UNCERTAINTIES IN LCA

Identifying uncertainty in the global warming impacts of biomaterials: an analysis of biosuccinic acid

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Abstract

Purpose Life cycle assessments of biosuccinic acid (bioSA) report a range of emissions compared to their fossil-based counterparts. Such uncertainty results from multiple factors including different processing options and modeling choices, making it difficult to interpret results and ensure emission reductions. Identifying uncertainty is thus crucial to ensuring the environmental benefits of biomaterials and is a crucial step toward a future bioeconomy.

Methods Comparing 15 life cycle assessments of bioSA production, factors such as feedstocks, downstream processing technologies, study scopes, coproduct handling, coproduct types, and study locations were assessed to identify the impact of different modeling choices and processing options on the global warming impacts of bioSA. Emissions were referenced to a fossil-derived equivalent product and selected case studies were developed for a more in-depth analysis of the impact of individual factors, such as enzymes, coproducts, and grid location on overall emissions.

Results Global warming impacts varied across differing processing and modeling factors. BioSA from sugar cane and energy crops consistently showed emission reductions while from corn starch, corn stover, and food waste, bioSA displayed impacts above and below fossil-based production depending on processing and modeling options. Uncertainty in individual factors such as enzyme production was significant, potentially resulting in impacts exceeding conventional fossil-based production. However, coproduct inclusion and handling methods were necessary for several feedstocks to ensure emissions remained lower than the fossil-based route.

Conclusions This study highlights the importance of identifying and quantifying uncertainties in the global warming impacts of biobased products. Doing so serves not only to ensure emission reduction benefits, but also strengthens trust in LCA studies and encourages more accurate and trustworthy results for policy makers, industrial partners, and LCA practitioners.

Keywords Biosuccinic acid · Bioeconomy · Global warming

1 Introduction

A transition to a bioeconomy is a crucial solution to address fossil fuel depletion and global climate change. As an alternative to petroleum-based products, biobased equivalents can reduce fossil fuel use and sequester CO_2 in biomass (Musonda et al. 2020; Bello et al. 2022). Biosuccinic acid (bioSA), $C_4H_6O_4$, is one chemical that is derived from biorefinery carbohydrates and is a growing platform chemical

due to the high value of its derivative products (Bechthold et al. 2008; Bozell and Petersen 2010). Currently, succinic acid (SA) is petrochemically produced from n-butane/butane through catalytic hydrogenation of maleic acid or maleic anhydride (Bechthold et al. 2008). However, increasing conservation efforts toward transitioning to a bioeconomy have called for increasing production of bioSA derived from several renewable feedstocks and microorganisms (de Jong et al. 2020).

BioSA production is still in its early phases with no commercial-scale production, despite several previous pilot and demonstration plants (Li and Mupondwa 2021). However, interest in bioSA is continuing to be driven by both its potential for reducing emissions compared with fossil-derived SA, it's wide applications in a variety of industries, and as a building block for a wide range of high-value products and

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Communicated by Guido W. Sonnemann.

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bulk chemicals (Choi et al. 2015; de Jong et al. 2020). BioSA can serve as a renewable source for a wide range of chemicals and products in the production of food, pharmaceutical products, detergents and solvents, and biodegradable polymers, such as polybutylene succinate (PBS) and polyamides (Ahn et al. 2016; Mazière et al. 2017). As an intermediate biomonomer, the process chain of bioSA is simpler than the full production of biopolymers, and thus, assessing the environmental impacts of bioSA can serve as a necessary starting point for chemicals with more complex structures. As a result, bioSA has previously been recognized by the Department of Energy (DOE) as a top ten priority biochemical whose production is crucial for a future bioeconomy (Werpy and Petersen 2004). However, in order to ensure biobased solutions remain environmentally beneficial, it is crucial to examine their total life cycle impacts. Given its early stage of development, wide industrial applications, and potential to serve as a starting point for more complex biobased polymers, bioSA represents an ideal candidate for assessing the environmental impacts of biomaterials more broadly.

Early life cycle assessment (LCA) studies of bioSA indicated that global emissions savings of 5 kg CO_2/kg were possible when replacing their functionally equivalent fossil-derived counterparts (Hermann et al. 2007). Later assessments showed emissions savings up to 86% for bioSA from corn stover feedstocks compared to a conventional fossil reference (Adom et al. 2014; Dunn et al. 2015). However, despite promising emission reductions, more recent assessments expanded to include multiple feedstocks, processing options, and methodological choices and display a range of emissions, even when produced from similar feedstocks (Weiss et al. 2012; Ogmundarson et al. 2020; Walker and Rothman 2020). In a recent review of biomaterials, global warming impacts of bioSA were both above and below its fossil counterpart regardless of the life cycle stages considered (Ogmundarson et al. 2020). Such large variations can lead to difficulty in drawing meaningful conclusions and highlight the need for identifying and quantifying significant areas of uncertainty.

Uncertainty in the life cycle emissions of bioSA and biomaterials, more broadly, arises from processing options (i.e., from differing feedstocks, processing technologies, and biorefinery locations) and methodological choices (i.e., differing study scopes and system boundaries, inclusion of coproducts, and different methods for handling coproducts) (Montazeri et al. 2016; Dunn 2019; Ogmundarson et al. 2020; Bishop et al. 2021). In existing LCAs, however, only uncertainty in the quantities of individual material and energy flows in the inventory assessment phase are considered. Yet, several individual choices, often made by the LCA practitioner, such as the chosen conversion technology, system boundaries, and inclusion of coproducts, have also been shown to significantly influence comparisons of

biobased with fossil-based products (Janssen et al. 2016; Montazeri et al. 2016; Tecchio et al. 2016; Dickson et al. 2021). In Germany, for example, bioSA has been shown to only produce significant emission savings when substituting its fossil counterpart if it is recycled at the end of its life and several cascading coproducts are obtained from its production (Musonda et al. 2020).

Addressing these issues, this study aims to identify areas of uncertainty in the greenhouse gas emissions of bioSA as a guide for future impact assessments of biomaterials. We survey the published environmental literature of bioSA production to answer two questions which address current gaps in knowledge: (1) What are the formative individual areas of uncertainty within LCAs of bioSA production and (2) Do the magnitude of uncertainties in emissions hinder conclusions regarding the environmental benefits afforded by bioSA compared to its fossil-derived counterparts? Compared to previous analyses, we analyze a much larger sample size of studies than has been previously considered (Montazeri et al. 2016; Ogmundarson et al. 2020). Where adequate, existing assessments are used as case studies to discuss and quantify priority areas of uncertainty and their magnitudes.

