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The role of feed-grade amino acids in the bioeconomy: Contribution from production activities and use in animal feed

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A B S T R A C T

Feed-grade amino acids contribute to the bioeconomy through both their production and use. Amino acids produced using biomass as feedstock are bio-based products and their production contributes to the bioeconomy in terms of value added and employment. The use of amino acids in animal feed allows to increase feed efficiency and thus to reduce the demand for feed. Their use helps to reduce the content of soybean meal in feed formulation, thereby reducing the demand for soybean meal and consequently the total area of arable land required for feed production. This article proposes a methodological approach for data collection as well as for the calculation of the mentioned effects and provides their first quantification. In the EU, the estimated contribution of bio-based amino acids in terms of value added (50 million €) and employment (400 employers) is quite low. Within the product group "feed-grade amino acids", the share of bio-based amino acids is 15% in the EU and much lower as on the global level (70%). The contribution through the use of amino acids in animal feed is argued to be significant. Our calculation shows that it already helps to avoid the use of millions ha of arable land.

1. Introduction

A sustainable and circular bioeconomy is an option for a better future (Sturm and Banse, 2021; Chavarria et al., 2020; Fritsche et al., 2020). Policymakers in the European Union (EU) recognize this and confirm the importance of a contribution that a sustainable and circular bioeconomy can make to achieving the Sustainable Development Goals (SDGs) as well as the Paris Agreement by the EU's 2018 Bioeconomy Strategy Update. With the European Green Deal, important steps of an integration of bioeconomy in other EU policies related to biodiversity, circularity, climate change, food systems, forest protection and restoration, and renewable energy are underway.

For the assessment of the status and the development of the bioeconomy a monitoring system is needed. One of the EU's 2018 Bioeconomy Strategy Update actions foresees the development of an EU-wide, international coherent monitoring system to track economic, social and environmental progress towards a circular and sustainable bioeconomy. The European Commission (EC) Joint Research Centre (JRC) is leading this action, in collaboration with several Commission Services and stakeholders. The approach for the EU bioeconomy monitoring framework was developed (Kilsedar et al., 2021; Robert et al., 2020) and the first release of the EU Bioeconomy Monitoring System[1] was launched in November 2020; further improvements should follow. At the same time, some bioeconomy monitoring activities are already taking place at the level of the EU member states and there are even initiatives to set up a national bioeconomy monitoring system (Lier et al., 2018). Thus, in 2016 the Federal Government of Germany initiated the development of a comprehensive bioeconomy monitoring system. Research projects based on this initiative resulted in a conceptual proposal for setting up a monitoring system in Germany and generated the first results (Banse et al., 2021; Iost et al., 2020; Bringezu et al., 2020). Furthermore, ongoing bioeconomy research projects result in additional proposals and recommendations with respect to establishing a bioeconomy monitoring system (Kardung et al., 2021).

Despite some differences in the proposed approaches for setting up a monitoring system and indicators used to track the developments in the bioeconomy, one is common for all of them – the need for a sound database. The EU-funded research project BioMonitor[2] addresses this issue by proposing and using different existing and new methodologies in order to fill existing bioeconomy data gaps and to safeguard the data availability in the short, medium and long term. To test and validate proposed methodologies (Piotrowski et al., 2019) case studies were conducted.

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[1] https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en.

[2] https://biomonitor.eu/.

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One of the conducted case studies focuses on the dynamics on the markets for feed-grade amino acids (Sturm et al., 2021). Amino acids contribute to a bioeconomy through associated producing activities as well as through their use in different applications. Relevant producing activities are related to the production of bio-based amino acids mainly through the fermentation process, although other approaches to produce amino acids from bio-based feedstocks are also gaining attention (Deng et al., 2018; Tian et al., 2021; Song et al., 2020; Hirasawa and Shimizu, 2016). Contribution to the GDP, value added or employment associated with these activities could be directly assigned to the bioeconomy. Besides direct contribution to the bioeconomy through the production activities, amino acids also contribute significantly to the bioeconomy through their use. The areas of application of free amino acids include the use in animal feed, food and dietary supplements, pharmaceuticals, cosmetics and as precursors for bio-based plastics and other chemicals. However, the use in animal feed is currently the most important application category and we focus on this looking into feed-grade amino acids.

Generally, positive effects from the use of free amino acids in animal feed arise in two ways. First, they help to rise feed efficiency and thereby, to decrease the total demand for feed (and negative effects associated with the production of feed) as well as to reduce nutrient excretion (and associated emissions). Second, free amino acids can be used to reduce the protein content in feed. An adoption of reduced-crude protein (CP) diets is seen as one of options to reduce the demand for soy in the EU. That would not only decrease the dependency of the EU on imported soybean (meals), but also help to reduce the overall negative impact coming from feed production, especially associated with a land use change and deforestation.

The industrial application of amino acids for feed has an almost 60-year history (Toride, 2004). First, in the late 1950s and 1960s, methionine (*Met*), produced by chemical synthesis, began to be used in poultry feed. Production of lysine (*Lys*) by a fermentation process was started in the 1960s. In the late 1980s, threonine (*Thr*) and tryptophan (*Trp*) also produced by fermentation process were introduced.

The order of the introduction of amino acids in animal feed reflects the typical discrepancy between the requirements for amino acids by species and their actual presence in feed. The first amino acid, absence of which interrupts protein synthesis of the other amino acids, is called the 'first limiting' amino acid. Table 1 shows based on Toride (Toride, 2004) the orders of limiting amino acids in pig and broiler feeds, composed of corn/wheat and soybean meals.

