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Monitoring of Performance-Based Environmental Impacts of Substituting Soybean Meal with Rapeseed Meal in the Rye-Based Diet of Weaned Pigs

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Abstract: Due to its favorable properties, soybean meal (SBM) is used especially in young growing animals. In terms of sustainability, there are various efforts to reduce the amounts of SBM in compound feeds and to increase the use of regional protein sources. This paper focuses on the effects of a partial to total substitution of SBM by regionally produced rapeseed meal (RSM) in different piglet diets regarding 10 important factors having an impact on the environment. Four diets, characterized by different shares (%) of both protein-rich ingredients (SBM/RSM: 18.1/0; 13.6/6.70; 8.10/16.1; 0/28.0), were fed to four groups of 10 piglets each in two runs. The impact was calculated related to feed (per t) and was performance-based for every piglet (impact·kg weight gain^{-1}) for each factor using methods according to life-cycle-analyses (LCA). Although feed intake and weight gains were not affected negatively, higher feed conversion ratios occurred, with high amounts of rapeseed inclusion. Nevertheless, the performance-based negative influence on climate change (kg CO_2 eq·kg weight gain^{-1}) was nearly halved when SBM was replaced by RSM. Since performance was not negatively affected, the use of RSM instead of SBM in piglet diets could be a viable tool for markedly reducing the negative impact on climate change.

Keywords: soybean meal; rapeseed meal; environmental impact; pigs; rye; sustainability; livestock

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1. Introduction

Pig diets are commonly based on wheat and soybeans [1]. Approximately 70–75% of the world's soybeans end up in animal feed [2]. The main producer in 2021/2022 was Brazil, followed by the United States and Argentina [3]. The cultivation of soybeans in Brazil forces deforestation [4]. The latter leads to massive emissions of greenhouse gases, and the transportation of soybeans to Europe also contributes to emissions [5]. It is also known that soybean meal (SBM) has the highest greenhouse gas (GHG) emissions of used protein sources, mainly due to land-use change, as it is mostly grown in regions where agriculture has been intensified in recent decades [6]. Rapeseed can be grown all over the world, with the highest production quantities being in Europe and Canada, where agriculture and cultivation have historically grown [3]. In general, if it is grown in Europe, emissions from transport are significantly reduced if it is used as animal feed for European production. Besides that, a production aside from South America on existing arable land also reduces emissions due to the deforestation of the rainforests [7,8].

In 2015, all members of the United Nations adopted, in total, 17 Sustainability Development Goals (SDGs) for Agenda 2030. These SDGs include goals encompassing all topics of sustainability: environmental, economic, and social. Many of these goals are related to more than one pillar. Focusing on the environmental pillar of sustainability, only at least eight of the SDGs deal with this issue [9]. In the production of pork, feed production is known to be the main contributor to environmental impacts [10]. To measure the environmental impacts of a product, the method of life cycle assessment (LCA) was invented in the industry in the 1960s [11]. The internationally used method is approved by the ISO 14040 and ISO 14044, recently revised in 2020 [12]. This standard specifies that LCA studies consist of four parts: (I) definition of the goal and scope of the study, (II) definition of the inventory data, (III) assessment of the data, and (IV) interpretation [13]. In the 2000s, the method was gradually transferred and adapted from the industry to agriculture and is now implemented in almost all agricultural sectors [14].

When SBM is partially or totally replaced by rapeseed meal (RSM) in the diet, a general adjustment in the composition and a supplementation (e.g., amino acids) may be necessary. As these feedstuffs mainly provide protein to the diet, the crude protein contents, as well as amounts of specific amino acids, are of crucial importance. In addition, the amount and composition of crude fiber are known to have a direct effect on protein digestibility, especially in young pigs [15,16].