2 Methods

2.1 Study overview

Life cycle assessment (LCA) is a systematic way to quantify the environmental impacts of a process or product over its lifespan (ISO 2006). Figure 1 shows an overview of the main LCA steps and processes of bioSA considered in this study. First, we contrast and examine the results of fifteen environmental assessment and LCA models (SI Table S1) of bioSA production to determine the variability of greenhouse gas emissions (GHG) due to different modeling choices and processing options. This is a substantial improvement over previous analyses which have considered only five and eight studies for bioSA in total (Montazeri et al. 2016; Ogmundarson et al. 2020). The examined modeling choices and processing options were those that have been previously identified as potentially having a large impact on the emissions of biobased systems. A total of six factors impacting bioSA emissions including feedstock, downstream processing technology, study scope, coproduct handling method, type of coproduct, and study location were examined. Finally, using existing samples as case studies, a more in-depth analysis is performed to further quantify the impact of several individual factors on the overall emissions of bioSA.

The examined studies canvassed all three generations of feedstocks in the US, Europe, and Brazil with one paper focused on India, yielding a total of $n = 64$ individual data points for the GWP of bioSA (SI Table S1). Only studies
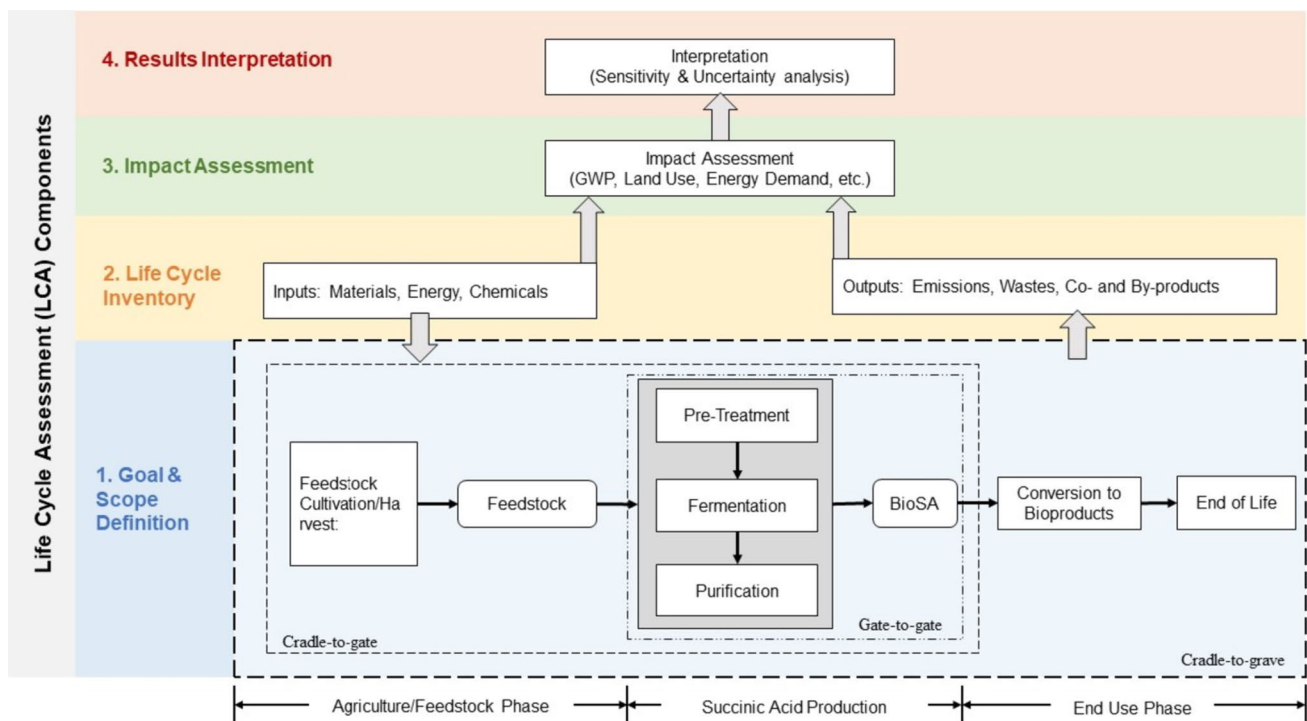
Fig. 1 Primary life cycle assessment components of biobased succinic acid (bioSA) from production to end of life

focusing exclusively on the production of succinic acid were included in the analysis. Studies whose primary focus was to assess an end product of bioSA were not included as these studies simply applied the results from those that focused on bioSA. The majority of examined studies adopted an attributional modeling approach; however, consequential studies were also included in the sample. In consequential modeling, the primary difference involved substitution of bioSA with a fossil reference. For these studies, the substitution with fossil SA was excluded to maintain consistency with the rest of the studies.

2.2 Measuring global warming impacts

Impact assessments of bioSA most commonly included the 100-year global warming potential (GWP), which represents the cumulative radiative forcing of the total life cycle emissions of a process over a 100-year period. For this study and due to data availability, GWP was used to represent the GHG emissions of bioSA.

2.3 Differences in functional units

While nearly every study applied a mass-based functional unit of 1 kg of produced and purified bioSA, a single study applied a functional unit of the feedstock (Maria Ioannidou et al. 2021). In this case, inventory and impact results were rescaled to the functional unit of 1 kg of bioSA

using yield data to maintain consistency with the rest of the studies. One study compared two different functional units including impacts per kg of produced bioSA and per kg of feedstock (Brunklaus et al. 2018). While the choice of functional unit can impact broad study outcomes, the purpose of this study was to assess variability in the global warming impacts of bioSA production itself. Further, the choice of functional unit does not introduce uncertainty to the impacts of bioSA production, but rather depends on the overall research question to be answered. Thus, only the former functional unit was included.

2.4 Feedstock grouping

Feedstocks were categorized into eight broad groups (sugar cane, energy crops, corn starch, corn stover, food waste, sugar beet, seaweed, and waste wood) based on the number of studies, sample size, and crop type. Due to a low number of data points, bread waste, waste cooking oil, apple cider waste, and winery waste were grouped into the broader category of "food waste." Similarly, fast-growing crops such as sorghum grain, canary grass, and giant reed grass were grouped into the "energy crops" category. Due to its small sample size (only a single sample) and structural similarity to other lignocellulosic energy crops, sugar cane bagasse was also included in the "energy crops" category.