Table 1
Order of limiting amino acids.

	First	Second	Third
Growing pigs	*Lys*	*Thr*	*Trp*
Broiler	*Met*	*Lys*	*Thr*

With the feed formulation becoming increasingly advanced besides these four main amino acids further amino acids such as valine (*Val*), isoleucine (*Ile*), leucine (*Leu*), arginine (*Arg*), histidine (*His*) and cystine (*Cys*) are considered to be used in feed. Besides the introduction of new free amino acids in feed for monogastric animals (poultry and swine), the introduction of amino acids in feed for ruminants (in particular dairy cows) takes place. Coated *Met* and *Lys*, which can escape microbial degradation in the rumen, are already available on the market; spatial formulations are also developed for free amino acids used for feed of aquacultures (Sturm et al., 2021).

Feed additives in general and amino acids specifically are usually not used on farms as such, and the feed additive value chain is composed of multiple actors, as described based on FAO (FAO, 2019) in Fig. 1. It can be implied that the use of amino acids for animal feed could be covered by producers of compound feed, as the vast majority of amino acids is supplied to livestock producers through this channel.

Generally, LCA analysis is an appropriate tool to assess the contribution of amino acids to the bioeconomy through their use in animal feed. The establishment of an appropriate database and methodologies, however, is very demanding and quite challenging. The Global Feed LCA Institute (GFLI) is developing an LCA database and tool, which aims together with the underlying UN FAO LEAP based methodology to be the reference for assessing and benchmarking feed industry impacts and improvement in LCA calculations. The GFLI database consists of the LCA of raw materials from various regions in the world. Currently, this LCA data base dose not incorporate free amino acids used in animal feed, but it might be the case in the future.

Some firms, i.e. producers of feed additives such as Evonik and BASF, have already developed dedicated tools that make use of LCA and should enable the assessment of the environmental impact of both feed and the final animal protein product (Sturm et al., 2021). These tools are also supposed to be able to assess what effects feed additives such as amino acids introduced into animal feed have.

Positive effects from the use of free amino acids in feed come from both bio-based and fossil-based free amino acids. The main contribution comes from the use of the first limiting amino acid. Therefore, in case of pigs, the main effect comes from bio-based free amino acids (mainly *Lys*), while in case of poultry, the main contribution is associated with the use of fossil-based free amino acid (*Met*). At a certain point, when the use of a second and subsequent limiting amino acid is required, the additional positive effect is attributed to the use of two or more free amino acids. The effect from further use of an additional unit of the first limiting amino acid decreases in favor of the second and subsequent limiting amino acids. Thus, due the cross-cutting effects, the cumulative impact is

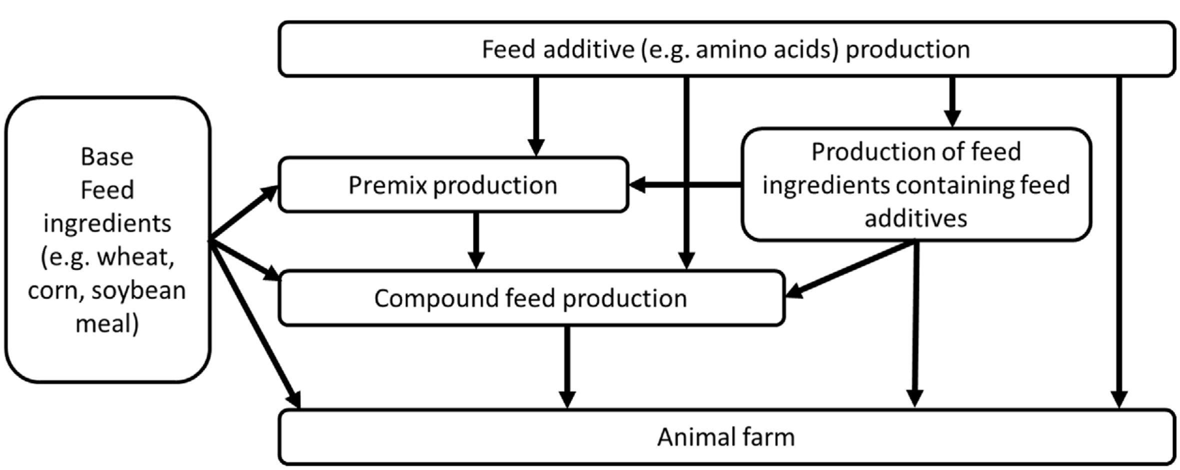

Fig. 1. The manufacturing and use of feed additives in livestock enterprises.

not equivalent to the sum of effects from the use of each individual free amino acid. This makes an analysis even more challenging, without even taking into consideration that positive effects could also be a result from an interaction from the use of free amino acids with other feed components, for example other feed additives.

The assessment of the impact from the use of free amino acids in feed will hopefully be more profound in the future due to the expected progress in LCAs of feed components as well as due to the development of dedicated tools. The amount of literature showing the positive environmental effects from the use of amino acids in animal feed is growing (Selle et al., 2020; Kebreab et al., 2016; Reckmann et al., 2016). However, it could hardly be expected that the quantification of the absolute impact from the use of free amino acids in feed will be possible. Most of the studies conduct comparative life cycle assessment and analyze the performance of different diets without or with a certain amount of free amino acids and cannot be used to generalize, which environmental effects the total amount of amino acids used in feed has in the EU.