As a by-product of rapeseed oil production, RSM contains high levels of protein [17]. However, a comparison of the protein content of SBM and RSM shows that the latter contains only 75% of the protein amount [18]. Especially in growing animals, the composition of the protein is particularly important because individual amino acid levels have a direct influence on growth. In young pigs, lysine is one of the limiting amino acids regarding growth performance [19]. It could be stated that SBM has a more lysin-rich amino acid profile [8,18]. In contrast, the contents of the sulfur-containing amino acids, methionine and cysteine, are of the same or slightly higher concentration [8,18]. Though, it must be considered that replacing SBM with RSM comes with generally lower protein digestibility, especially praececal [20,21]. The protein content, as well as the amount of various amino acids, should, therefore, be carefully considered when engaging in substitution. In particular, lysine supplementation may be necessary to achieve a sufficiently high lysine concentration. In general, higher amounts of neutral detergent fiber and acid detergent fiber can be expected in RSM, which is also due to higher amounts of lignin-containing shells [21–23]. In particular, the levels of fiber may set upper limits for replacement, as otherwise digestibility and performance may be reduced in young pigs [24,25]. RSM can be a valuable source of various minerals, including phosphorus (P). This mineral is particularly important—both from the point of view of bone growth in young pigs [26] and that of sustainability [27]. Due to high amounts of P in RSM, replacing SBM will increase the initial P content within the diet [8,18]. However, it must be considered that most of the P is bound to phytate ($InsP_6$) and, therefore, it is not digestible by most monogastric species, such as pigs [28]. In order to meet animal requirements and minimize P input into the environment, phytase should be used to a certain extent in RSM-based diets. Generally, using RSM could result in a reduced supplementation of phosphorus minerals, which is particularly important regarding resource efficiency, as P resources are limited and can only be obtained from mining [29]. Studies have shown that SBM can be partially replaced by RSM without affecting the performance of growing-finishing pigs [30,31]. However, especially in the feeding of young pigs, there are still uncertainties concerning the substitution of the commonly used SBM with RSM, resulting in higher levels of RSM within their diets. Nevertheless, with the adjustment of the diet and the feedstuffs used, together with the substitution of SBM by RSM, there are complex changes in terms of environmental impact.

As a first step, this paper focuses on the evaluation of the performance of young pigs fed with increasing levels of RSM instead of SBM. On this basis, an ingredient (LCA), as well as a performance-based LCA calculation, were performed so as to comply with the ISO 14040 and 14044 (with some adjustments).

2. Materials and Methods

2.1. Goal and Scope Definition

The aim of this study was to compare the environmental impacts of replacing SBM with RSM in diets for young pigs in relation to their performance. The scope of the study will be defined in the following sections.

2.1.1. Animals and Housing

In a trial with two consecutive runs, 2 × 20 young pigs (first run: age: 47.74 ± 0.49 days; bodyweight (BW): 15.1 ± 1.57 kg/s run: age: 50.0 ± 0.00 days; bodyweight (BW): 17.8 ± 2.86 kg) were housed in the stables of the Institute for Animal Nutrition of the University of Veterinary Medicine Hannover, Hannover, Germany. In the first run, the genetic of the cross-bred pigs was db. Viktoria (female) and db 77 (male) from BHZP GmbH, Dahlenburg, Germany. Whereas, in the second run, the genetic of the cross-bred piglets was Norwegian Landrace (female) and German large white (male). On the basis of body weight, sex ratio (female/male castrated), and the sow (siblings distributed to the groups), the pigs were selected for the formation of four comparable treatment groups in each run. The animals were housed individually in 1 m × 3 m pens with concrete flooring, equipped with a nipple drinker (permanent free access to water), and manipulable material as enrichment. Visual, olfactory, and tactile contact with other pigs was possible at all times. In both runs, an identical test protocol was used. The experiments were approved by the Animal Welfare Officer of the University of Veterinary Medicine, Hannover (reference: TiHo-T-2018-24).

2.1.2. Feed and Feeding

Four different pelleted diets based on rye and barley (regional carbohydrate sources) for weaned piglets were isoenergetically calculated and produced. Diet I contained only SBM and, therefore, was considered as the control. Besides this control, in the remaining three experimental diets, the amount of SBM was successively replaced with RSM. Regarding the provided protein amount, in diet II, 1/3 of the SBM was replaced with RSM. In diet III, this replacement involved 2/3 of the SBM, and, in diet IV, 3/3 of the SBM was replaced with RSM. The diets were analyzed for their chemical composition by standard procedures in accordance with the official methods of the Association of Agricultural Inspection and Research Institute (Verband Landwirtschaftlicher Untersuchungs- und Forschungsanstalten; VDLUFA), as described by Naumann and Bassler (2012). The ingredients and analyzed nutrient composition can be found in Table 1.

Feed and water were available to the animals ad libitum. The animals were fed every morning at 08:30 after removing the previous day's feed residue from the trough. The same feed batch was used for both runs.