2.5 Study scopes and carbon sequestration

The majority of the assessed studies used cradle-to-gate system boundaries which start with raw materials extraction and end with the production of purified succinic acid from the biorefinery. Only four studies used cradle-to-grave boundaries which included the degradation of bioSA in an end-of-life (EOL) scenario (Patel et al. 2006; Adom et al. 2014; Musonda et al. 2020; Dickson et al. 2021). A key difference between the two study scopes involved the treatment of biogenic carbon sequestration, or the carbon sequestered into the bioSA product itself during its production. In cradle-to-gate studies, biogenic carbon can be applied as a credit, reducing the overall emissions. For bioSA, biogenic carbon amounts to ~ 1.5 kg CO_2 eq./kg SA (Cok et al. 2014; Zucaro et al. 2017; Patel et al. 2018). In nearly all cradle-to-grave studies, bioSA was assumed to be landfilled at the end of its life, releasing the biogenic carbon sequestered during its production and thus being carbon neutral. In many cradle-to-gate studies, however, it was unclear whether biogenic carbon was included or not as many studies simply did not specify or mention biogenic sequestration. In these cases, and to avoid double counting, a conservative approach was taken, and it was assumed that biogenic carbon was included allowing for a consistent comparison with the other studies.

In addition to biogenic carbon, soil carbon sequestration may be an important factor in the carbon balance of many first- and second-generation feedstocks. However, issues of soil carbon sequestration were not included in most studies due to data availability issues (Moussa et al. 2016; Chrysikou et al. 2018; Maria Ioannidou et al. 2021). Only a single study considered changes in soil carbon storage (SCS) due to the cultivation of giant reed grass (Zucaro et al. 2017). In this case, SCS accounted for a relatively minor proportion ~ 11% (0.44 kg CO_2 eq./kg SA) of the gross global warming impact of bioSA. Thus, due to the lack of data and the minor contribution to overall emissions, issues of SCS were not considered in this study but still may represent an important future research avenue to consider.

2.6 Fossil-based reference product

To quantify the impacts of modeling choices and processing options on emissions of bioSA, GWP values were referenced to those of fossil-derived SA. However, uncertainty regarding the GWP of fossil SA does exist. Production of fossil-derived SA was based on the current conventional hydrogenation of maleic anhydride method (Pinazo et al. 2015). From the literature, a total of four values of the emissions of fossil-derived SA were found ranging from ~ 1.9 to ~ 7.1 kg CO_2 eq./kg SA (Patel et al. 2006; Cok et al. 2014; Dickson et al. 2021). The values on the upper range used by Patel et al. (2006) were based on SA from the ecoInvent

database (Althaus et al. 2007). Since then, these values have been updated to more accurately account for the coproduced steam (Cok et al. 2014). The fossil reference values used by Patel et al. (2006) are likely outdated and were thus excluded from this analysis. Therefore, we used values from Cok et al. (2014) and Dickson et al. (2021), who independently calculated the GWP of fossil SA based on proprietary industrial and literature data (Cok et al. 2014; Pinazo et al. 2015; Dickson et al. 2021). To account for the uncertainties in the GWP of fossil SA, the range of the reported values, from ~ 1.9 to ~ 3.9 kg CO_2 eq./kg SA with a mean of ~ 2.9, were taken as representative values for the conventional fossil-based route to produce SA.

2.7 Isolating the effect of individual factors on GWP

A more in-depth analysis regarding the impact of individual methodological choices and processing options on the overall emissions was performed using data from selected studies. These factors included the influence on emissions of changing the geographic location of the biorefinery, variability in the emissions of highly uncertain processes such as enzyme production, and the contribution of the inclusion of coproducts to overall emissions. Full details of the descriptions and modeling procedures of each of these factors can be found in the supplementary information.

3 Results

3.1 Variation in Global Warming Potential (GWP) due to modeling choices and processing options

Figures 2 and 3 show the variability in GWP under each of the six different modeling choices and processing options for bioSA production. Summary statistics of the variability in GWP for all factors can be found in the supplementary information (SI Tables S2 and S3). While GWP variability is high for each factor, several broad trends in the emissions of bioSA in comparison with fossil SA are noted:

3.1.1 Feedstock

BioSA GWP varies significantly when produced from different feedstocks (Fig. 2), ranging from − 1.4 to ~ 30 kg CO_2 eq./kg SA for bioSA from sugar cane and waste wood, respectively. Compared to fossil SA (ranging from ~ 1.9 to ~ 3.9 kg CO_2 eq./kg), the mean values of four feedstocks—sugar cane, energy crops, corn starch, and corn stover—remain below the lower range of fossil SA. However, wide variability exists within the results of each feedstock. Despite having mean values below fossil SA, the range of GWPs of corn starch and corn stover, for example, vary from ~ 0.3 to ~ 4.6

Fig. 2 Overview of the variation and mean (X markers) GWP values (in kg CO_2 eq./kg) of biobased succinic acid (bioSA) per feedstock from the existing literature. For comparison, the GWP of fossil-derived succinic acid (fossil SA) is also shown
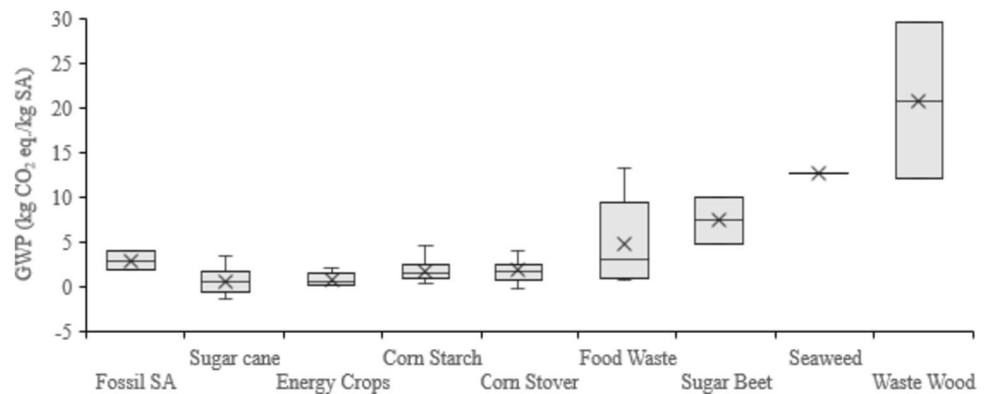
and ~ -0.2 to ~ 5.7 kg CO_2 eq./kg SA, respectively. For these feedstocks, such wide variability in GWP is enough to shift the comparison from favoring bioSA to favoring fossil SA. Four feedstocks—food waste, sugar beet, seaweed, and waste wood—display mean values above the mean and upper range of fossil SA. However, few data points exist for these feedstocks with only a single sample for seaweed, 5 for food waste, and 2 for sugar beet and waste wood.