The aim of this article is to contribute to the research on monitoring the bioeconomy in the EU by assessing the contribution from feed-grade amino acids. Using this product category as a showcase we step back from the usual sectoral approach often proposed for monitoring of bioeconomy. Methodological steps required when a product group or an application category is selected as the unit of analysis are described and associated additional data collection challenges are disclosed. We collect data on feed-grade amino acids and assess the current contribution of this product category to the EU bioeconomy through associated production activities as well as their contribution through the application in animal feed. In doing so, this article contributes both methodologically as well as in terms of real data to the ongoing research on bioeconomy monitoring.

2. Materials and methods

2.1. Data collection

The intention of each monitoring system is to have an approach for data collection behind it, that can be updated on the regular basis. Therefore, the official statistic is the preferable source of data. However, if the required data is not available other sources of data have to be used. Due to the fact that in our case current official statistics cannot fully satisfy the data needs multiple sources of data have been used, e.g. *official statistics, literature review and interviews.*

2.1.1. Official statistic

While “feed-grade amino acids” is a common product group for market experts or users, e.g. compound feed producers, it seems to be an “artificial" product group in the sense of grouping within official statistics. So, we break down this group into individual 20 standard proteinogenic amino acids. However, even this step is not sufficient in order to track individual amino acids in the statistics. The reason is that not every individual amino acid has its own dedicated code.

The highest level of disaggregation is provided by external trade statistics, where traded goods are assigned to 8-digit codes of the Combined Nomenclature (CN) used in the Eurostat trade database. For production statistics, more aggregated PRODCOM codes have to be used. The PRODCOM codes relate to one or more of the CN codes; the link can be established with the help of Correspondence Tables.

To identify the CN codes, PRODCOM codes for 20 standard proteinogenic amino acids as well as linkages between them, we proceed as follows:

1. Using the ECICS[3] (European Customs Inventory of Chemical Substances), which is an information tool managed by the European Commission's Directorate General (DG) for Taxation and Customs Union, we identify CN codes for each amino acid.
2. The Combined Nomenclature Search Engine[4] from Eurostat is used to get information on the respective CN codes and to identify the correspondent PRODCOM codes.
3. PRODCOM codes in the CN Search Engine are linked to explanatory notes that provide information on the description of PRODCOM codes as well as to which CN codes they are linked to. This information is used to identify whether PRODCOM codes are linked only to CN codes related to amino acids or also to other CN codes.

2.1.2. Literature review

We conducted a review of scientific and grey literature, as well as websites of the producers of amino acids, associations representing interests of producers of amino acids as well as producers of compound feed and other news-portals. We were searching for different types of information:

- general information relevant for understanding the market for amino acids,
- information on the production of individual feed-grade amino acids (producers, location of sites, capacities, production quantities, types of processes used for production, feedstock used, conversion rates etc.),
- information on the use of amino acids for feed (quantities, types of amino acids, effects from use of amino acids in feed, drivers of demand etc.),
- possible impacts of changing policies and regulations.

2.1.3. Interviews

We conducted three interviews to collect additional information. We were able to involve stakeholders that represent the supply side as well as the demand side of the market in the EU. Interviews held with stakeholders were semi-structured in-depth interviews. Each interview was carried out in a single sitting in November and December 2020.

2.2. Assessment of contribution to the bioeconomy

2.2.1. Contribution through production activities

Value added (VA) and employment are important indicators used to assess the contribution of specific activities to the (bio)economy. Information on production values of bio-based amino acids are combined with statistical information (SBS statistics) on VA and employment for corresponded sectors to calculate the contribution of amino acids production to the bioeconomy in the EU in terms of VA and employment.

2.2.2. Contribution through the use in animal feed

In order to get an impression of the contribution of free amino acids through their use in animal feed, we calculate their theoretical already existing positive impact on land use change. The rationale behind this calculation is that (1) cereals and soybean meal are the main feed ingredients (cereals such as wheat or corn are the main sources of energy and soybean meal is the main source of crude protein, followed by other oilseed meals and pulses) and (2) cereals, which are low in protein, are used to partially substitute soybean meal by adding free amino acids to the feed in order to maintain the amino acids content (Selle et al., 2020; IFIF and FEFANA, 2015).

For this calculation, formulas for a partial substitution of soybean meal by cereals with the simultaneous addition of free amino acids are to be defined first. Thereby, the following two conditions must be fulfilled: (1) The total quantity of feed needed to remain constant and (2) the quantity of the specific amino acid in feed must remain constant as well. These conditions can be expressed by the following equations:

[3] https://ec.europa.eu/taxation_customs/dds2/ecics/chemicalsubstance_consultation.jsp?Lang=en.

[4] https://eurostat.prod.3ceonline.com/.

$$SB = C + FAA \tag{1}$$

$$a * SB = b*C + c*FAA \tag{2}$$

where, SB: quantity of soybean meal in feed,

C: quantity of cereals in feed (corn, wheat etc.),
FAA: quantity of the specific free amino acid the content of which is controlled in the feed,
a: content of the specific amino acid (%) in soybean meal (SB),
b: content of the specific amino acid (%) in cereals (C),
c: content of the specific amino acid (%) in free amino acid additive (FAA).

Information on the content of specific amino acids in feed ingredients (Table 2) is used to define the magnitude of the coefficients (a, b, c). The values for soybean meal, corn and wheat are taken from the literature (Dalibard et al., 2014) and for amino acids used as additives we have made assumptions. We assume that total free *Lys* is used in the form of L-Lysine monhydrochloride with 78% active substance. *Met* is used in powder form (99% active substance) or in liquid form (40–95% active substance); for our calculation we assume that total Methionine is used as a product with 80% active substance.

