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RESEARCH

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# Environmental assessment of phosphorus reduction in rye bran fodder from processing to feeding

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**Abstract**
An innovative process enables the reduction of phosphorus (P) content in rye bran used as animal fodder. The goal of P extraction is to produce P-reduced feed that lowers P in animal excretion, thereby decreasing eutrophication risks from runoff or leaching into water ecosystems. This article assesses the environmental impacts of both the P extraction process and the use of P-reduced fodder in animal husbandry through a life cycle approach. The analysis includes two stages: (1) environmental assessment of P-reduced bran production via different extraction routes, and (2) assessment of its use as a fodder for pigs. Two extraction routes—thermo-chemical and enzymatic—are evaluated for the "Global Warming" and "Terrestrial Acidification" impacts. The results show that the enzymatic route is characterized by lower values in both impact categories, generating 150 kg $CO_2$ eq. and 0.2 kg $SO_2$ eq. compared to 1 863 kg $CO_2$ eq. and 7.5 kg $SO_2$ eq. from the thermo-chemical route. In the use stage, the effects of co-feeding pigs with P-reduced bran are analysed for "Global Warming" and "Eutrophication" impacts. P eq. emissions ("Eutrophication") are reduced by 4%. Yet, the energy-intense processing of P-reduced bran increases the overall greenhouse gas emissions. Feeding untreated bran results in 3 352 kg $CO_2$ eq. per 1 000 kg carcass weight, while the co-feeding with the P-reduced bran from the thermo-chemical and enzymatic routes leads to 5 672 kg $CO_2$ eq. and 3 911 kg $CO_2$ eq., respectively.

**Keywords** P-reduced feed, Life cycle assessment, Feed modelling, Eutrophication reduction, Circularity

## 1 Introduction

Phosphorus (P) is one of the essential nutrients for all forms of life and is only available on Earth in limited amount [1]. Currently, P is being increasingly mined, with an annual consumption of around 220 000 t phosphate rock (U.S. [2, 3]).

Most mineral P is deployed in the form of fertilizer to foster plant growth, while smaller amounts are utilized in food additives, cleaning agents, and others products [2]. As P is essential for biological processes, inorganic and—to a lesser extent—organic P compounds are vital for the survival of both humans and animals [4, 5]. In the context of animal farming, an oversupply of P and/or the supply of undigestible P in fodder (i.e., mostly fodder components with P bound in organic molecules) may lead to increased excretion levels of unused P in animal manure [6]. When such manure, containing significant amount of P, is spread over agricultural fields, the P may be translocated—through natural processes—into lakes and rivers. There, P has the potential to cause severe ecological damages such as eutrophication [7, 8].

To minimize these environmental impacts, new technologies aim to recover P from organic waste or side streams. Most commonly, P recovery via chemical or biological precipitation is realized during wastewater treatment, where P accumulates in sewage sludge [9]. Although different concepts have been developed and various process technologies exist, none has yet been universally established [10]—even due the fact that sewage sludge produced by the entire German wastewater treatment plants could, theoretically, cover a significant part of the total German P consumption (e.g., 40% of the fertilizer P demand in Germany) [2].

For applications requiring a higher P purity, other recyclable or waste-based P sources could be explored [11]. Promising feedstocks for P recovery include cereals and legumes with high organic P content being undigestible for certain farm animals due to their specific metabolism [12]. Recovering P from feed materials before feeding results in a P-reduced feed and, may lead to reduced P excretion, which is environmentally advantageous as it helps minimize the eutrophication risk. Additionally, this approach could provide recyclable P of food or feed quality as a substrate for the P-processing industry.

Building on this concept, this paper evaluates environmental impacts of two innovative rye bran processing routes—used as an exemplary P rich feedstock—for P extraction (and therefore the production of P-reduced bran), as well as the subsequent use of P-reduced bran as animal fodder. The environmental impact categories are selected based on their relevance to the respective bran processing routes. Accordingly, the following research questions arise:

- What are the environmental impacts of the two rye bran processing routes for producing P-reduced bran with respect to the impact categories “Global Warming” and “Terrestrial Acidification”?
- What are the environmental impacts of using P-reduced rye bran as animal fodder with respect to the impact categories “Global Warming” and “Eutrophication”?

To answer these questions, a life cycle assessment (LCA) is conducted evaluating the production and use of P-reduced animal feed. Due to the energy demand and chemical requirements in the processing process (production stage), the impact categories “Global Warming” and “Terrestrial Acidification” are considered relevant. The impact category “Eutrophication” is not considered in the production stage because P is not released into the environment at this point but is instead recovered. Therefore, to address the second research question, the use of P-reduced bran as animal fodder is evaluated with respect to the impact categories “Global Warming” and “Eutrophication”. The methodological approach of the use stage (Sect. 3.2) differs from that in the extraction stage (Sect. 3.1), as the focus here is placed on animal husbandry processes. For this purpose, feeding requirements and the digestive capacity of animals (here: pigs) are included as key parameters to estimate eutrophication risks within an environmental impact assessment for livestock farming.

The two parts of the environmental assessment are not designed to be compared, but to enable a holistic environmental assessment of two sequential stages: (1) production of P-reduced bran via bran processing to extract P and (2) the use of P-reduced bran in the animal feed industry. While the analysis of P-reduced bran production provides a detailed insight into emissions generated from P extraction routes, it cannot alone determine the environmental consequences of the product during its use. In the use stage, the P-reduced bran as a feed composition is only one of many contributors to the environmental emissions from animal husbandry. Therefore, it is relevant to assess whether the effort and energy invested in extracting P from bran result in environmental benefits when the entire life cycle of P-reduced bran is considered. Existing studies mainly address either the production of P-reduced feed or its application, whereas this article aims to bridge the gap by integrating the analysis of both stages in a comprehensive research approach.

A graphical overview is given in Fig. 1.

## 2 Theoretical background

### 2.1 Processing of rye bran for P-reduced fodder

Two processing routes for extracting P from rye bran to produce P-reduced bran are investigated.

- *Thermo-chemical route*: This processing route is a three-step process (Fig. 2). The first step, extraction, is realized by mixing rye bran with hydrochloric acid. After that, the bran is separated and the liquid phase (extract) is processed thermally and further cooled down to perform precipitation by adding magnesium chloride and sodium hydroxide. As a result, potassium magnesium phosphate is obtained.
- *Enzymatic route*: This route is a two-step process (Fig. 3). First, rye bran is treated with suitable enzymes (phytases) in water at relatively mild conditions. Thereby, phytate is dissolved and at the same time cleaved by the enzymes. Second, the bran is separated and the residual liquid phase (enzymatic hydrolysate) is led to another vessel together with magnesium chloride, ammonium chloride and sodium hydroxide to achieve P precipitation in the form of struvite. Both products, the P-reduced bran and struvite, are dried to ensure storage stability.

Both process routes aim to bring organically bound P occurring naturally in organic materials (phytate) into solution, release the phosphate groups and, lastly, recover phosphate in the form of a salt via precipitation (e.g., [13]). In this way, the processing of rye bran and subsequent P extraction result in two outputs: the main product, a P-reduced bran that can be used as animal feed, and the co-product, the recovered phosphorus.

### 2.2 Use of P-reduced rye bran fodder

The requirements of P in animal fodder are highly dependent on the type of animal and its growth stage [14]. Thus, to avoid negative effects on the environment (e.g., increased P content in manure), P in a digestible form should be available in animal fodder according to the actual given needs [7, 8]. To reduce the amount of nutrients in manure and as a consequence reduce the resulting environmental risks, the German Agricultural Society (*Deutsche Landwirtschafts-Gesellschaft*, DLG) issued guidelines for the nutrition of fattening pigs, including recommendations on P supply. The guide describes two feeding