3.1.2 Study scope

The analyzed system boundaries have a minor impact on bioSA (Fig. 3a), varying GWP from a mean of ~ 2.3 to ~ 3.0 kg CO_2 eq./kg SA under cradle-to-gate and cradle-to-grave boundaries, respectively. This variability was due to the fact that nearly all cradle-to-grave studies assumed bioSA was landfilled at the end of its life, releasing the biogenic carbon sequestered during its production (a value of ~ 1.5 kg CO_2 eq./kg SA). As a result, cradle-to-grave studies displayed higher emissions than cradle-to-gate studies, placing the mean GWP slightly above the mean of fossil SA and shifting the preference more in favor of fossil-based SA.

3.1.3 Downstream technology

Significant variability exists for bioSA produced using different downstream processing technologies, with mean GWPs ranging from ~ 1.4 to ~ 7.3 kg CO_2 eq./kg SA for reactive distillation (RD) and reactive extraction (REX), respectively, with values ranging both below and above the lower and upper ranges of fossil SA (Fig. 3b). In addition to the large variation across technologies, considerable variation exists among studies which used the same technology. This is largely attributed to differences in feedstocks as bioSA produced from different feedstocks may also have been produced with the same downstream technologies (see Sect. 3.2). It is important to note, however, that large disparities exist in the assessed sample sizes with only 1, 3, and 4 samples present for RD, membranes (MEM), and REX while

8, 21, and 26 samples were available for ion exchange (IX), electrodialysis (ED), and crystallization (CR) (SI Table S3).

3.1.4 Coproducts

Both the method of handling coproducts (Fig. 3c) and the type of coproduct obtained (Fig. 3d) are essential for ensuring emission reductions compared with fossil SA. Under different coproduct handling methods, mean GWP varied from ~ 0.1, ~ 1.8, and ~ 4.2 kg CO_2 eq./kg SA for studies which used multiple, system expansion, and allocation-based (either mass or economic) methods, respectively. Studies using allocation-based methods showed the largest variation in GWP, particularly influenced by the relationship between the coproduct and bioSA. For example, in the case of food waste, the mass of coproduced feed was more than 10 × that of the main bioSA product, yet their economic values were nearly identical at $4.8/kg and $5.0/kg, respectively (Gadkari et al. 2021). Mass and economic allocation would allocate ~ 10% and ~ 51% of the gross impacts to bioSA, respectively, leading to a 480% increase in impacts if economic rather than mass allocation was applied (Gadkari et al. 2021). Despite such large differences, the mass allocation was chosen due to the high impacts resulting from economic allocation. Other studies have also noted the unfavourability of economic allocation citing the high selling price of bioSA in comparison with many of its coproducts, resulting in large allocation factors applied to bioSA (Cok et al. 2014; Gadkari et al. 2021). Although the price of bioSA is expected to decrease with increasing production, in scenarios where its price greatly exceeds its coproduct (as is the case of ammonium sulfate), decreases in selling price are unlikely to reduce the environmental burden of bioSA under economic allocation approaches (Cok et al. 2014).

The mean GWP of obtained coproducts ranged from ~ 0.2 to ~ 1.4 kg CO_2 eq./kg SA for processes which produced multiple coproducts and energy coproducts, respectively, all values below the lower range of fossil SA. Studies which did not include or assess any coproducts displayed a mean GWP
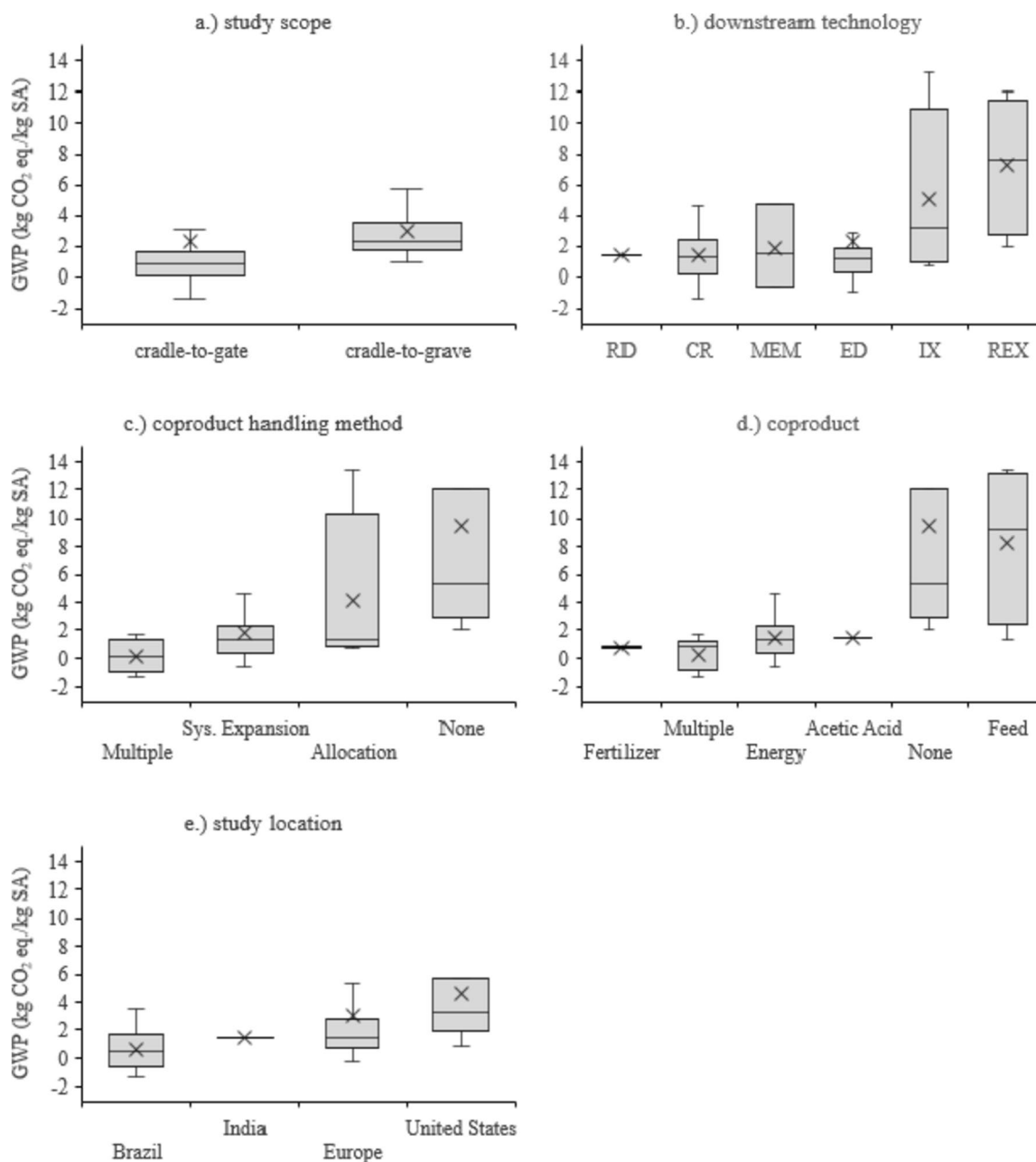
Fig. 3 Variation and mean GWP's (X markers) of bioSA broken down by **a** study scope, **b** downstream technology, **c** coproduct handling method, **d** coproduct, and **e** study location. Abbreviations for downstream technologies are reactive distillation (RD), crystallization (CR), membranes (MEM), electrodialysis (ED), ion exchange (IX), and reactive extraction (REX). For readability, the full range of GWP values (i.e., outliers) are not displayed on graphs. Corresponding ranges and summary statistics of each factor can be found in the supplementary information