After some derivations of equations (1) and (2) and assignments of values for the coefficients (a, b, c) the following formulas for a partial replacement of soybean meal with wheat or corn with the simultaneous addition of free *Lys* were defined (for details, see the Supplementary Materials):

$$33.1\ [kg\ soybean\ meal] = 32.1\ [kg\ wheat] + 1[kg\ Lys] \tag{3}$$

$$32.1\ [kg\ soybean\ meal] = 31.1\ [kg\ corn] + 1[kg\ Lys] \tag{4}$$

The formula for partial replacement of soybean meal with corn (or wheat), by maintaining the *Met* content in the feed by adding *Met* in the form of feed additive, is expressed as follows:

$$177.4\ [kg\ soybean\ meal] = 176.4\ [kg\ wheat\ /\ corn] + 1[kg\ Met] \tag{5}$$

Figures in equations (3), (4) and (5) are further used to calculate a theoretical reduction in use of soybean meal in feed due to an increased use of corn with a simultaneous addition of free amino acids (*Lys* or *Met*). For example, figures in equation (5) are to be read as follows: The use of 1 kg of *Met* as a feed additive make it possible to substitute 177.4 kg soybean meal by 176.4 kg of wheat or corn by maintaining the total *Met* content in the feed.

Once the formulas for partial substitution of soybean meal by grain with simultaneous addition of free amino acids in the feed are defined, next steps can follow: Information on estimates of quantities of *Met* and *Lys* used in feed can be combined with figures from equations (3), (4) and (5) to calculate the resulted reduction in demand for soybean meal as well as the accompanied increase in use of corn or wheat for feed. Based on assumed yields a theoretical reduction in land area needed for production of soybean and a theoretical increase in land area needed for production of wheat or corn can be calculated. Our consideration regarding the demand for land associated with the production of amino acids are as follows. As total *Met* used as a feed additive in animal feed is currently produced only via chemical synthesis (due to significant cost advantages), no land use is associated with its production. The production of *Lys* takes place via a fermentation process and the demand for land assuming that corn is used as feedstock can be calculated. A conversion rate of corn to glycose of 0.62 and a conversion rate of glucose to Lys of 0.55 (Anusree and Nampoothiri, 2015) can be applied. The sum of three effects – a reduction in use of land for production of soybean, an increase in use of land for production of cereals and a land use associated with the production of amino acids – results in a total land use effect.

Table 2
The content of amino acids (Lys and Met) in selected feed ingredients.

Feed ingredient	g/kg	
	Lys	Met
Soybean meal (44%)	26.6	6.2
Wheat	3.1	1.7
Corn	2.4	1.7
Lysine (78% active substance)	780	0
Methionine (80% active substance)	0	800

3. Results

3.1. Data availability from different sources

3.1.1. Official statistic

Using the procedure described in 2.1.1 we identified CN and PRODCOM codes for 20 standard proteinogenic amino acids as well as linkages between them. Table 3 summarizes our findings. It is shown that 20 amino acids are assigned to 10 CN codes, not each amino acid has its own dedicated CN code. Furthermore, by looking into the description of the CN code, it has to be noted that only 4 amino acids are explicitly named in the description of the CN code. The majority of amino acids is covered under the category “other”, and it is not clear how many other products have the same CN code. Therefore, statistics on external trade on the level of CN codes could be used directly for only 3 amino acids (and their salts): *Met*, *Lys* and glutamic acid (*Glu*).

20 amino acids are assigned to10 CN codes which are linked to 9 PRODCOM codes. However, only in cases of *Lys* and *Glu* a respective PRODCOM code corresponds to a single CN code. In most cases, one PRODCOM code is linked to many CN codes (3–25 CN codes) and the CN code associated with amino acids (marked bold) is only one of many other CN codes associated with other products. Therefore, PRODCOM statistics could actually be used for only 2 amino acids: *Lys* and *Glu*.

So, the first problem of data collection from the official statistics is, that most of the amino acids (group of amino acids) do not have dedicated CN and PRODCOM codes. The second problem, specifically related to the production statistic, is that even a small part of information that could be theoretically taken from the PRODCOM statistic, is practically not publicly available because of confidentiality issues.

To summarize, official statistics can hardly offer any data for analysis. The main problem is not even a lack of information specifically on bio-based products, but general data gaps on amino acids caused by a lack of dedicated codes for amino acids and confidentiality issues.

3.1.2. Literature review

It has to be concluded that apart from very few estimates on the global amino acid market, the scientific and other publicly available literature (company reports) provides hardly any information on the production of amino acids in individual EU countries or the EU as a whole. This situation is not surprising as the production of amino acids is dominated by few companies and the information about the amino acids market belongs to the firms’ know-how.

Market intelligence reports on amino acids market which are subject to a fee provide some figures. In addition to high costs of obtaining such reports and restrictions with regard to re-publication of the figures, the problem is that users cannot be sure that the figures are reliable.

Another problem associated with getting data for a specific region (EU total or EU member states) results from the way the information on amino acids market is reported. For example, most fee-based reports provide figures on the market, i.e. demand for amino acids in individual countries/regions (production plus net import). By reporting figures on production, authors often use individual producing companies as a unit of analysis. As most of the companies producing amino acids are international companies with their sites around the globe, it is almost impossible to obtain figures on production in individual countries/

Table 3
Table of concordance between amino acids and CN and PRODCOM codes.

