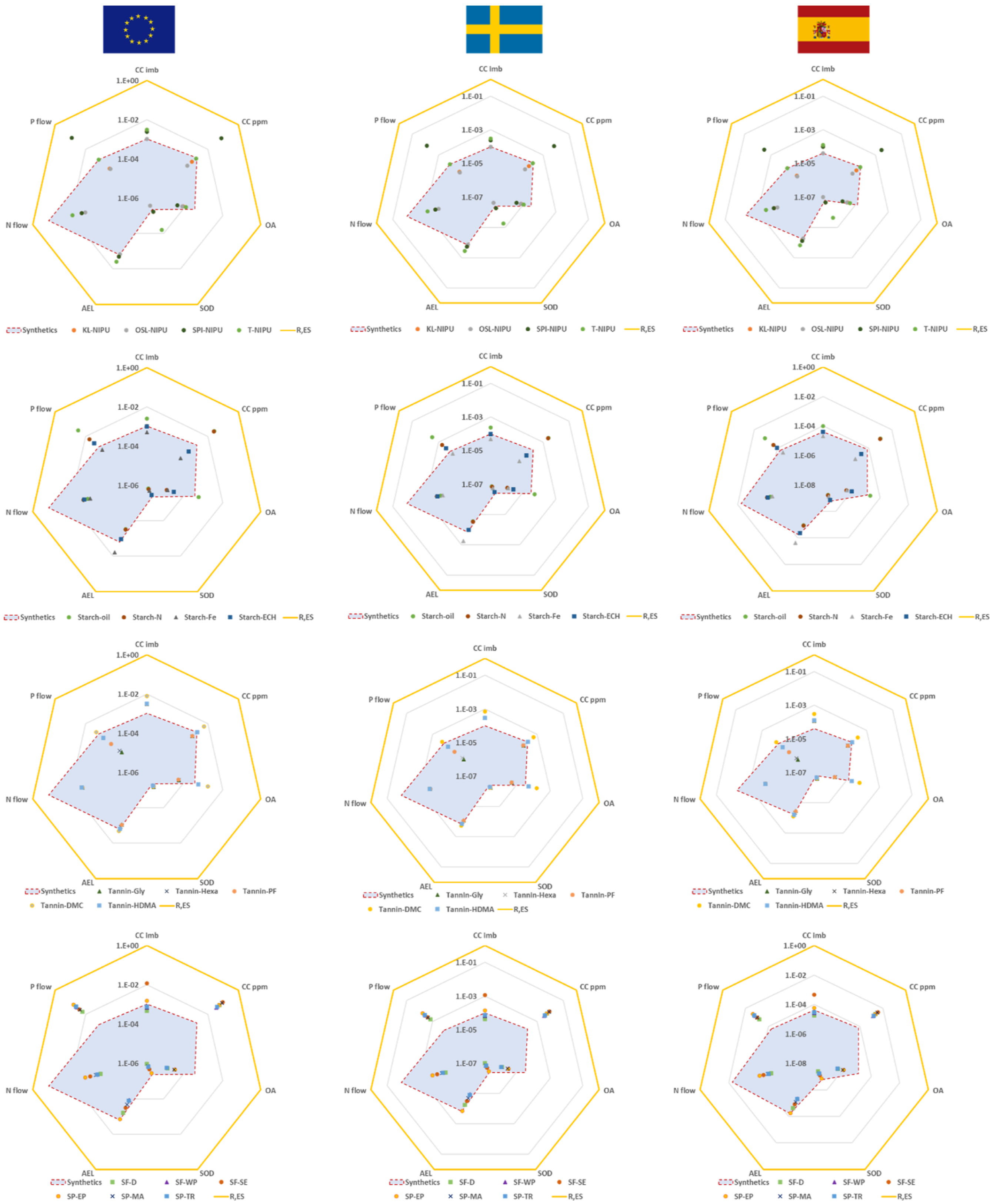

Figure 4. R_{ES} scores for both bioadhesives and synthetic resins obtained, considering $aSOS_{FCE,\ ind+POP}$.