of ~ 9.5 with a significant range from ~ 2.0 to ~ 12 kg CO_2 eq./kg SA, values above the lower and upper ranges of fossil SA. For studies which generated feed as a coproduct, GWP displayed significant variability, ranging from ~ 1.3 to ~ 13.3 with a mean of ~ 8.2 kg CO_2 eq./kg SA, values both below and above the lower and upper range of fossil SA. Such large variability is explained by the method used to treat the coproduct and the quality of the coproduct itself. The

existing production of feed is not a fossil-intensive process. Thus, in the studies which treated the coproduced feed using the system expansion approach, the applied credit from the substitution of feed with the existing production was not large enough to significantly reduce the overall GWP of bioSA (Dickson et al. 2021).

Taken together, these results highlight not just the importance of the inclusion of coproducts in reducing overall

emissions, but of the quality of the obtained coproduct and the method used to handle the issue of coproduction in LCA. Obtaining multiple or high-value coproducts (such as fertilizers) from the process chain is preferred and can be identified as a goal for securing emission reductions of bioSA and biomaterials, more broadly.

3.1.5 Study location

While the majority of studies analyzed were from European countries, significant variability in the GWP of bioSA production exists, regardless of the study location (Fig. 3e). The mean GWP values varied from ~ 0.6, ~ 1.4, ~ 3.0, and ~ 4.6 kg CO_2 eq./kg SA for studies from Brazil, India, Europe, and the United States, respectively. However, studies from the United States and India are constrained by small sample sizes as only a single study and sample exists for bioSA from India while 7 samples exist across four feedstocks in the United States (SI Table S1). The low impact of bioSA from Brazil can be attributed to the use of sugar cane as the sole feedstock, whose production is much less energy-intensive than corn-based feedstocks typical of Europe and the United States (Patel et al. 2006; Cok et al. 2014; Smidt et al. 2016).

3.2 Comparison of multiple factors which impact the variability of GWP benefits

While the results thus far identify variability in each of the modeling and processing factors which contribute to the global warming impacts of bioSA, the combination of factors behind the variability is crucial to ensuring emission reductions. Figure 4 shows a breakdown of the GWP values of bioSA from each feedstock paired with each modeling choice and processing option in comparison with fossil SA. For bioSA derived from energy crops, emission reductions are nearly always secured compared to fossil SA irrespective of the considered modeling choices or processing options. For sugar cane, emission reductions are likely secured, but display more variability depending on the chosen downstream technology, coproduct handling method, and coproduct obtained.

While many studies have noted the potential environmental benefits of bioSA derived from corn starch (Patel et al. 2006; Cok et al. 2014; Smidt et al. 2016; Musonda et al. 2020), these benefits are highly variable where the inclusion of multiple coproducts and the use of less energy-intensive downstream technologies such as membranes are essential
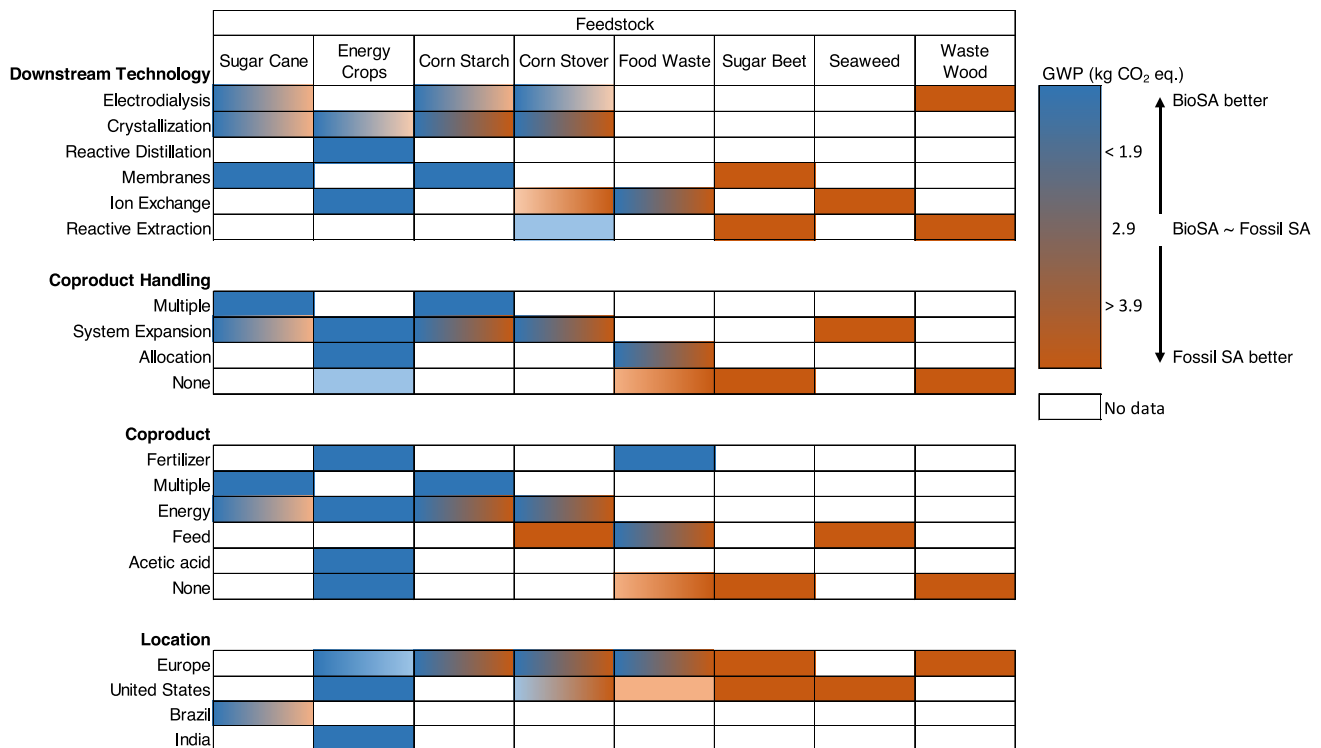