Name	Abbrev.	CN code details		PRODCOM code details		
		Code	Description	Code	Description	References to CN codes
alanine aspartic acid glycine phenylalanine valine isoleucine leucine	Ala Asp Gly Phe Val Ile Leu	29224985	Other	20144290	Oxygen-function amino-compounds (excluding amino-alcohols, their esters and ethers and salts thereof, lysine and its salts and esters, glutamic acid its salts and esters)	2922[.21 + .29 + .31 + .39 + .43 + .44 + .49(.20 + **.85**) + **.50**]
tyrosine serine threonine	Tyr Ser Thr	29225000	Amino-alcohol-phenols, amino-acid-phenols, etc.			
arginine	Arg	29252900	Other	20144340	Imines, their derivatives; salts thereof	2925[.21 + **.29**]
methionine	Met	29304010 29304090	**Methionine** (INN) **Methionine** (excl. **Methionine** (INN))	20145133	Thiocarbamates and dithiocarbamates; thiuram mono-, di- or tetrasulphides; **methionine**	2930[.20 + .30 + **.40(.10 + .90)**]
cystine	Cys	29309013	Cysteine and **cystine**	20145139	Other organo-sulphur compounds	2930[.60 + .70 + .80 + **.90(.13** + .16 + .30 + .40 + .50 + .98)]
histidine	His	29332990	Other	20145230	Heterocyclic compounds with nitrogen only hetero-atom(s); etc.	2933[.29(.10 + **.90**)]
proline tryptophan	Pro Trp	29339980	Other	20145280	Compounds containing in the structure an unfused pyridine ring or a quinoline or isoquinoline ring-system, not further fused; lactames; other heterocyclic compounds etc.	2933[.31 + .32 + .33 + .39(.10 + .20 + .25 + .35 + .40 + .45 + .50 + .55 + .99) + .41 + .49(.10 + .30 + .90) + .71 + .72 + .79 + .91(.10 + .90) + .92 + **.99**(.20 + .50 + **.80**)]
lysine	Lys	29224100	**Lysine**, its esters; salts thereof	21102010	**Lysine** and its esters, and salts thereof	**2922 41**
glutamic acid	Glu	29224200	**Glutamic acid** and its salts	21102020	**Glutamic acid** and its salts	**2922 42**
asparagine glutamine	Asn Gln	29241900	Other	21102060	Acyclic amides and their derivatives, and salts thereof	2924[.11 + .12 + **.19**]

regions from such reports; in the best-case, information about capacities could be gained.

The web search via various portals (mainly related to feed industry) such as www.feedinfo.com and www.allaboutfeed.net or subscribing to their newsletter accrues some content information but is a very time-consuming undertaking.

3.1.3. Interviews

The interviews helped to obtain and validate content information, but provided very little 'hard' data. Only some of the collected figures on production and use were validated. The reasons for this were confidentiality issues or simply the unavailability of data even for the interviewees.

3.2. Contribution to the bioeconomy through production activities

Already in 2000, the global production of feed-grade amino acids was estimated at 1–1.2 million tons (Table 4). In 2019, feed additives remain the major end-use market of the amino acids industry with *Lys* in the lead followed by *Met*, *Trp* and *Thr*.

An assessment of different sources of information revealed that the production landscape of feed-grade amino acids in the EU is dominated by three companies: Evonik Industries AG ("Evonik"), Adisseo France SAS and Adisseo España SA (collectively, "Adisseo") and Ajinomoto Animal Nutrition Europe S.A.S. (AANE) ("Ajinomoto") or METabolic EXplorer (METEX) as of mid-2021 (see details below). Main findings with regard to the production of amino acids in these companies are:

- Evonik is the main producer of *Met* at a global and European level. In 2020, it announced that *Met* production will be clustered at three international hubs: Mobile, Alabama (the American hub), Singapore (the Asian hub) and Antwerp, Belgium (the Europe hub); Evonik closed its smallest plant producing *Met* with a capacity of 65,000 tons per year, located in Wesseling, Germany, by the end of the first quarter, 2021. In 2018, Evonik closed a facility for production of *Thr* in Hungary (Kaba) (Sturm et al., 2021).
- Adisseo produces amino acids including *Met* in France and Spain (U.S. International Trade Commission, 2020). It also reports about their activities in research and development actions aimed to produce *Met* (or its precursor) via fermentation process (Rous, 2018), but no industrial production takes place so far (Sturm et al., 2021).
- Ajinomoto, up to 2020, produced *Lys*, *Trp*, *Val* and other "speciality" amino acids (*Ile*, *Leu* and *Arg*) in France (Amiens). The company also once had a facility in Italy (Bottrighem), but it was closed more than a decade ago. (FEEDinfo, 2020). Thus, in 2020, company was the only producer of bio-based feed-grade amino acids in the EU. However, in May 2021, Ajinomoto Animal Nutrition Europe was acquired by METabolic EXplorer (METEX), a specialist in the design, development and industrialisation of bioprocesses to produce functional ingredients. Although METEX has announced that its industrial plan foresees the introduction of new specialty products at the Amiens site, the company will continue to produce *Lys* and other amino acids there (FEEDinfo, 2021c).

Table 4
Estimated global production of amino acids in 2000, 2011 and 2019, in tons.