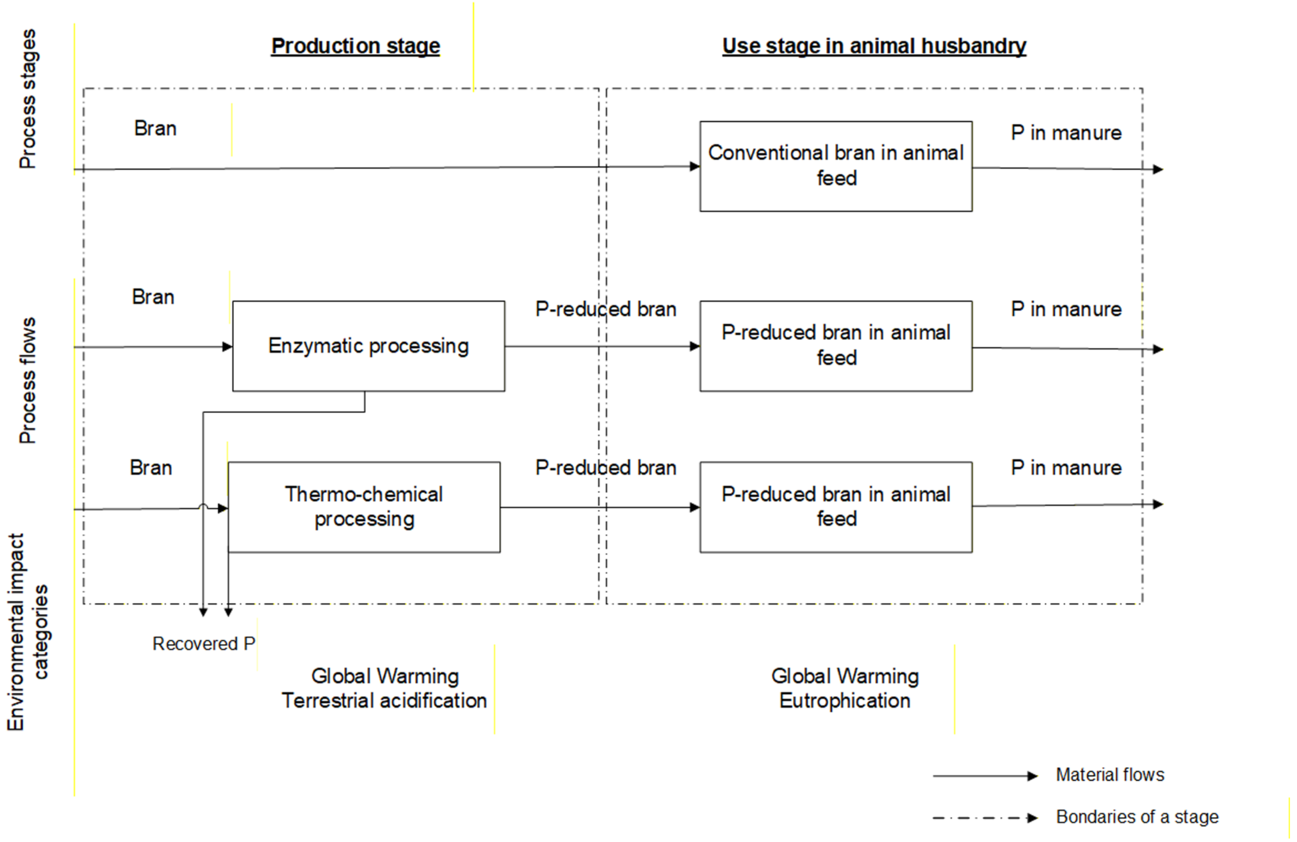

**Fig. 1** Overview of the article's methodology

strategies, namely a "*strong nitrogen and phosphorus reduced feeding*" and a "*very strong nitrogen and phosphorus reduced feeding*" with a recommended amount of crude protein or rather N and P for the feeding of sows, piglets and fattening pigs along different weight categories [15].

In this consideration, feed with a lesser P content—P-reduced rye bran—is evaluated on fattening pigs in scenario calculations, that serve as a model for general processes in animal nutrition [16]. Fattening pigs can be fed with bran in any stage of their development and especially at the end of the fattening period due to its reduced level of starch and higher levels of crude fiber [17], Grześkowiak et al. 2022). The resulting environmental assessment outlined in the Sect. 3.2 focuses on changes in the impact categories "Global Warming" and "Eutrophication" due to the use of P-reduced rye bran in animal fodder.

## 3 Materials and methods

The methodology for the environmental assessment of P extraction from rye bran to produce P-reduced bran (production stage, Sect. 3.1) and the use of the resulting P-reduced feed in animal husbandry (use stage, Sect. 3.2) is presented below.

### 3.1 Environmental assessment of P-reduced bran production

The life cycle assessment (LCA) method is applied to systematically analyze all inputs and outputs involved in rye bran processing, along with the associated environmental impacts within the defined boundaries. This assessment method [18, 19] consists of four main steps: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment analysis; (4) interpretation of the results (Fig. 4).

This method is selected because it allows for a consideration of case specific data for the main processes (foreground system) and the use of default data on upstream flows (background system). Such a procedure provides a precise and comprehensive picture of the overall emission inventory. Furthermore, the methodology covers the allocation between different co-products, which is the case in the processing stage of rye bran.

### 3.2 Frame conditions and data

For the processing stage of rye bran, laboratory data of the thermo-chemical and enzymatic processing routes are used [20]. The upstream flows of energy and chemicals required in the processing stage are assessed with data from public available data sources (i.e., Ecoinvent database 3.10). A detailed description of the case studies in accordance with the LCA follows below.

#### *3.2.1 Goal and scope*

The goal of the assessment is to conduct an attributional LCA of the thermo-chemical and the enzymatic route of rye bran processing and P recovery. The system boundaries are defined as cradle-to-gate for both the thermo-chemical and the enzymatic route. When considering the environmental impacts of P-reduced bran, the functional unit (FU) for both processes is 1 t of P-reduced rye bran (dried to 10 wt.%) as a main product; the recovered phosphate salt is considered to be a co-product.

The thermo-chemical route follows the main treatment steps of rye bran: extraction and washing, hydrolysis and precipitation. Rye bran as the feedstock is considered to be

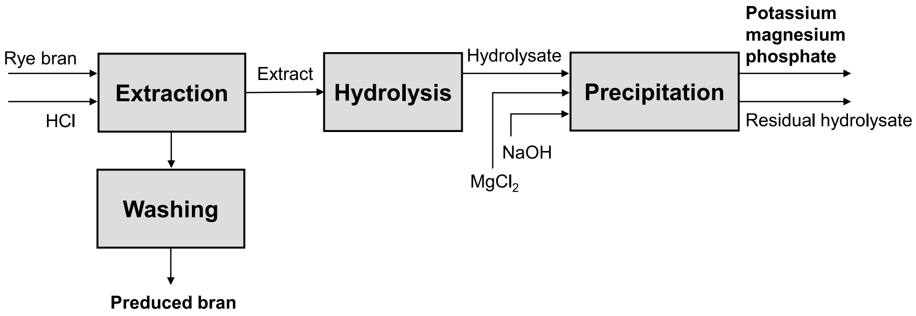

**Fig. 2** Process scheme of the thermo-chemical P recovery from rye bran

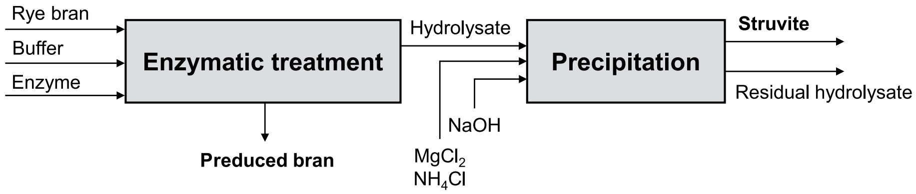

**Fig. 3** Process scheme of the enzymatic P recovery from rye bran

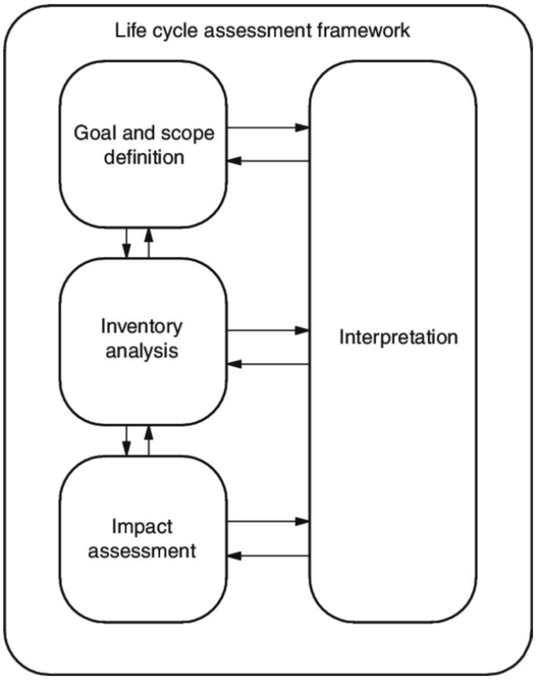

**Fig. 4** Life cycle assessment (LCA) methodology [27]

a waste product provided during rye processing and, therefore, enters the system boundaries with no emission burden. The sourcing of electrical and thermal energy for the treatment as well as the procurement of chemicals and material for the process is taken into account (Fig. 5). The use phase of the main product—P-reduced bran -is further considered in Sect. 3.2.