Fig. 4 Comparison of the modeling and processing factors which impact the emissions of bioSA for each feedstock and compared with fossil SA. The color of each box represents the range in GWP of bioSA in comparison with fossil SA. Solid blue boxes represent those cases where GWP remained below the low end of fossil SA (1.9 kg CO_2 eq.) while solid red boxes are those where GWP was above the upper end (3.9 kg CO_2 eq.) of fossil SA. Boxes with gradients from blue to red are cases with multiple samples which displayed GWP values ranging from better than to worse than fossil SA

for securing emission reductions. BioSA from corn stover and food waste produce widely variable emissions that range from both better-than to worse-than fossil SA across nearly all factors. While for bioSA derived from sugar beet, seaweed, and wood waste, emissions are worse than fossil SA regardless of the considered modeling and processing factors, however, these feedstocks may be constrained by a relatively small sample size of data points in comparison with the others (SI Table S1) and additional GWP data are needed as more studies become available for these feedstocks.

3.3 Impact of individual factors on overall GWP

Finally, a more in-depth analysis was performed on selected case studies to isolate the effects of several individual factors on the overall emissions of bioSA. These factors include (1) a change in the location of the biorefinery to regions with differing power grids (SI Table S4) resulting in variations in overall emissions, (2) variation in the emissions of enzyme production, a process whose carbon footprint has previously been identified as highly uncertain, and (3) the impact of including/excluding coproducts on overall emissions of bioSA.

3.3.1 Plant location

GWP of bioSA varies with biorefinery location from ~ 0.1 to ~ 3.4 kg CO_2 eq./kg SA (Fig. 5). At the extremes, using direct crystallization (DC) technology, moving from the average European (RER) power mix to that of Greece (GR) increases GWP by 0.9 generating a total of ~ 1.7 kg CO_2 eq./SA and conversely, changing plant location to

Switzerland (CH) decreases GWP by 0.8 resulting in a total of ~ 0.1 kg CO_2 eq./SA. For the more energy-intensive electrodialysis (ED) process, GWP increases by 1.7 and decreases by 1.5 kg CO_2 eq./SA for the Greek and Swiss grids, respectively. For ED processing, a change from the European average to Central Europe (CENTREL), Greece, and the United States (US) resulted in GWP values above the mean and upper range of fossil-derived SA (Fig. 5, red dashed and upper dotted line) while a change to Denmark (DK) and Italy (IT) resulted in values above the lower range (Fig. 5, lower dotted line). ED processing is more energy-intensive, requiring almost double the electricity as the DC process (3.3 compared to 1.7 kWh) (Cok et al. 2014). For DC processing, changes in location had a large impact on total GWP but were not enough to increase the GWP above the lower range of fossil-derived SA. Despite the large impact of biorefinery plant location on overall process GWP, the electricity mixes of the above countries are likely to become cleaner over time as the proportion of renewables in the production mixes increases, reducing the GWPs for the energy-intensive technologies.

3.3.2 Enzyme production

For two selected feedstocks, bread waste and corn stover, the overall emissions of bioSA production were recalculated accounting for uncertainty within the GWP of enzyme production (see SI Sect. 1.2). Uncertainty in the GWP of enzyme production displays wide variation, ranging from ~ 1.2 to ~ 22 kg CO_2 eq./kg of enzyme (SI Table S5). For bioSA from bread waste, this variability is not enough to significantly alter the GWP due to the very low quantity
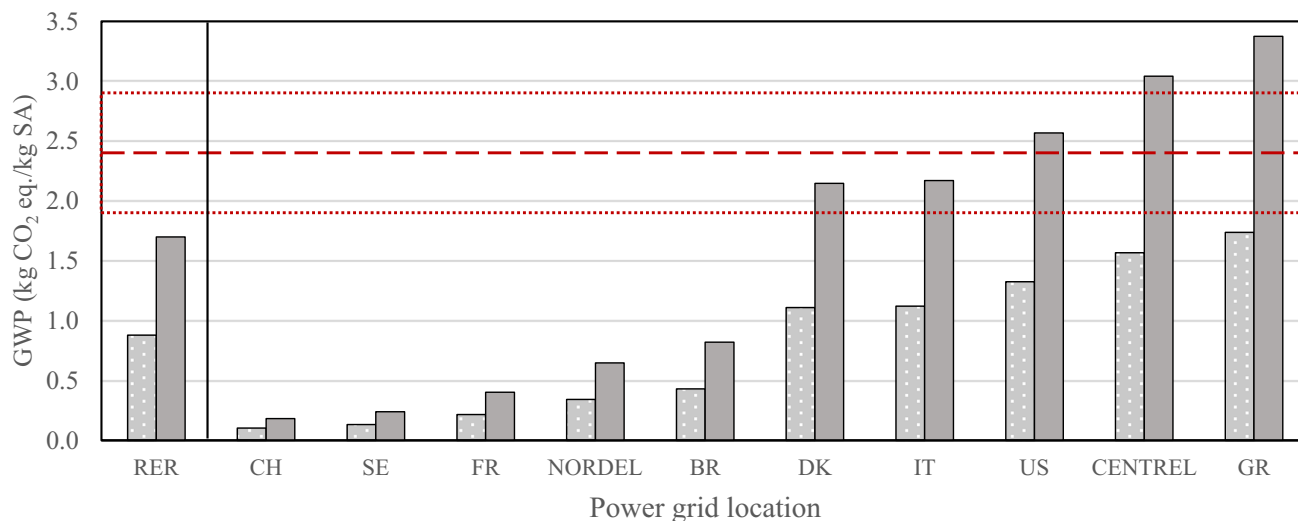

Fig. 5 Location-dependent effects on GWP of bioSA production with direct crystallization (DC, light grey dotted bars) and electrodialysis (ED, dark grey solid bars) as downstream technologies. GWP values are compared to the average European power mix (RER, black box) and the mean (red, dashed line) and upper and lower ranges (red, dotted lines) of fossil-derived succinic acid

(0.007 kg per kg of SA) of enzymes required (Gadkari et al. 2021). For corn stover, however, the uppermost estimate of enzyme production is enough to increase GWP above fossil SA, shifting the preference to favor fossil SA (Table 1). However, these results are dependent upon the production technology used. For bioSA from a less energy-intensive liquid–liquid extraction (LLE) technology, variability in enzyme production is enough to vary GWP from ~ 1.9 to ~ 2.6 kg CO_2 eq./kg SA, values ranging from slightly below the lower range to below the mean of fossil SA. Under a more energy-intensive electro-deionization (EDI) technology, however, GWP varies from ~ 3.3 to ~ 4.1 kg CO_2 eq./kg SA, values above the mean and upper range of fossil SA.