Amino acid	Year		
	2000[a]	2011[b]	2019[c]
Methionine	500,000–600,000	>900,000	1,100,000–1,600,000
Lysine	500,000–600,000	1,700,000	2,400,000–2,800,000
Threonine	30,000	260,000	200,000–260,000
Tryptophan	1000	5500	10,000–17,000

[a] Toride (2004).
[b] Hirth and Busch (2014).
[c] Feedinfo (2021a); GMI (2020).

Table 5 presents the estimated production capacities of the main feed-grade amino acids in the EU, in 2020, differentiated by producer and plant location. It shows, that facilities for *Met* production account for 85–87% of the total feed-grade amino acids capacity in the EU in 2020. The remaining 13–15% belong to a single plant in France producing *Lys* and *Trp* (as well as small quantity of *Ile*, *Leu* and *Arg*) via a fermentation process, that is, bio-based amino acids.

Table 5
Estimated annual production capacities of main feed-grade amino acids in the EU in 2020.

Amino acid	Producer, Location	Capacity, t/year
Methionine	Evonik, Antwerp (Belgium)	260,000–295,000 [a]
	Evonik, Wesseling (Germany), *closed in 2021*	65,000 [b]
	Adisseo, Roches-Roussilion & Commentry (France)	160,000 [c]
	Adisseo, Burgos (Spain)	155,000 [c]
	SUM (Methionine)	**640,000–675,000**
Lysine	Ajinomoto, Amiens (France); *acquisition by METEX in mid-2021*	100,000 [d]
Threonine	–	0
Tryptophan	Ajinomoto, Amiens (France); *acquisition by METEX in mid-2021*	7,500 [d]
SUM (all amino acids)		**747,500 – 775,500**

[a] Evonik (2007-2020).
[b] Byrne (2020).
[c] Adisseo (2015-2020); Willke (2014).
[d] FEEDinfo (2021c).

A closer look at the figures at a global level (Table 4) reveals that worldwide, within the application category "feed-grade amino acids", the bio-based share of total production is around 70%, which is significantly higher than 13–15% in the EU. The main reason should be seen in a low level or absence of production of *Lys* and *Thr* in the EU, despite quite high demand.

Lys is currently produced in the EU, but despite a rising demand over the last decades to approximately 500 t/year in 2019 (Sturm et al., 2021), the production capacity went even down when another facility for *Lys* production with an annual capacity of approximately 20,000 tons/year in Italy (Bottrighem) once owned by Ajinomoto was shut down (FEEDinfo, 2020). Due to a large gap between production and demand for feed-grade *Lys*, the EU relies heavily on imports of feed-grade *Lys*, mainly from Asia.

As for *Thr*, in 2009 the total EU demand for feed-grade *Thr* was estimated at about 74,000 tons and was completely covered by the *Thr* production within the EU (about 76,000 tons) (ECOSYS, 2011). Since then, the demand for *Thr* in the EU has grown to about 120,000 tons, but there is no longer any production of feed-grade *Thr* in the EU. Both producers in the EU - Evonik and Ajinomoto – stopped the production of *Thr* in the EU and moved the production to Asia. The reasons given were the lack of possibility to maintain economic production in the long term despite considerable and continuous optimization, or the low profitability of *Thr* (and *Lys*) production in Europe (Sturm et al., 2021). As a result, in case of feed-grade *Thr* the EU is also in a situation of a permanent dependency on imports from third countries, especially from China.

Fermentation processes used to produce *Lys* and *Thr* have already reached a high level of maturity, the demand for both feed-grade amino acids is high enough to enable large scale production and competition between producers is already tight. Therefore, keeping production costs low has become essential. The EU seems to have disadvantages as a production location due to higher production costs as well as stricter environmental standards.

The EU-based production of *Trp* as well as of some further “newcomers” of feed-grade amino acids such as *Ile*, *Leu* and *Arg* takes place only at a single factory. The quantities of these amino acids used in animal feed are much lower in comparison to quantities of *Met*, *Lys* and *Thr*. Furthermore, in most cases, benefits from adding these amino acids to the feed could only be achieved if the deficiency of the previous limiting amino acids is compensated, and generally, a knowledge-based feed formulation is required. That is the reason for an EU-based production of these “new” amino acids. However, as soon as the benefits from the use of these free amino acids in animal feed become more tangible, it is expected that global demand will grow and production will be scaled up with a potential relocation of EU-based production to other places, as observed in the case for *Lys* and *Thr*.

To summarize, the direct contribution of bio-based feed-grade amino acids to the bioeconomy via production in the EU is mainly associated with the *Lys* and *Trp* production in France. According to Eurostat data for 2019 the EU production of *Lys* accounts for about 90,000 tons with an estimated production value of 106 million Euro (all grades of *Lys*). *Trp* is the second important feed-grade amino acid produced in the EU; the possible production volume is capped by the production capacity of 7,500 tons. There is no dedicated PRODCOM or CN code for *Trp* and, therefore, no information about the output value available. Consequently, trade unit values cannot be calculated. However, considering that the *Trp* price in 2020 was on about 8 Euro/kg (FEEDinfo, 2021b), production value of about 60 million Euro could be derived.