The R_{ES} scores for both bioadhesives and synthetic resins, considering $aSOS_{FCE,\ ind+POP}$, are shown in Figure 4, while the R_{ES} scores using $aSOS_{FCE,\ ind+POP+VC}$ are displayed in Figure 5. The threshold value for assessing the scenario as sustainable or non-sustainable is represented by the solid yellow line. To compare the potential of bioadhesives with that of resins formulated with formaldehyde, the region colored in light blue and dotted with red dashed line is included, representing the scoring values of the synthetic resins in the different PBs. Therefore, those bioadhesives that have R_{ES} values within the

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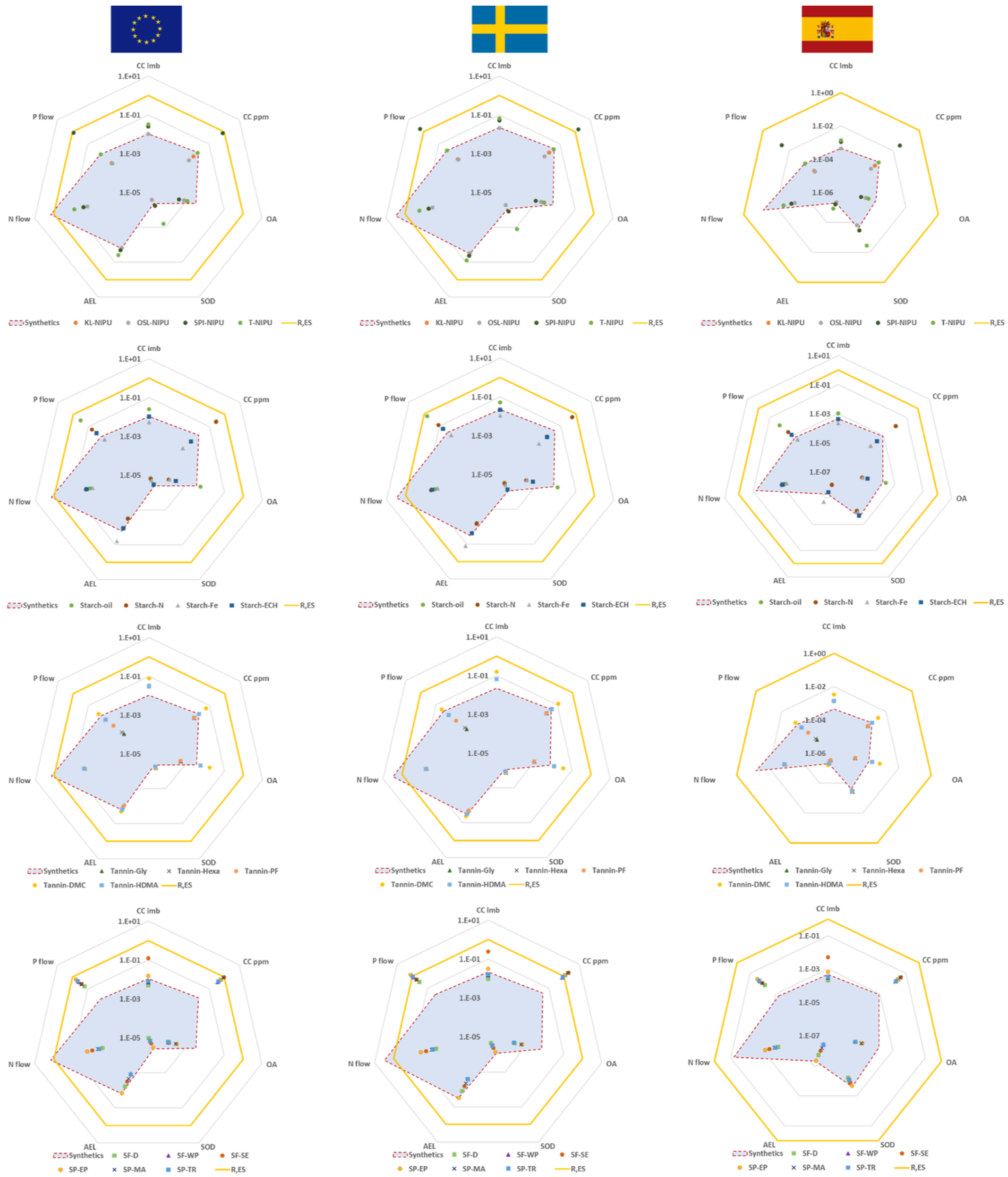

Figure 5. RES scores for both bioadhesives and synthetic resins obtained, considering $aSOS_{FCE,ind+POP+VC}$.

shaded region have a lower impact contribution on PBs and could be considered as more sustainable wood adhesive options.