Table 1. Chemical composition and analyzed nutrient composition of the diets (%).

Ingredients	Diet I	Diet II	Diet III	Diet IV
Rye	60.0	60.0	60.0	60.0
Barley	15.1	13.5	10.0	6.5
Rapeseed meal	-	6.7	16.1	28.4
Soybean meal	18.1	13.6	8.10	-
Ligonocellulose	2.0	1.5	1.0	-
Monocalcium phosphate	0.90	0.80	0.60	0.45
Calcium carbonate	0.80	0.75	0.75	0.70
Sodium chloride	0.45	0.45	0.45	0.45
Soybean oil [1]	0.65	0.70	1.00	1.50
Feed additives [2]	2.0	2.0	2.0	2.0
DM-content	89.0	89.0	88.9	88.8
Crude ash	5.36	5.42	4.48	5.73
Crude protein	19.4	19.6	19.5	18.8
Crude fat	2.81	2.78	3.42	4.23
Crude fiber	4.30	4.41	4.98	5.47
Starch	436	432	417	412
Phosphorus	0.63	0.64	0.65	0.64
ME (MJ/kg DM)	14.9	14.9	14.7	14.6

[1] Soybean meal (steam heated with soapstock) made from genetically modified soybeans. [2] Feed additives (per kg as fed); nutritional additives: vitamin A (12,000 IU), vitamin D3 (2000 IU), vitamin E (150 mg), copper from copper-(II)-glycinate chelate hydrate (4 mg), copper from copper-(II)-sulfate pentahydrate (110 mg), manganese from manganese glycine manganese chelate hydrate (35 mg), manganese from manganese-(II)-oxide (45 mg), zinc from glycine zinc chelate hydrate (40 mg), zinc from zinc oxide (80 mg), iron from iron-(II)-sulfate monohydrate (200 mg), iodine from calcium iodate anhydrous (2.0 mg), and selenium from sodium selenite (0.40 mg); zootechnical additives: 5.0×10^9 CFU *Saccharomyces cerevisiae*.

2.1.3. Performance

The pigs were weighed weekly, whereas the consumed feed was recorded every day. Based on the recorded data, the average daily gains (ADG) and the feed conversion (FCR) ratio were calculated.

2.2. Functional Unit

The analyses of the environmental impacts focused on the feed only. The system used the composition of the feed, the location of the feed mill, and the energy usage of the feed mill. The functional unit was the impact of 1000 kg feed.

2.3. Inventory

It was assumed that 0.0039 kWh·kg feed^{-1} was used to produce the feed and that 100% of the electricity from the feed mill came from the national grid of Germany. These values represent the default values of the used software.

For the life cycle assessment, the transportation distances were also taken into account. The feed mill was located in Germany. The origins of the ingredients can be found in Table 2.

Table 2. Origins of the ingredients.

Ingredients	Origin
Rye	Germany
Barley	Germany
Rapeseed meal	Germany
Soybean meal	South America
Ligonocellulose	Germany
Monocalcium phosphate	Germany
Calcium carbonate	Germany
Sodium chloride	Germany
Soybean oil	South America
Feed additives	Germany

2.4. Impact Assessment

The assessment of the environmental impact was performed using the online software application Opteinics® (BASF Lampertsheim GmbH, Lampertsheim, Germany), which is based on the Global Feed LCA Institute (GFLI) database. The software determines the environmental impact of 10 different categories. The impact on climate change is expressed in kg of CO_2 equivalent (kg CO_2 eq), while 1 kg CO_2 eq equals the global warming potential of the emission of 1 kg CO_2 into the environment [32]. The impact of ozone depletion is expressed in kg clorofluorocarbon-11 equivalent (kg CFC-11 eq), while 1 kg CFC-11 eq equals the impact of the emission of 1 kg cloroflurocarbon-11 into the ozone layer [33]. The impact of acidification is expressed in mol H+ equivalent (mol H+ eq) and, therefore, 1 mol H+ eq means that the substance has the same acidification potential as 1 mol H+-ions [34]. The impact of eutrophication is split into three categories: terrestrial, marine, and freshwater. For the terrestrial category, this impact is expressed in mol nitrogen equivalent (mol N eq), and for the marine eutrophication it is expressed in kg nitrogen equivalent (kg N eq), and for the eutrophication of freshwater it is expressed in kg phosphorus equivalent (kg P eq). One unit implies that the eutrophication potential of this actual life cycle equals the eutrophication potential of 1 mol N (terrestrial), 1 kg N (marine), or 1 kg P (freshwater) [35,36]. The category particulate matter is expressed in disease incidence in humans related to the emission of particulate matter. The increase in one disease incidence equals approximately one more person suffering from diseases related to particulate matter (e.g., lung and heart diseases) [37]. The water use is expressed as m^3 water equivalent deprived (m^3 water eq. deprived), i.e., the consumption of water leaving out green water, rainwater, seawater, and fossil water [37]. The usage of fossil resources is expressed in MJ, which could be released using these fossils as energy carriers [37]. For the evaluation of land use, the soil quality index based on LANCA (adjusted) is used. This index uses four indicators for evaluating impacts on the soil: erosion resistance, mechanical filtration, physiochemical filtration, groundwater regeneration, and biotic production [37,38].