Compared to the original GWP values reported for these feedstocks of ~ 1.9 and ~ 3.3 kg CO_2 eq./kg SA under each respective technology, uncertainty in enzyme production alone is enough to increase the GWP of bioSA from corn stover by ~ 39% and ~ 24% on the extreme ends (Table 1). Thus, as a single process, uncertainty in the GWP of enzyme production can have a large impact on the overall GWP of bioSA production and can significantly hurt the performance of bioSA when compared to fossil SA. Despite the large uncertainty attributed to enzyme production, many studies did not include enzymes within the study scope or considered their impact to be negligible. The case studies above considered enzyme production as a background process,

where enzymes were produced off-site and added as an input to the pre-treatment reactor. Bioethanol studies have shown that reductions in GWP of ~ 20% and ~ 60% can be achieved if enzymes are recycled or produced on-site (Janssen et al. 2016). Future research is needed to assess whether such scenarios can ensure GWP reductions remain below that of the conventional fossil-based SA route when uncertainty in enzyme production is considered.

3.3.3 Coproduct inclusion

The coproduct(s) produced in seven selected studies were removed to isolate the effect of coproduct inclusion on the overall emissions of bioSA (see SI Sect. 1.3). Regardless of the handling method or coproduct type, the impact of including a coproduct was substantial and variable, ranging from ~ 7 to ~ 91% lower GWP (Table 2). For example, the inclusion of coproducts for four feedstocks (sorghum grain, food waste, sugarcane bagasse, corn starch) was required to reduce emissions below the lower range of the conventional fossil-based SA route. The cases where coproduct inclusion displayed the largest reduction in GWP were those where either a small fraction of the total impact was allocated to bioSA (as in the coproduction of large quantities of feed and fertilizers from bread waste) or where large credits were applied when the coproduct substituted for the

Table 1 Mean and range of recalculated GWP values of bioSA production (in kg CO_2 eq./kg SA) for two different feedstocks resulting from variation in the GWP of enzyme production. The original reported GWP values from each feedstock are included for comparison (left column). The rightmost column represents the percent difference between the upper end of the resulting GWP due to variation in the emissions of enzymes and the originally reported values. Thus, this value represents the extreme impact of the uncertainty in enzymes on the GWP of bioSA

Feedstock	Reported GWP	Recalculated GWP values			% Change between upper and reported	Ref
		Lower GWP	Mean GWP	Upper GWP		
Bread waste	1.3	1.3	1.3	1.4	9.4	(Gadkari et al. 2021)
Corn stover (LLE)	1.9	1.9	2.2	2.6	39	(Adom et al. 2014)
Corn stover (EDI)	3.3	3.3	3.6	4.1	24	(Adom et al. 2014)

Table 2 The isolated effect of including coproducts on the GWP of bioSA production. Bold values represent those cases where inclusion of the coproduct reduced GWP below the lower range of fossil-based SA (~ 1.9 kg CO_2 eq.). Units are kg CO_2 eq./kg SA. For corn starch, coproducts included fertilizer and excess electricity

Feedstock	Coproduct method	Coproduct	Without coproduct	With coproduct	% Change	Ref
Seaweed	System expansion	Feed	14.5	12.7	13	(Dickson et al. 2021)
Corn stover	System expansion	Feed	6.11	5.68	7	(Dickson et al. 2021)
Corn starch	Multiple	Multiple	2.50	**1.47**	41	(Cok et al. 2014)
Sugarcane bagasse	Economic allocation	Acetic acid	1.93	**1.39**	28	(Shaji et al. 2021)
Bread waste	Mass allocation	Feed	15.1	**1.30**	91	(Gadkari et al. 2021)
Sorghum grain	System expansion	Fertilizer	4.89	**0.87**	82	(Moussa et al. 2016)
Bread waste	Mass allocation	Fertilizer	5.00	**0.67**	87	(Brunklaus et al. 2018)

existing conventional production of fossil-intensive ferti-lizers (Moussa et al. 2016; Brunklaus et al. 2018; Gadkari et al. 2021). As a single factor, the inclusion of coproducts is potentially the most important factor for reducing the emis-sions of bioSA. More broadly, for a future bioeconomy, the identification and management of useful coproducts can be seen as a requirement to ensure sufficient emission reduc-tions of bioSA and associated biomaterials.

4 Discussion

This analysis identifies uncertainty in the emissions of vari-ous reported bioSA production processes and has limitations. To contrast production processes, this study used only GWP as a comparative metric and specifically did not include other impact categories. This is a limitation and is due to data avail-ability in the literature. The concern would be that trade-offs between greenhouse gas (GHG) emissions and other ecosys-tem-based impact categories (such as land use, ecotoxicity, and eutrophication) are especially relevant for biobased prod-ucts and may shift the preference to favor the conventional fossil-based routes (Smidt et al. 2016; Ogmundarson et al. 2020). To this point, a variety of impact factors are reported inconsistently across the literature. However, GWP perfor-mance was reported in all of the studies cited, and this is why GWP is used exclusively in our analysis. Notably, only a single cradle-to-grave study of bioSA included full coverage of impact categories beyond just GHG emissions and fossil-energy consumption, highlighting a critical avenue for future research (Dickson et al. 2021).

The factors identified which impact bioSA emissions in this study were based on those previously identified in existing assessments. Yet, the suite of factors considered in this study was not exhaustive and other factors such as land use change (LUC) emissions and scale were not included. While LUC emissions have been shown to be significant for biofuels (Valin et al. 2015), including the impacts of direct and indirect LUC into a biomaterial LCA still remains chal-lenging (Montazeri et al. 2016; Dunn 2019). Further, many of the assessed feedstocks in this study included low-impact crops and waste products such as sorghum grain, corn stover, and food waste, feedstocks for which LUC issues may not apply. LUC emission factors are also not readily available in most existing databases and would require product-specific and location-specific data on behalf of the LCA practitioner. As a result, none of the assessed studies have included LUC emissions in their analyses of bioSA. However, given their importance, LUC emissions do represent a significant area of uncertainty for feedstocks such as sugar cane (Valin et al. 2015). Future research should focus on assessing whether the inclusion and variability of LUC emissions are enough to significantly increase the emissions of bioSA.