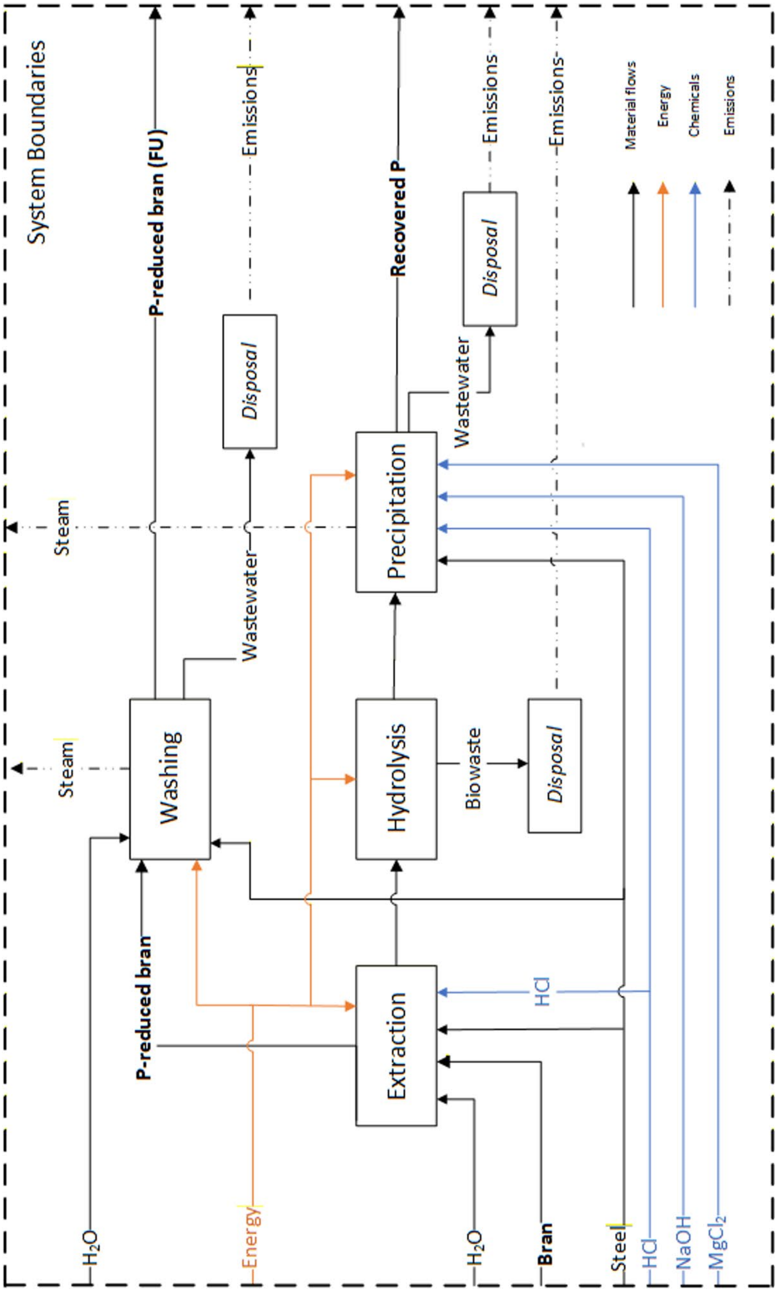

**Fig. 5** System boundaries of the thermo-chemical process route

Also, the enzymatic route is based on cradle-to-gate system boundaries. It comprises two main steps of feed processing (i.e., enzymatic treatment, precipitation) with the respective needs for energy, enzymes, chemicals and other materials (Fig. 6).

#### *3.2.2 Inventory analysis*

The substrate streams are quantified according to the optimum ratios determined within the practical experiments (the process design is described in [20] and [21]) and analyzed for a production amount of 1 t of P-reduced bran. Both extraction routes follow the same assumptions during process design,i.e., the results are directly comparable between each other. The necessary mount of steel is determined for vessel sizes according to the stream volumes and with a filling ratio of 70%; energy consumption is considered for stirring, heating, pumping, separation and drying within the processes. Regarding waste treatment, the hydrolysate remaining after P precipitation and a subsequent neutralization can be disposed within a regular wastewater treatment plant. All solid waste streams are considered to be biological waste.

For the energy supply, the German energy mix is assumed. The production of chemicals (HCl, $MgCl_2$, NaOH and $NH_4Cl$) is based on EU production data and the materials needed for the various vessels (e.g., steel, iron-nickel–chromium alloy) are assumed to come from the global material markets. Energy and material flows are listed in Table 1 for both process routes.

Additionally, in environmental assessment of multifunctional (two or more final products) production process, allocation is used to distribute environmental impacts amount all final products based on predefined criteria such as mass, economic value or energy content. The production of P-reduced bran presents multifunctionality as it results in two valuable products: the P-reduced bran as a main product and the recovered P as a co-product. For the allocation criterion, an allocation according to the economic value cannot be applied, since the P-reduced bran is an innovative product for which no market price yet exists. Allocation by energy content is not possible because the recovered P has no energetic value. Allocation by mass through all the process steps is also inappropriate as the recovered P achieves a significantly lower mass (compared to P-reduced bran) but requires additional energy-intense process steps and material input. Therefore, allocation by mass with a causal approach is applied: the production steps required for the P-reduced bran and the recovered P are allocated by mass (i.e., the extraction step in thermo-chemical processing and the enzymatic treatment step in enzymatic processing). The environmental impacts of other production steps, required for either P-reduced bran (i.e., the washing step in the thermo-chemical process) or recovered P (i.e., hydrolysis and precipitation in the thermo-chemical route and precipitation in the enzymatic route) are attributed fully to the product in question.

Equation (1) represents the calculation of the allocation factor (*AF*), where $m_n$ corresponds to the mass of a product and the $\sum_{n=i}^{x} m_n$ to the total mass of all products.

$$AF = \frac{m_n}{\sum_{n=i}^{x} m_n} \quad (1)$$

#### *3.2.3 Impact assessment*

Due to energy and chemical inputs into bran processing, two midpoint categories are selected: the impact category "Global Warming" and the impact category "Terrestrial Acidification" [9, 22–25]. Since P is recovered as a co-product and not released into the environment, the impact category "Eutrophication" is not considered and assumed to be 0 kg P eq. at this stage.

To assess the robustness of the results, the two impact categories are further analysed in a sensitivity analysis, which examines how variation in key input parameters—in this case, energy and material flows—affect the environmental outcome of rye bran processing. Therefore, energy und material flows as process inputs are varied by ± 50% and two energy supply scenarios—a conventional energy mix and an energy mix based only on renewable sources—are evaluated.

- Scenario P1 represents the base case involving the use of conventional heat (natural gas) and the current German electricity mix. The latter includes both renewable energy sources and fossil fuel energy (data according to [26]).
- Scenario P2 describes a case where both heat and electricity are derived only from renewable sources of energy. The electricity mix for Germany is modelled according to [26] and heat generation is assumed to be provided from biogas (data according to Ecoinvent database 3.10).

### 3.3 Environmental assessment of P-reduced bran use as animal feed

To evaluate the environmental impact of the use of P-reduced bran, the complete life cycle of an animal is assessed [18, 19, 27, 28] (Sect. 2.2). In particular, the assessment is based on fattening pigs, used as an exemplary case commonly applied in studies on animal production.

#### *3.3.1 Frame conditions and data*

The system boundaries of the complete life cycle of a fattening pig include three feeding phases (from 28 to 118.3 kg), housing and the slaughtering process. The functional unit (FU) refers to the slaughtering weight of the pigs: 1 t carcass weight. The environmental analysis is based on the case study: feeding fattening pigs with fodder, which includes the share of P-reduced bran compared to feeding fattening pigs with fodder containing native (unprocessed) rye bran.

For this case study, two components are taken into account:

- Determination of the feeding phase and the respective feed rations.
- Use scenarios of P-reduced bran in each respective feeding phase.

In general, the feed composition for fattening pigs contains rye and barley as well as rye bran. Due to a P-content in the rye bran, its inclusion rate (percentage of rye bran) in the feeding ration is limited. With a lower P-content of the P-reduced rye bran, a higher inclusion rate within rations is possible without exceeding the nutritional requirements of the fattening pigs. In this way, the difference between total P in feed and available P for the animal after digestion is minimized.

Additionally, the feeding rations depend on the feeding phase of fattening pigs referring to the weight of animals. Feeding phase 1 includes fattening pigs from 28.0 to 40.4 kg weight, feeding phase 2 refers to fattening pigs until a weight of 70.1 kg, and feeding

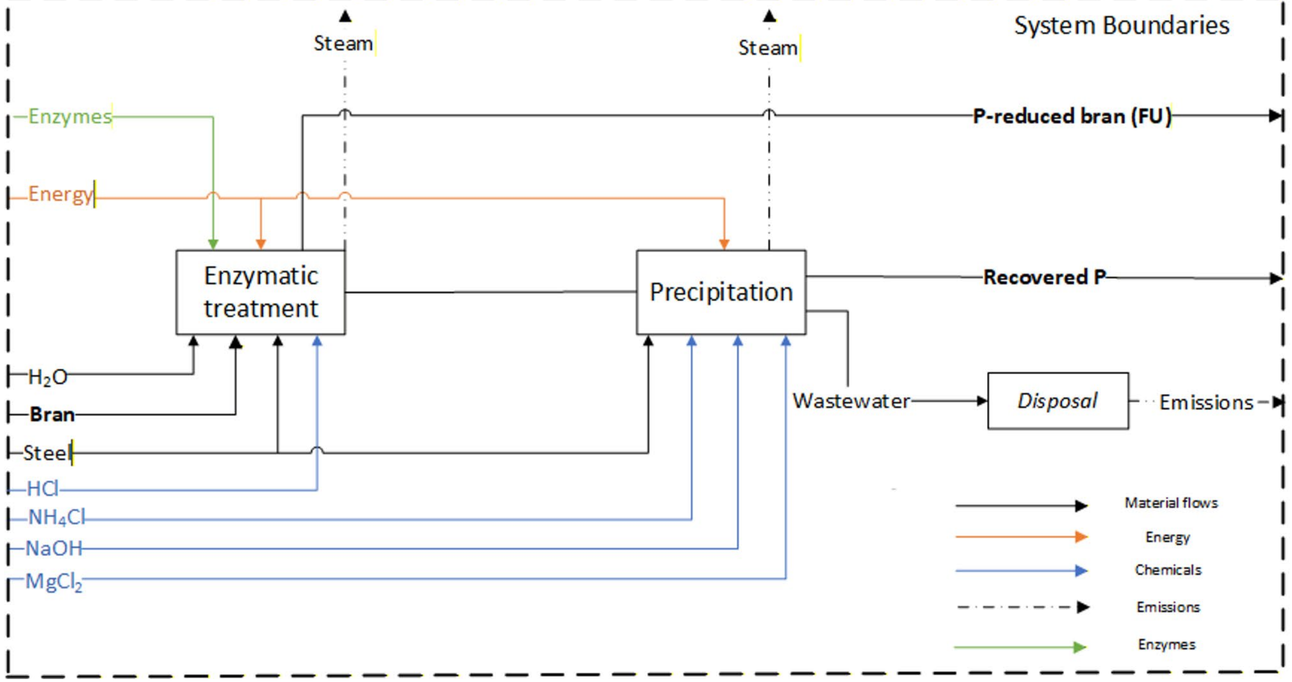

**Fig. 6** System boundaries of the enzymatic process route

phase 3 until a weight of 118.3 kg. These three feeding phases together build the whole life cycle of a pig considering its growing in weight. The piglet phase is modelled with default values and are therefore not varied.