2.5. Statistics

Available performance data were analyzed using the Statistical Analyses System for Windows, SAS® 9.4 via Enterprise Guide Client Version 7.1 (SAS Institute Inc., Cary, NC, USA). A test for normal distribution was performed by means of distribution analysis using the Shapiro-Wilk test for analytical evaluation. The model residuals were then tested by analysis using the Ryan-Einot-Gabriel-Welsch test.

The environmental impacts for each ingredient were extracted from the software directly. Afterwards, these values were used to calculate the relative impact per kg feed stuff using the included amount of the ingredient per kg feedstuff.

The performance-based impacts were calculated for each pig individually. Therefore, the total feed intake during the trial period was multiplied by the environmental impact of the respective feed. Afterwards, this value was divided by the total weight gain of the specific pig (impact$\cdot$kg weight gain^{-1}).

The differences per diet (for each run) were analyzed using ANOVA and the post-hoc Tukey-HSD test. All of these calculations were conducted in R [39].

The significance level was determined as alpha = 5% ($p < 0.05$). Significant differences were indicated by appending different superscript letters (a,b,c, . . .).

3. Results

3.1. Performance of the Animals

The mean feed intake of the diet varied between 1002 g/day (run 1, diet IV) and 1175 g/day (run 2, diet III). The body weight gain showed the lowest mean value for diet IV and the highest mean values for diet III and diet I. The FCR showed a significantly higher value for diet IV in run 1 (1.79 kg$\cdot$kg^{-1}) and significant differences between diet I (1.62 kg$\cdot$kg^{-1}), diet III (1.81 kg$\cdot$kg^{-1}), and diet IV (1.79 kg$\cdot$kg^{-1}) in the second run. All values concerning feed intake, body weight gain, and FCR of both runs can be found in Table 3.

Table 3. Feed intake, body weight gain, and feed conversion ratio (±standard deviation).

Run	Diet	Feed Intake ($DM \cdot day^{-1}$)	Body Weight Gain ($g \cdot day^{-1}$)	FCR ($kg \cdot kg^{-1}$) *
1	I	1014 ± 293	724 ± 122	$1.58^{b} \pm 0.129$
	II	1038 ± 286	715 ± 140	$1.65^{b} \pm 0.224$
	III	1131 ± 299	781 ± 97.6	$1.64^{b} \pm 0.212$
	IV	1002 ± 293	674 ± 100	$1.79^{a} \pm 0.269$
2	I	1110 ± 227	774 ± 149	$1.62^{b} \pm 0.164$
	II	1109 ± 187	733 ± 64.4	$1.71^{ab} \pm 0.070$
	III	1175 ± 221	733 ± 55.1	$1.81^{a} \pm 0.182$
	IV	1147 ± 268	727 ± 166	$1.79^{a} \pm 0.135$

* kg feed (fresh matter)·body weight gain $(kg)^{-1}$; ^{a,b} significant differences between the groups in each run ($p < 0.05$).

3.2. Impacts on Climate Change

3.2.1. Impacts of the Feed

The highest impact on climate change was found for diet I (1219.16 kg CO_2 eq per t), followed by diet II (1053.90 CO_2 per t), diet III (869.38 kg CO_2 per t), and diet IV (601.09 kg CO_2 per t). The impact per ingredient varied between 0.01 kg CO_2 eq per feedstuff (calcium carbonate) and 7.34 kg CO_2 eq per kg feedstuff (soybean oil). For SBM, the relative impact was 4.42 kg CO_2 eq per kg feedstuff, while the relative impact of RSM was 0.59 CO_2 eq per kg feedstuff. All values and the relative impact per ingredient can be found in Table 4.