Using the approach proposed in 2.2.1 and data from SBS statistic [dataset] (Eurostat, 2021) we estimated contribution to the bioeconomy through the production of *Lys* and *Trp* in terms of VA and employment (Table 6). Production of *Trp* is reported under “Manufacture of chemicals and chemical products”, therefore, we use information on %-share of VA in production and on VA per person employed in this sector to calculate VA (18,5 million €) and employment (155 persons) associated with the production of *Trp*. Production of *Lys* is reported under “Manufacture of basic pharmaceutical products and pharmaceutical preparations”, similar, we use information on %-share of VA in production and on VA per person employed in this sector to calculate VA (31,8 million €) and employment (250 persons) associated with the production of *Lys*. Since we know that both amino acids are produced in France, we use the latest available data for France for both sectors. In total, we estimated that production of *Lys* and *Trp* in the EU results in approximately 50 million € value added and employment for about 400 persons (Table 6).

3.3. Contribution to the bioeconomy through the use in animal feed

Farmers in the EU use feed-grade amino acids mainly by using compound/mineral feed. Therefore, the producer's demand for compound/mineral feed for feed-grade amino acids could be seen as a good proxy for the total demand of feed-grade amino acids. The EU producers of compound feed use the free amino acids directly or in the form of ‘premixtures’ (mixtures of feed additives or mixtures of one or more feed additives with feed materials or water used as carriers). The premixes used in the formulation of feed in the EU are mainly produced in the EU,

Table 6
Estimated Value Added and Employment associated with the Lys and Trp production in the EU.

	Manufacture of chemicals and chemical products[a]	*Trp*	Manufacture of basic pharmaceutical products and pharmaceutical preparations[b]	*Lys*
Production value, million €	80,864.6	60	41,110.4	106
%-share of VA in production value	31%	31%	30%	30%
Value added at factor cost, million €	24,944.1	18.5	12,320.9	31.8
Value added pro 1 person employed, million €	0.119	0.119	0.127	0.127
Persons employed, number	209,170	155	96,992	250

[a] in France in 2019.
[b] in France in 2017.

hardly any import of premixes from non-EU countries takes place. However, EU producers of premixtures export their products to other EU countries as well as to non-EU countries.

The use of amino acids in animal feed is driven by the level of feed efficiency that should be achieved and the quantity of animals. In the EU, conventional livestock farming shows a high level of feed efficiency, that goes along with a relatively intensive use of amino acids in feed. The demand for individual amino acids depends on the number of individual species as a requirement for supplemented amino acids in feed vary depending on the species and age of animals.

Table 7 shows the current occurrence of amino acids in animal feed. The differentiation is made with regard to the species, their age and husbandry objectives as well as the frequency of use.

According to Table 7, the use of *Met*, *Lys*, *Thr*, *Trp* and *Val* in feed for poultry and pigs is already a “common practice” or at least “partly used”. But as the formulation of feed is getting more and more advanced, the use of further amino acids such as *Ile*, *Leu* and even *Arg*, *Cys* and *His* is taking off.

Currently, the use of amino acids in feed for calves, dairy cows or fattening bulls plays only a minor role in the EU. The use of coated *Lys* and *Met* in feed for dairy cows could be the next important future application area of amino acids in animal feed in the EU. Free amino acids, in particular the special formulation of *Met*, are also used in feed for fish and aquacultures. However, in the EU the importance of this application is quite low.

Besides the level of feed efficiency and the numbers of individual species, there are further important drivers for the use of free amino acids in animal feed. One of them is the expansion of organic livestock husbandry. The point is that free amino acids practically cannot be used in organic livestock farming. The Commission's Farm-to-Fork and the Biodiversity Strategy include the target of reaching 25% of agricultural land under organic farming by 2030. If this target will be applied to animal husbandry, and if the rules on the use of amino acids in organic livestock husbandry will maintain, the use of (and demand for) feed-grade amino acids in animal feed is expected to decline.

Another important driver on the market of feed-grade amino acids is the growing awareness of negative environmental effects of livestock farming, especially with regard to nitrogen emissions. As amino acids help to rise feed efficiency and to reduce N-leakage, the use of amino acids is supposed to increase if regulations to reduce N-leakage are implemented. The use of Life Cycle Assessments (LCAs) for amino acids as proposed by the FAO (FAO, 2019) could possibly reveal further positive effects of feed-grade amino acids. By taking such effects into account, policies could further foster the use as well as the production of amino acids in the EU.

In order to provide an insight into the contribution of free amino acids through their use in animal feed, we apply methodology proposed in 2.2.2 to calculate theoretical already existing positive impact on land use change from use of two most important amino acids - *Met* and *Lys* -, that are the first limiting amino acids in feed for poultry or pigs (Table 8).

The effects from both amino acids cannot be summed up as explained in section 1 (“Introduction”). However, this rough estimation still reveals that the use of amino acids in feed already helps to avoid the use of millions of hectares of arable area for production of animal feed.

Table 7
Occurrence of amino acids in animal feed (pigs and poultry) in the EU.

Species	“common practice”	“partly used”	“selective assignment”
Poultry			
laying hens	Met, Lys	Thr, Val, Ile	
broilers	Met, Lys, Thr	Val	Ile, Arg, Leu, Cys, His
turkey	Lys, Thr, Met		
Pigs			
fattening pigs	Lys, Thr	Val, Trp	
piglets	Lys, Thr, Met, Val, Trp		Ile, Leu, Cys, His
sows	Lys, Thr	Met, Trp	Arg

Met = Methionine; Lys = Lysine; Thr = Threonine; Trp = Tryptophan; Val = Valine; Ile = Isoleucine; Arg = Arginine; Leu = Leucin; Cys = Cystine; His = Histidine.

Table 8
Land use effects from replacement of soybean meals by corn and amino acids in feed.