All bioadhesives analyzed in this report are below the threshold values (the ones depicted on Table 2 for each of the impact categories) of the environmental sustainability ratio using the allocation criteria of $aSOS_{FCE,ind+POP}$, when considering the allocation approaches to European, Swedish, and Spanish regions. This is an indicator of their suitability for wood-based panel production. However, there are some impact categories where a higher contribution is observed, that is, where the R_{ES} ratios obtained are higher than those of synthetic resins, and therefore, this is where efforts and sensitivity analyses to reduce environmental burdens should be focused. The categories where this is the case are those corresponding to CC, that is, PB_{CCimb},

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PB_{CCppm}, and $PB_{BF,P}$, although for some bioadhesives, such as T-NIPU, Tannin-DMC, and Tannin-HDMA, the planetary limits of formaldehyde-based resins are also exceeded in the PB_{OA} and PB_{AEL} categories.

Soy-based bioadhesives show the highest exceedances of the limits set for synthetic resins in the PB_{CCppm} and $PB_{BF,P}$ categories, where all of them have reached higher values and, therefore, show a lower degree of environmental sustainability. In a previous report (Arias et al., 2020), it was concluded that the use of some chemicals as crosslinking agents, such as dicyandiamide or HDMA, is one of the causes of such a high impact.[47] This is why a reduction in the dosage of these chemicals and the option of modifying the crosslinking agent used in the formulation of the bioadhesive were considered as viable and appropriate alternatives in the search for impact reduction. Regarding the use of soy protein, SPI, it is worth mentioning that its extraction process is characterized by high energy consumption, which will imply a high environmental contribution, a fact that is observable in Figure 3, where the SPI-NIPU bioadhesive exceeds the limit values of the synthetic resins in the previously mentioned categories, and it is also worth mentioning that it is very close to the limit values in all the PBs, with the exception of PPB *N*-flow where this bioadhesive is surpassed by T-NIPU. On the other hand, analyzing the different bioadhesive scenarios at the global level, it can be considered that tannin-based bioadhesives seem to be the most environmentally sustainable alternative as all scenarios are below the limits of formaldehyde-based resins, with the only exception of a slightly higher value in the PB_{CC} and PB_{OA} categories but lower than that of the other bioadhesive scenarios. Contrary to what happened in the case of the use of GVA as an indicator of a country's economic prosperity, where the enlargement of Europe to the national level implied a decrease in GVA and thus a "negative" impact on the environmental sustainability ratio, as it is inversely proportional to the aSOS. This fact resulted in an increase in the value of R_{ES}, leading to a ratio above 1, indicating the lack of sustainability of the analyzed bioadhesive scenario. However, in the case of the FCE, a downscaling to national regions results in a higher aSOS value, which has a "positive" impact on the sustainability score as it contributes more to a lower R_{ES} value. However, it is important to mention the point that despite the lower aSOS value for the European continent, environmental sustainability is also achieved for all studied bioadhesive scenarios. However, it is important to note that not all bioadhesive scenarios have lower R_{ES} values than those characteristic for synthetic resins. This fact of exceeding the limit for formaldehyde-based resins but remaining below the RES limit mainly affects the categories associated with the phosphorus cycling cycle, $PB_{BF,P}$ and CC, that is, $PB_{CC,imb}$, $PB_{CC,ppm}$, and, in the particular cases of some tannin bioadhesive scenarios, also the PB_{OA} category.

The R_{ES} scores using $aSOS_{FCE,\ ind+POP+VC}$ are displayed in Figure 5, where a similar trend to that of using $aSOS_{FCE,\ ind+POP}$ could be seen since for the regional allocation of Spain, better results are obtained as a lower value for R_{ES} is obtained, which implies a huge sustainability potential of the adhesive scenarios under assessment. The reason for this fact is based on the same premise as for the previous case, the value of the aSoS for Spain is the highest compared to that of Sweden or Europe, which provides a larger margin in the value of the sustainability ratio obtained. However, it is important to bear in mind that the value chain of wood products in the Spanish region is smaller, indicating a lower productive capacity.

Bearing this in mind, it is observed that the most affected PB, that is, where a higher contribution value and, therefore, a lower degree of sustainability are obtained, is that of biogeochemical nitrogen flow. The R_{ES} score obtained is higher than the planetary limit for the case of synthetic resins but nevertheless remains below the permitted value for all bioadhesive scenarios. Therefore, it could be concluded that in this case, the potential of bioadhesives to be considered as sustainable production models is higher than that of synthetic resins. On the other hand, the values obtained for the other BPs are within the limits established to maintain the natural balance of the earth, with the exception of the $PB_{CC,ppm}$ category for the case of starch-based bioadhesives, where some exceeding of the limit is appreciated, although not to a great extent.