Study scale is an important factor which can drive the emissions of bioSA and is not addressed herein (Curran 2013; Brunklaus et al. 2018). Scale impacts downstream conversion yields which then varies energy and material requirements to produce the same functional unit. Increases in yield reduce energy and material inputs leading to lower overall emissions (Janssen et al. 2016; Brunklaus et al. 2018). Thus, as bioSA production matures, increases in con-version yields are expected, leading to decreases in GWP and other impact categories in comparison to fossil-derived SA, whose production has already reached commercial scale (Tecchio et al. 2016). Currently, bioSA production is still in the early phases with only pilot plant and lab-scale data available. Thus, while GWP may be sensitive to the scale chosen in existing LCA models, its sensitivity alone does not negate the benefits of bioSA compared with fossil-derived SA. The fact that many existing studies already display emis-sions comparable to, or lower than, fossil SA despite their early stage of development is promising and will continue to improve over time.

5 5 Conclusion and recommendations

5.1 Conclusions

The bioeconomy is a solution to concerns over fossil fuel depletion and global climate change. Biobased succinic acid (bioSA) has been identified as a key platform chemical, with the potential to compete both economically and environmen-tally with fossil-based production. However, uncertainties in life cycle assessments (LCAs) of bioSA, resulting from dif-ferences in processing options and modeling choices, make it difficult for decision-makers to interpret results. Addressing these concerns, this study assessed existing LCAs of bioSA production to identify areas of uncertainty and variability due to different processing and modeling options. The sub-sequent goal was to clarify areas of uncertainty in the LCAs of bioSA and most importantly whether such uncertainties negate previous conclusions regarding the emissions savings of bioSA compared with their fossil-derived counterparts.

Despite the large variability in emissions, bioSA from sugar cane and energy crop feedstocks display the lowest emissions and are likely to reduce emissions compared to the conventional production of fossil-derived SA, regard-less of the considered processing options or methodologi-cal choices. Emissions of bioSA produced from corn starch, corn stover, and food waste feedstocks are less certain and display more variability depending on processing technol-ogy, coproduct handling, and coproduct type. Conversely, bioSA from sugar beet, seaweed, and waste wood feedstocks display emissions above the upper range of the conventional fossil-based route, however, these results may be hindered by

Table 3 Conclusions and key recommendations for life cycle assessments of future biomaterials

Main conclusion	Recommendation and future research
BioSA from sugar cane and energy crops display emissions lower than the conventional route, regardless of other factors, whereas feedstocks such as corn starch, corn stover, and food waste are less certain	Future production should focus on those feedstocks that can already guarantee emission reductions while future research is needed to clarify the emissions of those that are less certain
For bioSA from corn starch, corn stover, and food waste, combinations of the coproduct, coproduct handling method, and downstream technology are crucial for ensuring emissions reductions	Collaboration between industrial partners and LCA researchers is required to ensure the selection of factors which will help guarantee emission reductions in these cases
The uncertainty in single processes such as enzyme production can be enough to shift the preference toward fossil production. However, research from biofuels suggests that producing and recycling enzymes on-site can lead to reduced emissions	Additional care should be taken when considering enzymes for biobased processes. Future studies and production plants should consider better integration of enzymes into the overall production process chain
The obtainment of multiple, high-value coproducts is essential for securing emission reductions for several feedstocks. Inclusion of coproducts alone may be the single most important factor in ensuring emission reductions of bioSA	Industry practitioners should strive to not only identify and produce as many coproducts as possible from the biobased production process but should ensure that as many high-quality coproducts (such as fertilizers) as possible are obtained

a lack of studies and small sample sizes for these feedstocks indicating the need for further research.

Several individual factors were associated with large uncertainty with the potential to have large impacts on overall emissions. As an individual process, variability in the emissions of enzyme production represents a large source of uncertainty for bioSA from food waste and corn stover. For food waste, this uncertainty was not enough to increase GWP above the conventional fossil route. However, for corn stover, uncertainty was enough to shift the preference to favor the conventional fossil-based production route. Similarly, changes in biorefinery location can have significant impacts on emissions due to differences in the regional power mixes of different geographic locations. A switch in plant location from the European average to Central Europe, Greece, Denmark, Italy, and the United States resulted in emissions greater than that of fossil-derived SA for bioSA produced with an energy-intensive downstream technology. This was not the case for a less energy-intensive downstream technology, demonstrating the importance of the downstream processing technology in ensuring emission reductions of biobased materials.

Finally, the inclusion of coproducts was essential in ensuring emissions below that of fossil-derived SA. However, the quality of the obtained coproduct and the method used to handle the issue of coproduction in LCA was also significant. High-quality coproducts such as biobased fertilizers and energy that can substitute for existing fossil-intensive products can provide substantial credits to the biobased product, making them crucial for ensuring emissions reductions.

5.2 Recommendations

Given the uncertainties present in the LCAs of bioSA and the subsequent conclusions, four key recommendations will help to direct future environmental assessments and production of bioSA and biomaterials, more broadly (Table 3). First, despite its early stage of development, bioSA from several feedstocks including sugar cane and energy crops consistently exhibit lower emissions than the conventional route. It is recommended that future production focus on these feedstocks, which can already guarantee emission reductions.

For bioSA derived from corn starch, corn stover, and food waste, however, impacts are more uncertain. For these feedstocks, securing emission reductions requires careful consideration of coproducts, coproduct handling methods, and downstream technology. Further collaboration between industrial partners and LCA researchers is needed to select factors that ensure emissions reductions. Additionally, uncertainty in individual processes such as enzymes can have a significant impact on overall emissions, making them large enough to shift the preference toward fossil production. However, strategies such as on-site production and recycling of enzymes can also be effective in reducing emissions. Thus, additional care should be taken when considering enzymes in biobased LCAs and future research should prioritize better integration of enzymes into the overall production process chain.

Finally, the attainment of multiple high-value coproducts is essential for securing the emission reductions of biomaterials. Industry practitioners are encouraged not only to identify and produce a variety of coproducts from the biobased production process but also to ensure that many high-quality coproducts, such as fertilizers, are obtained. The inclusion of these recommendations into future LCA studies of biomaterials will appropriately strengthen LCA methodology, encourage more accurate and trustworthy results for policymakers, industrial partners, and LCA practitioners, and help ensure the sustainable future production of bioSA and biomaterials.

Declarations

Competing interests The authors declare no competing interests.

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