	Met		Lys	
	global	EU	global	EU
Use of amino acids in feed, 1000 t	1100	250	2400	450
Coefficient used for calculation of …				
decreased demand for soybean meal	−177.4	−177.4	−32.1	−32.1
increased demand for corn	176.4	176.4	31.1	31.1
Change in use of …				
soybean meal, 1000 t	−195,140	−44,350	−77,117	−14,460
corn, 1000 t	194,040	44,100	74,717	14,010
Applied yields for …				
soybean meal, t/ha	3	3	3	3
corn, t/ha	10	10	10	10
Land use change associated with …				
change in use of soybean meal, 1000 ha	−65,047	−14,783	−25,706	−4820
change in use of corn, 1000 ha	19,404	4410	7472	1401
production of used amino acids, 1000 ha	–	–	1005	189
TOTAL land use change effect, 1000 ha	**−45,643**	**−10,373**	**−17,229**	**−3230**

4. Discussion

Despite the fact that amino acids have been identified as potentially important bio-based products (ECOSYS, 2011; Lammens et al., 2017; Spekreijse et al., 2019), their contribution to the EU bioeconomy has not yet been quantified. Our analysis discloses the main hurdles in data collection as well as the methodological challenges associated with such assessments and provides a first attempt to close existing gaps.

There is an urgent need of detailed production data to assess the contribution of amino acids to the bioeconomy. As official statistics are the most preferable source of data for monitoring, we first intensively explored this source of data. “Feed-grade amino acids” form a product or application category which does not have a counterpart in official statistical classification. The first step required to conduct an assessment is to identify relevant products and to find out under which activities their production is reported in the official statistics. In our case, we considered all twenty proteinogenic amino acids, and identified under which codes they are reported in official statistics. Our analysis reveals that 20 amino acids are assigned to 10 codes in trade statistics which are linked to 9 codes in production statistics. *Lys* is the only amino acid used in feed that has its own dedicated code in trade as well as in production statistics. The production and even trade of other amino acids are reported under a number of different codes, each covering a range of products. This fact makes the use of official statistics for other amino acids practically impossible. But even data for *Lys* which has its dedicated code reveal significant gaps because of confidentiality of data and only a rough estimate for production in the entire EU is available. Therefore, the official statistics only provide parts of a database necessary for a comprehensive analysis. The main problem is not only a lack of information specifically on bio-based production, but general data gaps on amino acids caused by a lack of dedicated codes for amino acids and confidentiality of data. Our finding can be generalized as follows: Data collection and monitoring of the contribution of a specific product group to the bioeconomy is a very challenging and demanding task, especially if no clear link (mapping) to the classification within production and trade statistics is established.

We conducted a literature review and interviews to collect further information. Our results reveal that the production of feed-grade amino acids in the EU is dominated by three companies. *Met* produced from fossil-based feedstock is the most important amino acid produced in the

EU. Some other bio-based feed-grade amino acids produced through fermentation (*Lys*, *Trp*, *Ile*, *Leu* and *Arg*) are produced in the EU by a single producer and their production volumes are quite low. The production of bio-based amino acids generates about 50 million euros value added and provides jobs for about 400 employees. The bio-based share in total production of feed-grade amino acids in the EU is about 15% and low compared with a share of 70% at global level. The main reason is a low level or absence of production of *Lys* and *Thr* in the EU, because its disadvantages as a production location due to higher production costs as well as higher environmental standards. As a consequence, the contribution from the production of bio-based feed-grade amino acids to the bioeconomy in the EU is quite low and is not expected to increase if current operating conditions remain unchanged.

The assessment of the contribution of feed-grade amino acids to the bioeconomy through their use in animal feed is even more challenging, as in addition to the data gaps identified previously (results in problems by estimation of use quantities), methodological challenges exist. Generally, this contribution arises in two ways. First, amino acids help to rise feed efficiency and, thereby, to decrease the total demand for feed (and negative effects associated with the production of feed) as well as to reduce nutrient leakages (and associated emissions). Second, free amino acids may contribute to reduce the protein content in feed. A reduced crude protein (CP) diet is seen as one of the options to reduce the demand for soybean (meals) in the EU. That would not only decrease the dependency of the EU on imported soybean (meals), but also help to reduce the overall negative impact coming from feed production, especially associated with a land use change and deforestation. We argue that a LCA analysis could be an appropriate tool to assess the contribution of amino acids to the bioeconomy through their use in animal feed. Currently, the GFLI partners are developing an LCA database and tool, which aims to serve as a reference for assessing and benchmarking feed industry impact and improvement in LCA calculations for feed. As soon as amino acids are included in the database, a more profound assessment will be possible.

In order to get an impression of the contribution of free amino acids resulting from their use in animal feed, we calculate their theoretical already existing positive impact on land use change. This rough theoretical calculation shows that the use of amino acids in feed already helps to avoid the use of millions of hectares of arable land for production of animal feed. If these various positive environmental effects stemming from the use of amino acids in animal feed will be recognized in the future, their use in animal feed would increase not only because of positive effect on costs of animal husbandry. However, besides this positive driver for the use of amino acids in feed, there might be are negative drivers such as a decline in European livestock farming driven by a decreasing demand for animal products or an expansion of organic agricultural production in the EU, which does not tolerate the use of free amino acids in feed. At this moment it is difficult to estimate which of these drivers will dominate.

To conclude: The contribution of bio-based amino acids to a more sustainable EU bioeconomy is much more significant if not only the contribution through the related production activities but also the contribution through their use in animal feed is considered.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2022.100073.

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