The feeding phases of the fattening pigs and the feeding requirements are modelled with the software Opteinics™ [29] based on data from the Global Feed LCA institute [30]. Three feeding composition scenarios are defined to evaluate the environmental impacts of using P-reduced bran in pigs diet.

- Scenario U1: Use of native rye bran in feed composition.
- Scenario U2: Use of P-reduced rye bran from the thermo-chemical process.
- Scenario U3: Use of P-reduced rye bran from the enzymatic process.

Besides the type of rye bran (native or P-reduced), Scenario U1 differs from Scenario U2 and Scenario U3 in the feed composition (including the percentage of rye bran in the feed). All scenarios are designed to meet the imputed nutritional values on "*very strong nitrogen and phosphorus reduced feed*" [15] concerning crude protein (CP), N, P, and metabolizable energy. Furthermore, the rations within a feeding phase are isonitrogenous, ensuring comparable levels of metabolizable energy for pigs and the percentages of crude protein, phosphorus, calcium and lysine. The amount of P-reduced bran is increased in feeding phase 2 and 3 in order to take advantage of its reduced P-content and its positive effects in the nutrition of pigs. In Scenario U2 and U3, in addition to P-reduced rye bran, native rye bran is also included in the rations to ensure a sufficient amount of P without adding phosphates. The assumptions for the feed rations in all scenarios are shown in Table 2 (for the complete formulations see supplementary material).

The input data are standard values [29] including 28 piglets per sow and year and a mortality of 1% in the rearing period as well as 3% in the fattening period. Energy is needed with 0.0039 $kWh/kg_{feed}$ to produce the feed and 14.11 kWh/pig during a complete life cycle on the farm, both powered by electricity from the German grid. Additionally, 0.96 L diesel, 15.62 L oil and 1.1 L gas (LPG) is consumed per pig. The use of water is assumed to be 8.67 L per pig (including water for drinking, cleaning and cooling). The carcass yield of the slaughtering process is assumed to be 72% [31].

Data for the impact category "Global Warming" and "Eutrophication" of feed ingredients (including rye bran) are taken from [30]. These values are used to assess the contribution of fodder to the overall environmental impacts of husbandry. For the P-reduced rye bran, the values are adapted in order to include the impact of the previous thermo-chemical or enzymatic processing stage. For instance, the default value of the $CO_2$ eq. of producing 1 t rye bran amounts to 759.87 kg $CO_2$ eq. In order to model the $CO_2$ eq. of feeding pigs with processed P-reduced rye bran, 1 862.87 kg $CO_2$ eq. and 149.76 kg $CO_2$ eq. corresponding to thermo-chemical and enzymatic processing route, respectively, are added to the default value. This results in an adapted value of 2 622.74 kg $CO_2$ eq. per kg of thermo-chemically processed rye bran and 909.63 kg $CO_2$ eq. per kg of enzymatically processed rye bran.

For the impact category "Eutrophication" it is assumed that the P eq. from the thermo-chemical or enzymatic processing of rye bran is zero because P is not released to the environment, but recovered. Therefore, no addition is needed to the default value. Furthermore, in the use stage, the P eq. is mainly linked to the P content of the feed. The P content per kg native rye bran is set to 12.17 g while the lab data shows a 9.2% lower P

**Table 1** Energy and material flows for the production of 1 t of P-reduced bran

| Input | Thermo-chemical process | Enzymatic process |
|---|---|---|
| Rye bran (in t) | 1.59 | 1.18 |
| Enzymes (Phytase Natuphos E in t) | – | $4.70 \times 10^{-4}$ |
| Electricity, high voltage (in MJ) | $1.16 \times 10^{4}$ | $8.05 \times 10^{2}$ |
| Heat, natural gas (in MJ) | $4.02 \times 10^{3}$ | $3.04 \times 10^{3}$ |
| Hydrochloric acid, 30% solution state (HCl in t) | 2.51 | $3.74 \times 10^{-2}$ |
| Fresh water (in $m^3$) | $1.88 \times 10^{2}$ | 8.20 |
| Ammonium chloride ($NH_4Cl$ in t) | – | $1.92 \times 10^{-2}$ |
| Magnesium chloride ($MgCl_2$ in t) | 0.11 | $7.27 \times 10^{-2}$ |
| Sodium hydroxide (NaOH in t) | 1.96 | $5.26 \times 10^{-2}$ |
| Chromium steel (in t) | $2.40 \times 10^{-3}$ | $3.61 \times 10^{-3}$ |
| Iron-nickel–chromium alloy (in t) | $3.54 \times 10^{-4}$ | – |
| *Output* | | |
| Rye bran, modified (in t) | 1.00 | 1.00 |
| Recovered phosphate (in t) | 0.17 | 0.10 |
| Biowaste (in t) | 2.46 | – |
| Wastewater (in $m^3$) | 188.7 | 7.12 |

**Table 2** Target parameters of the feed (all scenarios); the assumptions made concerning feeding days and feed conversion ratio and the inclusion rate of P-reduced rye bran in Scenario U2 and U3

| | Phase 1 | Phase 2 | Phase 3 |
|---|---|---|---|
| Crude protein (in g per $kg_{feed}$) | 165 | 155 | 140 |
| Phosphorus (in g per $kg_{feed}$) | 4.4 | 4.0 | 4.0 |
| Feeding days | 14 | 30 | 51 |
| Feed conversion ratio (in $kg_{feed}$ per $kg_{gain}$) | 1.98 | 2.34 | 3.02 |
| Inclusion rate (%) of rye bran in Scenario U2 and U3 (native rye bran/P-reduced rye bran) | 5.0/25.0 | 5.0/35.0 | 12.5/45.0 |

content of the processed rye bran (1.12 g P per kg P-reduced rye bran). Based on this, the P eq. value of the P-reduced rye bran is adjusted in the model: 0.038 kg P eq. for the P-reduced rye bran instead of 0.42 kg P eq. from the untreated rye bran.

To investigate the sensitivity of the results, a different composition of rations (soybean meal from the US instead of rapeseed meal; barley from Poland instead of barley from Germany), the feed conversion ratio (amount of feed needed per kg weight gain ± 10%) and the pig mortality (± 10%) is varied.

## 4 Results and discussion

### 4.1 Environmental impacts of P-reduced bran production

The environmental impact of the P-reduced bran is, according to the allocation described above, only related to the process steps used for the P removal from bran. Below the results are discussed in detail.

#### *4.1.1 Impact category "Global Warming"*

Figure 7 presents the environmental impact in the category "Global Warming", which results from the energy and material flows attributed to the production of 1 t of P-reduced bran. Absolute values for the thermo-chemical and enzymatic process routes are represented above the columns of Fig. 7.

The thermo-chemical processing of rye bran release ca. 10 times as much $CO_2$ eq. into the environment compared to the enzymatic route (Fig. 7). Main reasons are the over 50

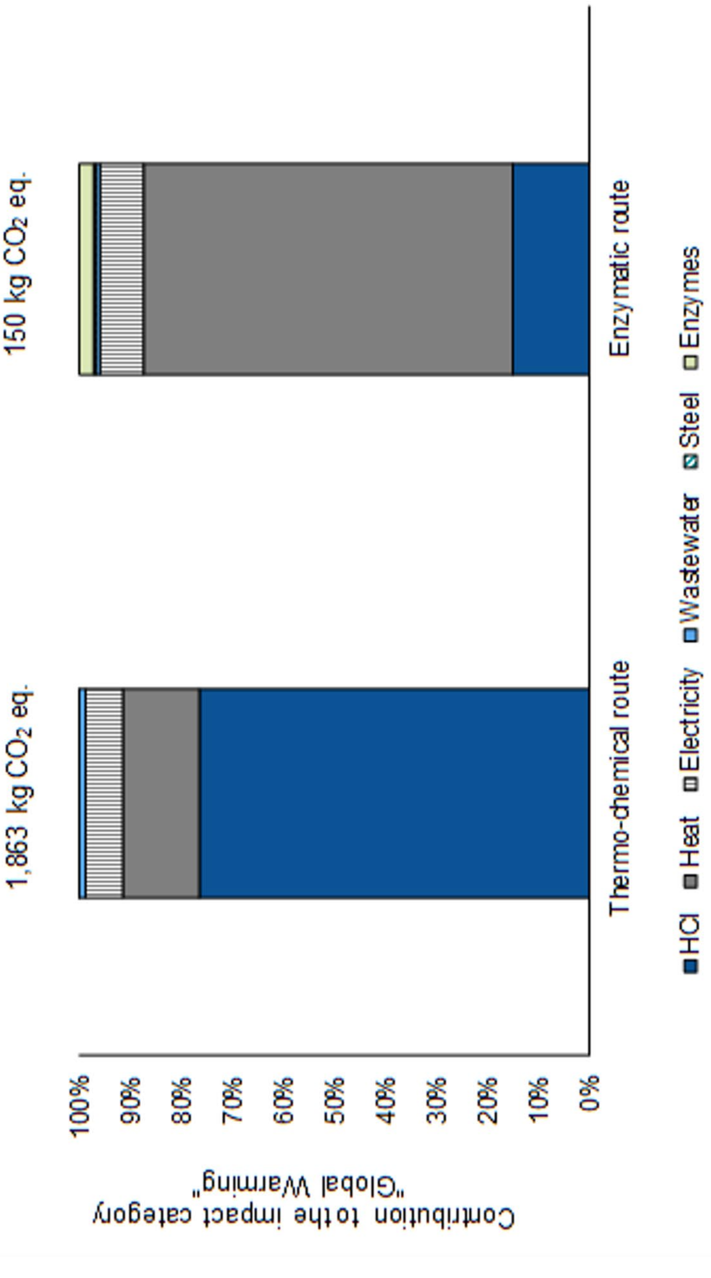

**Fig. 7** Contribution of energy and material flows to the impact category "Global Warming" in thermo-chemical and enzymatic processing routes