4. CONCLUSIONS

This report presents a methodological procedure to assess the potential of various wood bioadhesives considering an extension of the LCA results to the scope of PBs. In this sense, it is possible to analyze the sustainability perspective within a global level, taking into account the thresholds for planetary boundaries necessary to ensure the stability of the Earth system in order to avoid endangering the habitability of the planet. On the other hand, seeking to provide a wider scope of the PB score obtained, different allocation principles were considered (utilitarian, egalitarian, and grandfathering), which have been scaled to different regions: Europe, Sweden, and Spain. In this way, it could be assessed whether the allocated share of SoS is exceeded in the regional and continental approaches under evaluation.

It has been observed that the bioadhesive alternatives analyzed within this article could be considered as potential substitutes for synthetic resins for wood-based panel manufacturing. In most of the scenarios, the environmental sustainability ratio is lower than that of synthetics, but there are some PBs where great efforts should be made as higher unsustainability scores were obtained. This is the case for the PBs associated with CC and is also seen for the category of biogeochemical flows in some bioadhesive alternatives.

On the other hand, the sharing principle considered for the assessment has given rise to far-reaching results, while in the case of GVA, Spain was the most disadvantaged territory as it gave rise to sustainability ratios above 1, which is indicative of a production scenario classified as unsustainable; when studied according to the FCE, the opposite occurred: Spain was the region in which the best potential for sustainable development was obtained.

Although it is certainly complex to identify the most suitable renewable-based raw material alternative for the formulation of wood bioadhesives, given the variability of the sustainability scores obtained for the different principle approaches and territorial scales, it could be roughly concluded that starch is the most suitable raw material. In most cases, its impact values are below those characteristic of synthetic resins, and its damage scores, in general, do not exceed the established planetary boundaries. However, it is important to mention that in the case of the allocation principle considering the GVA as an indicator parameter, some exceedance of the safe limits of the planetary limits is observed for all the adhesives studied. Therefore, it is important to define a universal standard methodology that establishes which allocation approach is the most appropriate when assessing production processes on a planetary scale. This is what future research should focus on developing for sustainability assessment of biobased processes across planetary boundaries. On the other hand, to avoid limitations in conducting these studies, it will be necessary to have access to the most recent data on GVA, FEC, emissions, and production level by facility type and market estimates of future economic value for each country and continent as the quality, precision, and validity of the PB values depend to a larger extent on the data available to further develop the methodology.

Besides, the evaluation of environmental impacts at the global level implies an advantage for the identification of the affectation of industrial processes on the quality of the environment as well as on the economic profitability of countries and on the level of social welfare. The development of PB assessments could be considered as the next step to the LCA methodology, which, despite being a suitable and precise impact assessment method, has certain limitations when it comes to establishing the global sustainability associated with a production scheme.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.2c03058.

LCA values by applying the classical LCA methodology; comparison of planetary impact scores between isocyanate-free bioadhesives and synthetic resins; comparison of planetary impact scores between starch bioadhesives and synthetic resins; comparison of planetary impact scores between tannin bioadhesives and synthetic resins; and comparison of planetary impact scores between soy bioadhesives and synthetic resins (PDF)

LCA values of the scenarios by applying the classical LCA methodology (PDF)

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Author Contributions

A.A.: methodology, formal analysis, investigation, and writing—original draft. G.F.: writing—review and editing. M.T.M.: conceptualization, supervision, and writing—review and editing.

Notes

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■ ACRONYMS

CC	climate change
SOD	stratospheric ozone depletion
IR	ionizing radiation, human health
RU	resource uses, fossils
EF	eutrophication, freshwater
EM	eutrophication, marine
PB_{CC,CO_2}	planetary boundary: climate change, CO_2 concentration
$PB_{CC,imb}$	planetary boundary: climate change, energy imbalance
PB_{OA}	planetary boundary: ocean acidification
PB_{SOD}	planetary boundary: stratospheric ozone depletion
PB_{AAL}	planetary boundary: atmospheric aerosol Loading
$PB_{BF,P}$	planetary boundary: biogeochemical flows, phosphorous
$PB_{BF,N}$	planetary boundary: biogeochemical flows, nitrogen cycle

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