times higher amount of hydrochloric acid (HCl) and the 4 times higher overall energy consumption needed for the thermo-chemical process route.

In terms of the proportional contribution of production components to the impact category "Global Warming", HCl causes 77% of all $CO_2$ eq. per t of P-reduced bran in the thermo-chemical route, and only 15% in the enzymatic route. The impact of HCl on this impact category is attributed to its quantity required for the processing route as well as to the fact that the entire provision chain of HCl, including the energy-demanding production of hydrogen ($H_2$) and the production of chlorine ($Cl_2$), is taken into account.

Other relevant contributors to the $CO_2$ eq. emissions in the thermo-chemical route are heat (15%) and electricity provision (7%). Although in absolute terms the use of electrical energy is higher than the use of thermal energy (Table 1), heat consumption in the thermo-chemical route results in a larger proportional contribution to the GHG emissions because it is produced from natural gas. The use of electrical energy is based on the German electricity mix, which also includes renewable energy sources and therefore, produces less $CO_2$ eq. emissions.

In the enzymatic route, 72% to all $CO_2$ eq. emissions are generated from heat consumption, followed by the use of HCl and electricity, which cause 15% and 8% $CO_2$ eq. emissions, respectively. As in the case of the thermo-chemical route, natural gas for heat production is assumed. Finally, enzymes' production and utilization in the enzymatic processing route cause with less than 3% a relatively small contribution.

As the process routes analyzed here are in a very early stage of development and no upscaling into an industrial implementation has been realized so far, the energy demand is a rough estimation and also the HCl demand might vary. Thus, Fig. 8 shows the range of $CO_2$ eq. for the thermo-chemical (left) and the enzymatic (right) process route for different HCl amounts, various heat and electricity inputs, different wastewater amounts, various steel masses and different enzyme demands. Again, HCl dominates the $CO_2$ eq. of the thermo-chemical process route; these emissions could be reduced by ca. 12 kg $CO_2$ eq. per percent HCl reduction respectively vice versa. Compared to this, the influence of the other varied characteristic values is only limited. For the enzymatic route, the main influencing parameter is the heat input with 1 kg $CO_2$ eq. per percent heat reduction, directly followed by the amount of HCl and electricity input with only 0.2 kg $CO_2$ eq. per percent parameter variation each.

Additionally, the source of energy can significantly influence the emissions released within the various routes. As a comparison to the current German energy mix, a scenario using only renewable sources of energy is analyzed (Table 3).

For both routes, the use of renewable energy sources reduces the $CO_2$ eq. However, the variation is more pronounced within the enzymatic route as energy hereby plays a more significant role. The $CO_2$ eq. of the enzymatic processing route can be reduced by ca. 67% in Scenario P2. One reasons for that is that in Scenario P1 heat from natural gas contributes with 79 kg $CO_2$ eq. per t of enzymatically processed bran being substituted by biogas in Scenario P2 causing no direct $CO_2$ eq. This reduction would be even more significant if the indirect emissions from biogas provision (e.g., biowaste sourcing, transportation) would not be considered. In case of the chemical processing, varying energy sources have a rather moderate impact on the total $CO_2$ eq.; these emissions could be reduced by ca. 19% while using only renewable energy sources (Scenario P2). In absolute numbers, the direct contribution of heat is 277 kg $CO_2$ eq. in Scenario P1 and drops down to 19% of that in Scenario P2.

#### *4.1.2 Impact category "Terrestrial Acidification"*

Figure 9 presents the environmental impact in the category "Terrestrial Acidification". In absolute terms, the emissions of $SO_2$ eq. within the thermo-chemical process route are ca. 34 times as high as within the enzymatic process and are mainly attributed to the significantly greater demand for HCl.

Relative, HCl causes 95% of all $SO_2$ eq. within the thermo-chemical processing route. The production of HCl combines the chlor-alkali and the Mannheim production processes [32], requiring, among others, input chemicals like sodium chloride (NaCl) and sulfuric acid ($H_2SO_4$). The contribution of HCl to the acidification impact is due to the chemical input in the HCl production as well as the possibly assumed fugitive HCl emissions during the production process (e.g., the HCl release into the atmosphere and its further precipitation in form of acid compounds). As for the energy use, its contribution to the acidification impact in the thermo-chemical route accounts to less than 5%, of which 2.8% correspond to the electricity and 1.6% to the heat consumption.

In the enzymatic route, the share of emissions with an acidification impact is distributed between various production components: HCl (51%), heat (20%), enzymes (17%), and electricity (9%). In case of enzymes, the acidification impact arises from agricultural feedstock, which is used for the enzymes production (e.g., potato starch). Therefore, agricultural feedstock implies agricultural production and the use of fertilizers causing environmental pollution, including acidification.

Regarding the sensitivity analysis in the impact category "Terrestrial Acidification", the amount of HCl is varied for both processing routes (Fig. 10). The environmental burden of HCl is more pronounced in the thermo-chemical route and therefore, a variation of 1% HCl amount in the thermo-chemical route leads to 0.1 kg $SO_2$ eq. reduction or elevation. For the enzymatic route this influence is 50 times smaller but still the major impact on the $SO_2$ eq.

As for the variation of energy sources, the scenario with renewable sources of energy is considered (Table 4).

The emissions with an acidification impact slightly increase due to the substitution of natural gas by biogas (Scenario P2). Similar to the results outlined above for the $CO_2$ eq., the $SO_2$ eq. do not increase due to the direct emissions from biogas, but because of the indirect emissions. Biowaste treatment by anaerobic digestion cause increased $SO_2$ eq. compared to natural gas [32] resulting in more $SO_2$ eq. in Scenario P2.

### 4.2 Environmental impacts of P-reduced bran use as animal feed

#### *4.2.1 Impact category "Global Warming"*

The impact category "Global Warming" resulting from the use of the P-reduced bran as animal fodder for fattening pigs is analyzed and compared to a direct feeding of the untreated native rye bran. Figure 11 shows the absolute value of $CO_2$ eq. per 1 t carcass weight considering the life cycle of fattening pigs. Compared to Scenario U1 of using native rye bran, the overall $CO_2$ eq. after the inclusion of processed bran in the feed rations increased by ca. 65% due to the thermo-chemical process route and by 16 to 17% due to the enzymatic route.

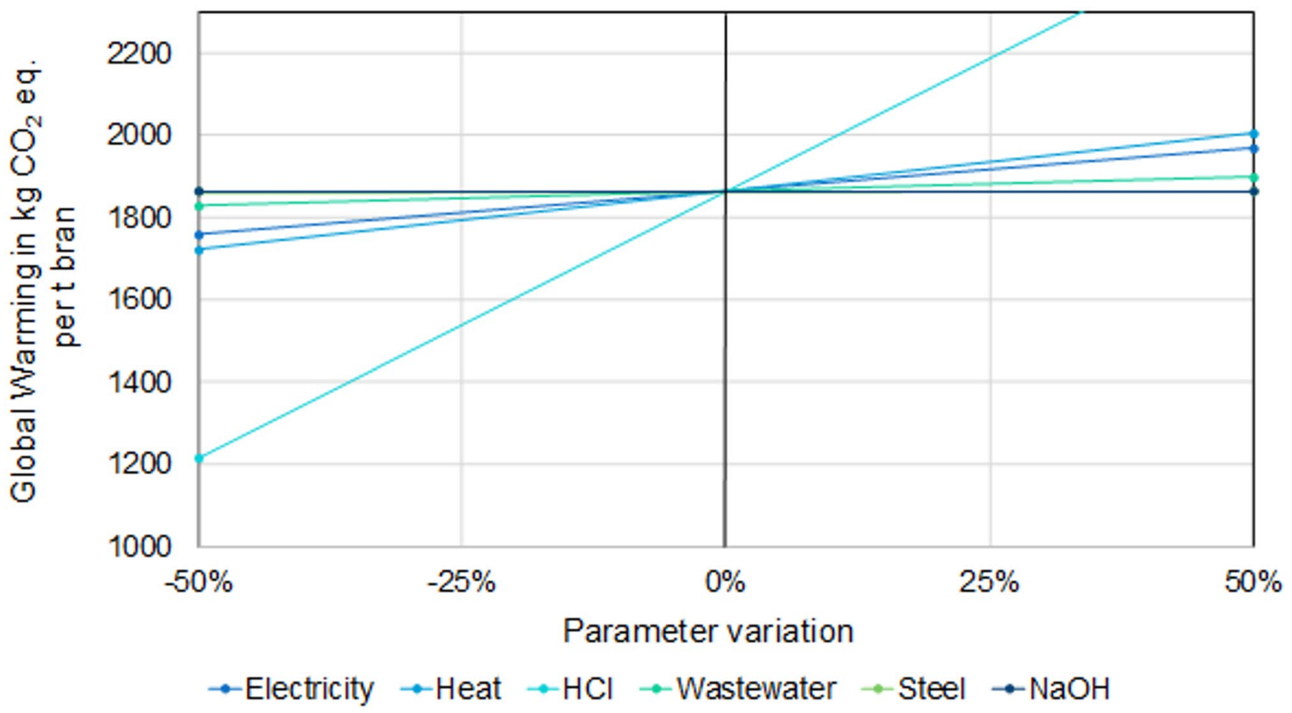

**Fig. 8** Sensitivity analysis of bran processing for the impact category "Global Warming" (thermo-chemical process, left; enzymatic process, right)

**Table 3** Energy scenarios for the sensitivity analysis of bran processing in the impact category "Global Warming"

| Scenario | Energy source | "Global Warming" in kg $CO_2$ eq | |
|---|---|---|---|
| | | Chemical | Enzymatic |
| P1 | Conventional heat and electricity | 1 863 | 150 |
| P2 | Renewable heat and electricity | 1 517 | 51 |

In Scenario U1 with native rye bran, cereal grains and their products contribute with 35% to the total $CO_2$ eq. per t of carcass weight; this is primarily attributable to rye as the main ingredient of the feeding ration (up to 43%). In comparison, their contribution rises to 62% in Scenario U2 with thermo-chemically processed rye bran and to 45% in Scenario U3 with enzymatically processed rye bran. In both scenarios the contribution to $CO_2$ eq. of cereal grains may be primarily attributed to the processed rye bran as it is the main feed ingredient in the rations of these scenarios (up to 58%).

The impact of oil seeds and their products (soybean meal, rapeseed meal and rapeseed oil), however, is higher in the scenarios with processed rye bran (165.7 kg $CO_2$ eq. per t carcass weight, 3–4%) than in the rations with native rye bran (26.3 kg $CO_2$ eq. per t carcass weight, 1%) which may be traced back to the higher mean proportion of oil seeds in the rations with processed rye bran (7% compared to 2%). The impact of tubers, roots and their products (sugar beet pulp and molasses) is lower in the scenarios with processed rye bran (29.5 kg $CO_2$ eq. per t carcass weight, 1%) than in Scenario U1 with native rye bran only (184.9 kg $CO_2$ eq. per t carcass weight, 6%) due to a lower mean proportion (6% compared to 16%). Further categories contributing to the $CO_2$ eq. are related to pigs, their housing and manure management being identical for all scenarios.

Several parameters affected the $CO_2$ eq., as for example the type and origin of the feed components, feed conversion ratio and mortality rate of animals.

Regarding the feed components, the primary protein source in Germany are soybean and rapeseed. The rapeseed is very similar in its mineral content to rye bran as it is particularly P rich limiting its inclusion in feed rations. This restriction is especially relevant when combined with unprocessed rye bran, as the total P content must remain within acceptable limits. A theoretical change from rapeseed meal (Germany) to soybean meal (US) results in slightly lower $CO_2$ eq. per t carcass weight (below 1% compared to the results discussed above). Additionally, the replacement of rapeseed meal by soybean meal as well as the replacement of barley from Germany with barley from Poland shows higher $CO_2$ eq. (0.7–1.2%) (Table 5).

As there is a huge variety of options to adapt the rations without influencing its nutritional value, further combinations could be calculated. All ingredients come with their specific $CO_2$ eq. from the cultivation and production processes, yet the grain production processes are known to differ widely all over the world [33].

The sensitivity analysis (Table 5) shows that the adaptation of the feed conversion ratio (± 10%) can decrease the overall $CO_2$ eq. by 5.2% and increases it by 7.7%. This indicates a relatively high effect on the overall $CO_2$ eq. Compared to this, the adaptation of the mortality (± 10%) results in a decrease/increase of less than 1%. Therefore, the mortality may be considered as a marginal contributor to the overall $CO_2$ eq.

Under consideration of the whole cycle, namely the production of P-reduced bran and the subsequent feeding, the overall $CO_2$ eq. of the fattening pigs increased by 65.2%

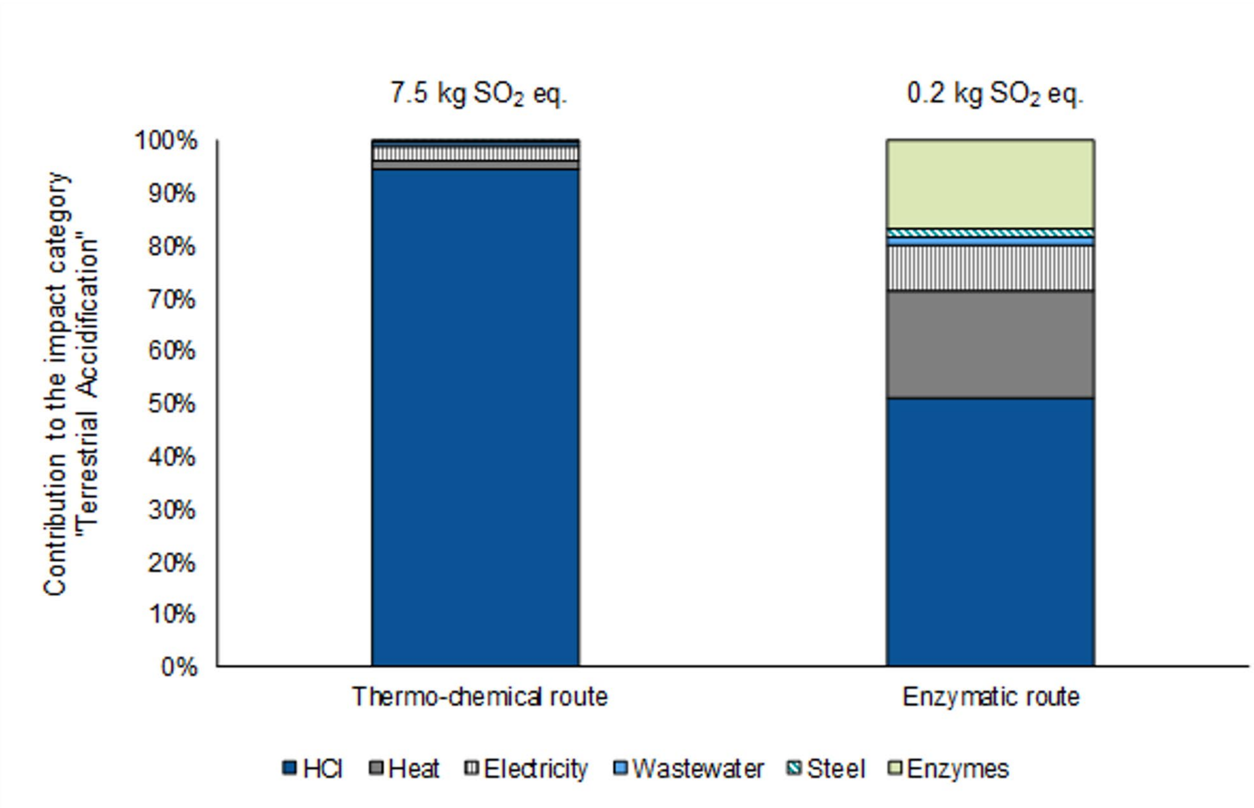

**Fig. 9** Contribution of energy and material flows to the impact category "Terrestrial Acidification" in thermo-chemical and enzymatic processing routes

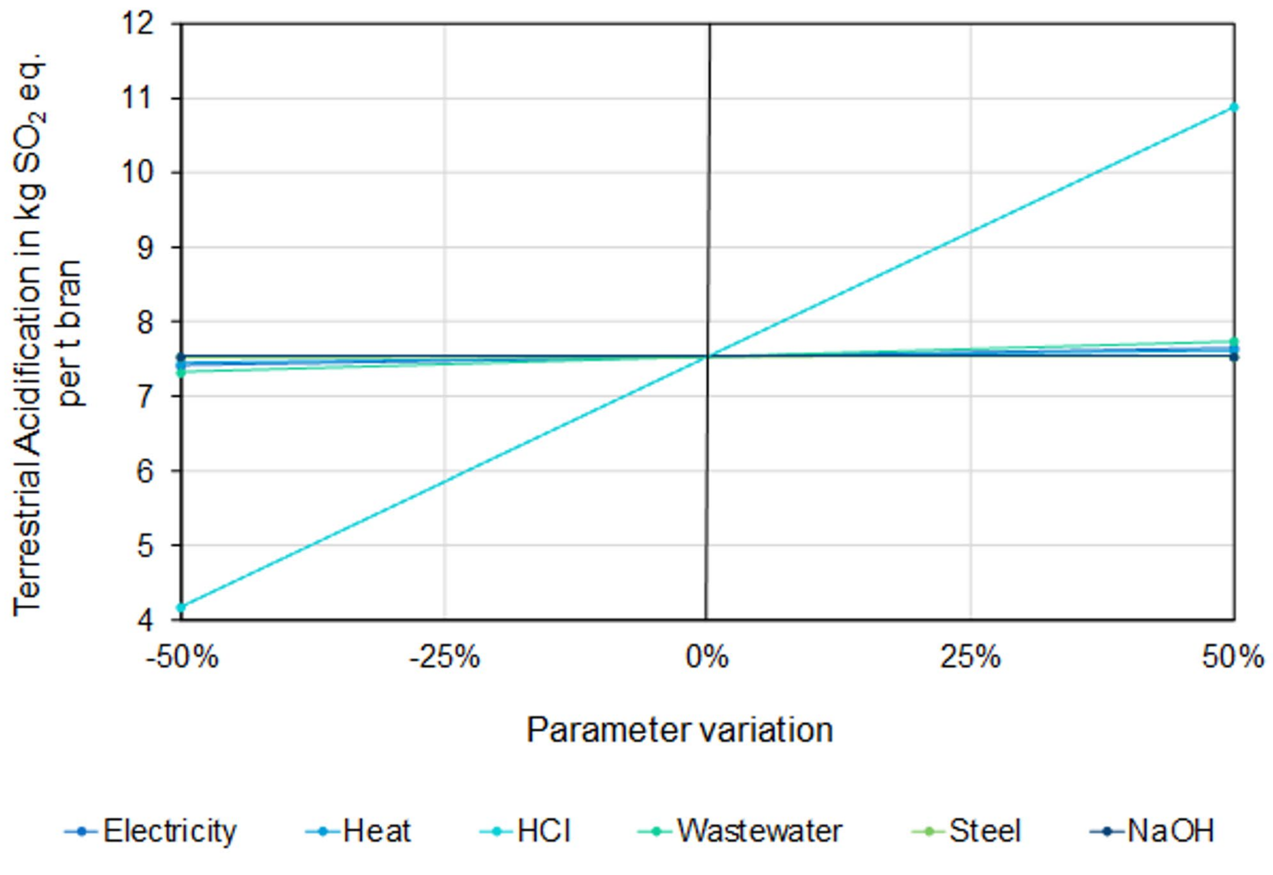

**Fig. 10** Sensitivity analysis of bran processing for the impact category "Terrestrial Acidification" (thermo-chemical process, left; enzymatic process, right)

**Table 4** Energy scenarios for the sensitivity analysis of bran processing in the impact category "Terrestrial Acidification"

| Scenario | Energy source | "Terrestrial Acidification" in kg $SO_2$ eq | |
|---|---|---|---|
| | | Chemical | Enzymatic |
| P1 | Conventional heat and electricity | 7.5 | 0.2 |
| P2 | Renewable heat and electricity | 7.9 | 0.4 |

(thermo-chemically processed rye bran) and 16.5% (enzymatically processed rye bran), respectively, as the impact of the processing stage must be taken into consideration.

### *4.2.2 Impact category "Eutrophication"*

Figure 12 shows the absolute value of the impact category "Eutrophication" considering the life cycle of fattening pigs in P eq. per t carcass weight as well as categories contributing to the P eq. Thus, the overall impact on P eq. decreased by 4.2% in scenarios with thermo-chemically and enzymatically processed rye bran. As the processed bran is assumed to have the same P-content, the impact on the P eq. is also identical in Scenario U2 and U3. Additionally, both scenarios assume the same portion of P-reduced bran in the feeding composition.

The contribution of cereal grains in Scenario U1 with native rye bran amounts to 46% of the total P eq. per t of carcass weight (0.57 kg $PO_4$ eq.), while the cereals contribution in Scenario U2 (thermo-chemically processed rye bran) and Scenario U3 (enzymatically processed rye bran) is 35% of the total P eq. (0.41 kg P eq.). Scenario U1 is mainly driven by the use of rye as a main ingredient (up to 43% per ration) while in Scenario U2 and U3 the main contribution to the P eq. results from barley, even though rye bran is included with higher percentages than barley. The difference in the order may be related to the considerably lower P eq. of rye bran compared to the rye and barley. The impact of oil seeds and their products (soybean meal, rapeseed meal and rapeseed oil), however, is higher in the scenarios with processed rye bran (0.10 kg P eq. per t carcass weight, 9%) than in the rations with native rye bran (0.02 kg P eq. per t carcass weight, 2%) which may be traced back to the higher mean proportion of oil seeds in the rations with processed rye bran (7% compared to 2%). The impact of tubers, roots and their products (sugar beet pulp and molasses) is lower in the scenarios with processed rye bran (0.01 kg P eq. per t carcass weight, below 1%) than in Scenario U1 (native rye bran) only (0.02 kg P eq. per t carcass weight, 2%) because of a lower mean proportion (6% compared to 16%). Further impact on the impact category "Eutrophication" derives from pigs, their housing and manure management and are therefore also hereby identical for all scenarios.

Analogously to the impact category "Global Warming", also the impact category "Eutrophication" is influenced by the composition of feed rations. A replacement of rapeseed meal (Germany) with soybean meal (US) did not affect the P eq. in all three scenarios (Table 6). However, when replacing barley from Germany with barley from Poland (assuming the same nutritional value), the P eq. per 1 t carcass weight increases by 9.8–10.2% compared to the original results.

The adaptation of feed conversion ratio (± 10%) decreased the overall P eq. by 7.1% and increased P eq. up to 8.5%; i.e., this adaptation has a lower effect than replacing barley from Germany with barley from Poland but a higher influence than replacing rapeseed

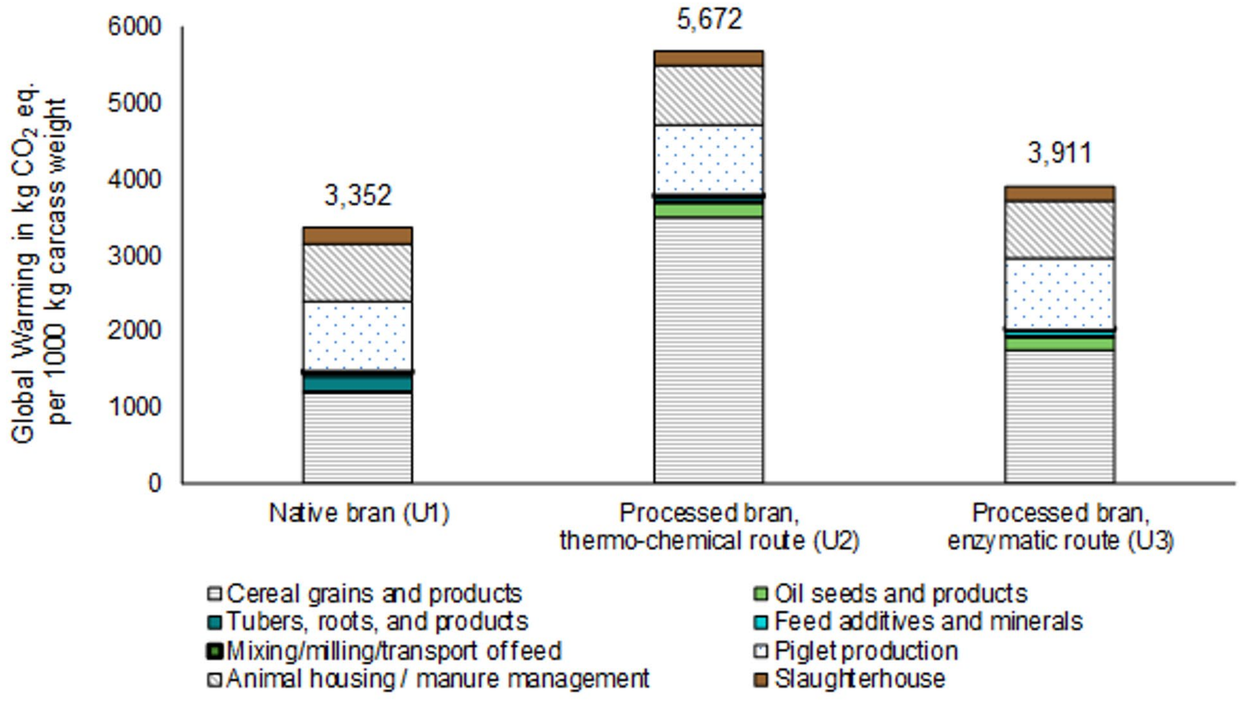

**Fig. 11** Impact category "Global Warming" of the fattening pigs feed with rations including native rye bran, chemical rye bran and enzymatic rye bran

**Table 5** Sensitivity of the impact category "Global Warming"

| | Rations including native rye bran | Rations including thermo-chemical processed rye bran | Rations including enzymatic processed rye bran |
|---|---|---|---|
| | in kg $CO_2$ eq. per t carcass weight | | |
| Replacing rapeseed meal (Germany) by soybean meal (US) | 3 351 | 5 667 | 3 906 |
| Replacing barley (Germany) by barley (Poland) | 3 393 | 5 713 | 3 951 |
| Decrease in feed conversion ratio (− 10%) | 3 177 | 5 267 | 3 681 |
| Increase in feed conversion ratio (+ 10%) | 3 527 | 6 077 | 4 141 |
| Decrease in mortality (− 10%) | 3 341 | 5 654 | 3 898 |
| Increase in mortality (+ 10%) | 3 364 | 5 691 | 3 924 |

meal (Germany) with soybean meal (US). The adaptation of the mortality results in a decrease/increase of less than 1% or even zero; i.e., mortality is a marginal contributor to the overall P eq. All in all, the sensitivity analysis reveals that the biggest impact on P eq. is caused by ingredients, followed by the feed conversion ratio. Thus, the biggest potential to decrease the P eq. of fattening pigs arises from animal nutrition (Table 6).

All over, the use of processed rye bran has the potential to decrease the impact category "Eutrophication" of fattening pigs. In order to achieve this goal, an additional effort in terms of energy and material during processing has to be accepted (i.e., higher $CO_2$ eq.; see above). The lower P content of thermo-chemically and enzymatically processed rye bran allows for a higher inclusion rate of rye bran in the feed of fattening pigs without exceeding guidelines about the optimal P amount in the rations. Consequently, this could enhance the proportion of bran used as a feed material resulting in an increase of the overall rye bran consumption in pig feed or animal feed in general and may therefore help to overcome the feed-food-competition as the proportion of human edible products in the feed of animals may be further reduced [34, 35]. Additionally, this would also allow P—recovered from the processed rye bran—to stay within the nutrient circle leading to an increase of circularity and reduce P mining [36–38].

## 5 Conclusions and final consideration

The goal of this research is to analyse, using a life cycle approach, environmental impacts of both the process designed to reduce the phosphorus (P) content in rye bran and the subsequent feeding of this P-reduced bran to animals (fattening pigs). The underlying concept of P extraction from rye bran is to decrease P excretion in fattening pigs, thereby lowering the eutrophication risk caused by P runoff or leaching to water ecosystems.

The environmental assessment of the bran processing and use stage of P-reduced bran shows that feeding the P-reduced bran to animals increases the impact category "Global Warming" (more significantly in the thermo-chemical than in the enzymatic processing route), but, at the same time, reduces the impact category "Eutrophication". Both process routes perform equally related the impact category "Eutrophication" as the same P reduction within the bran used as a fodder is realized. Also, lower P contents allow for a higher share of rye bran in feed rations thus raising the amount of usable rye bran.

The following main conclusions were obtained during the environmental assessment of the rye bran processing stage.

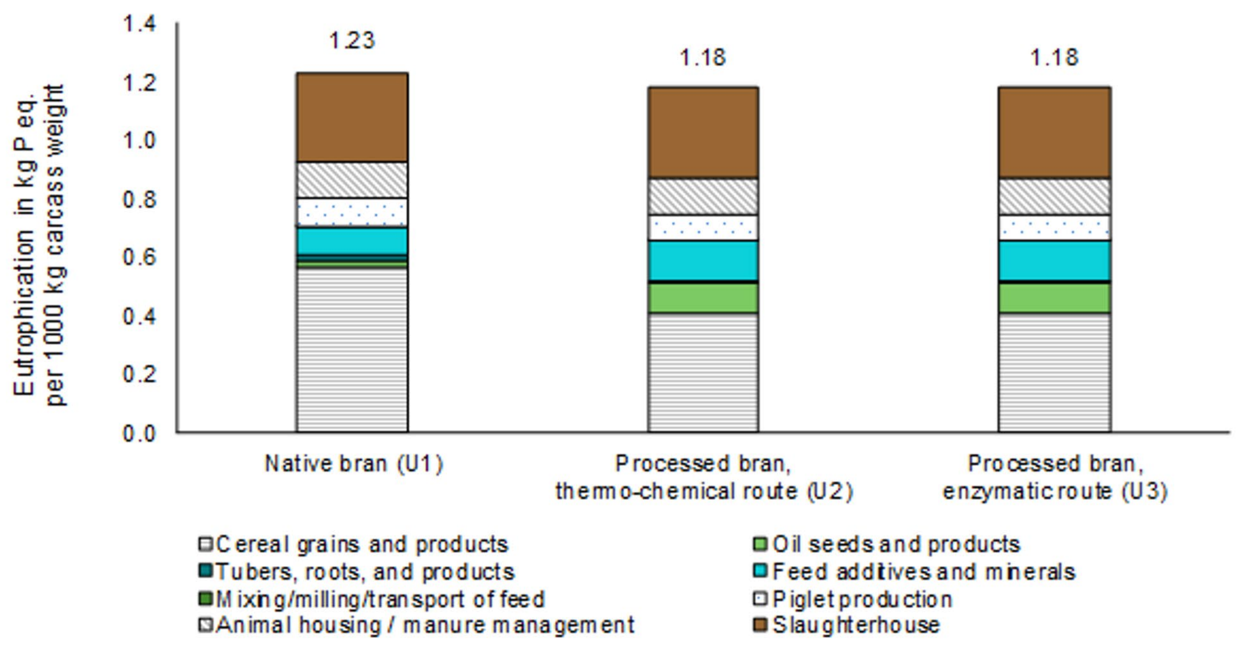

**Fig. 12** Impact category "Eutrophication" of the fattening pigs feed with rations including native rye bran, chemically modified rye bran and enzymatically modified rye bran

**Table 6** Sensitivity of the impact category "Eutrophication"

| | Rations including native rye bran | Rations including thermo-chemical processed rye bran | Rations including enzymatic processed rye bran |
|---|---|---|---|
| | in kg P eq. per t carcass weight | | |
| Replacing rapeseed meal (Germany) by soybean meal (US) | 1.23 | 1.18 | 1.18 |
| Replacing barley (Germany) by barley (Poland) | 1.35 | 1.30 | 1.30 |
| Decrease in feed conversion ratio (– 10%) | 1.13 | 1.08 | 1.08 |
| Increase in feed conversion ratio (+ 10%) | 1.33 | 1.27 | 1.27 |
| Decrease in mortality (– 10%) | 1.23 | 1.17 | 1.17 |
| Increase in mortality (+ 10%) | 1.24 | 1.18 | 1.18 |

- The environmental impact categories "Global Warming" and "Terrestrial Acidification" of the thermo-chemical process route are higher compared to the enzymatic processing of bran to achieve a P-reduced bran fodder and the recovered P. Emissions from the thermo-chemical process route to provide P-reduced bran are mainly caused by the input of HCl and for the enzymatic process route the main contribution is energy for the impact category "Global Warming" and the input of HCl for the impact category "Terrestrial Acidification".
- By using only renewable sources of energy, the impact category "Global Warming" can be reduced by 18% and 67% for the thermo-chemical and enzymatic route, respectively. The impact category "Terrestrial Acidification" slightly increases with the use of heat from biogas due to emissions released during anaerobic digestion.

The following main conclusions were obtained during the environmental assessment of the use of P-reduced bran as animal fodder.

- Cereal components contribute significantly to the impact category "Global Warming"; this category of P-reduced bran as a fodder is higher compared to feed rations with native bran due to the processing beforehand (65% for the thermo-chemical process and 16% for the enzymatic route).
- The impact category "Eutrophication" of fattening pigs is slightly reduced by the use of P-reduced rye bran (by 4%) and can significantly be influenced by the origin of complementary feed components.

To sum up, the presented processes of P reduction in rye bran have the potential to lower environmental impact category "Eutrophication" during animal feeding—though this benefit comes at the cost of increased greenhouse gas (GHG) emissions in the impact category "Global Warming". The enzymatic extraction route, however, shows comparatively low additional GHG emissions, making it more sustainable extraction option. Through the extraction process, a larger share of rye bran could be used as feed (since P limits are no longer exceeded), while the recovered phosphate can be potentially reused in the feed or fertilizer industries.

The study, however, has certain limitations. In the production stage of P-reduced bran, the data are based on small-scale laboratory trials of P extraction, which may not fully represent industrial-scale conditions. In the use stage of P-reduced bran, the environmental assessment considers only one animal category—fattening pigs—which could be limiting for the generalization of the results to other livestock systems.

## Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s43621-025-02355-7.

Additional file1 (DOCX 18 KB)

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The authors declare, that the work described has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

### Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors did not use AI or any AI-assisted technologies in the writing process and take full responsibility for the content of the publication.

### Author contributions

Liliya Shmyhelska: Conceptualization, data curation, formal analysis, methodology, software, validation, visualization, writing original draft, review and editing. Natalie Mayer: Conceptualization, data curation, formal analysis, methodology, validation, visualization, writing original draft, review and editing. Julia Gickel: Conceptualization, data curation, formal analysis, methodology, writing original draft. Christian Visscher: Supervision, validation, writing review and editing. Martin Kaltschmitt: supervision, validation, writing review and editing.

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### Data availability

The used data is publicly available, the process of P extraction from rye bran is described in Mayer et al. [20] and Widderich et al. [21].

## Declarations

### Ethics approval and consent to participate

The paper reflects the authors' own research and analysis in a truthful and complete manner. Furthermore, the paper does not contain any ethically questionable information, nor were any ethical questionable experiments performed in order to gain the results. The authors mutually agree that they participated in the preparation of the manuscript.

### Consent for publication

The authors declare that the manuscript is their intellectual property and that they want to publish it in the Journal "Clean Technologies and Environmental Policy".

### Clinical trials

No clinical trials were conducted in this study.

### Competing interests

The authors declare no competing interests.

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