Table 4. Impact of 1 t feed on climate change per ingredient (kg CO_2 eq per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (kg CO_2 eq per kg Feedstuff)
Rye	250.95	250.95	250.95	250.95	0.42
Barley	61.07	54.60	40.44	26.29	0.40
Soybean meal	799.61	600.81	357.84	-	4.42
Rapeseed meal	-	39.26	94.35	166.43	0.59
Ligonocellulose	5.41	4.06	2.70	-	0.27
Monocalcium phosphate	14.12	12.55	9.41	7.06	1.57
Calcium carbonate	0.06	0.06	0.06	0.05	0.01
Sodium chloride	0.40	0.40	0.40	0.40	0.09
Soybean oil	47.69	51.36	73.37	110.06	7.34
Feed additives	32.32	32.32	32.32	32.32	1.62
Grid Electricity Use Feed Mill	7.53	7.53	7.53	7.53	0.01
Total	1219.16	1053.90	869.38	601.09	

3.2.2. Impacts Based on the Performance of the Animals

The highest mean performance-based impact on climate change could be found in diet I for both runs (run 1: 1.95 kg CO_2 eq·kg^{-1}, run 2: 1.97 kg CO_2 eq·kg^{-1}). In both runs, the relative impact decreased between diets I and IV, the lowest value being shown in diet IV (run I: 1.01 kg CO_2 eq·kg^{-1}, run 2: 1.07 CO_2 eq·kg^{-1}). Both runs showed significant differences between the mean values of all diets.

All values regarding the performance-based impacts and their significances can be found in Table 5.

Table 5. Mean performance-based impact on climate change per run and diet (kg CO_2 eq·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (kg CO_2 eq·kg^{-1})	Performance-Based Impact at Run 2 (kg CO_2 eq·kg^{-1})
I	1.95 ± 0.08 ^{a}	1.97 ± 0.10 ^{a}
II	1.74 ± 0.07 ^{b}	1.80 ± 0.09 ^{b}
III	1.43 ± 0.08 ^{c}	1.58 ± 0.09 ^{c}
IV	1.01 ± 0.05 ^{d}	1.07 ± 0.07 ^{d}

$^{a–d}$ significant differences between the groups in each run ($p < 0.05$).

3.3. Ozone Depletion

3.3.1. Impacts of the Feedstuffs

The highest value for the total impact on ozone depletion of the diets was shown in diet I (8.02×10^{-6} kg CFC-11 eq per t), followed by diet II (7.49×10^{-6} kg CFC-11 eq per t), diet III (6.99×10^{-6} kg CFC-11 eq per t), and diet IV (6.22×10^{-6} kg CFC-11 eq per t). The relative impact per ingredient varied between 1.26×10^{-14} kg CFC-11 eq per kg feedstuff (calcium carbonate) and 4.84×10^{-8} kg CFC-11 per kg feedstuff (soybean oil). The relative impact of SBM (2.06×10^{-8} kg CFC-11 per kg feedstuff) was higher than the relative impact of RSM (6.81×10^{-9} kg CFC-11 per kg feedstuff). All values and the relative impact per ingredient can be found in Table 6.

Table 6. Impact of 1 t feed on ozone depletion per ingredient (kg CFC-11 eq per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (kg CFC-11 eq per kg Feedstuff)
Rye	3.24×10^{-6}	3.24×10^{-6}	3.24×10^{-6}	3.24×10^{-6}	5.40×10^{-9}
Barley	5.14×10^{-7}	4.60×10^{-7}	3.41×10^{-7}	2.21×10^{-7}	3.41×10^{-9}
Soybean meal	3.73×10^{-6}	2.80×10^{-6}	1.67×10^{-6}	-	2.06×10^{-8}
Rapeseed meal	-	4.56×10^{-7}	1.10×10^{-6}	1.93×10^{-6}	6.81×10^{-9}
Ligonocellulose	1.23×10^{-7}	9.25×10^{-8}	6.17×10^{-8}	-	6.17×10^{-9}
Monocalcium phosphate	4.47×10^{-10}	3.98×10^{-10}	2.98×10^{-10}	2.24×10^{-10}	4.97×10^{-11}
Calcium carbonate	1.01×10^{-13}	9.46×10^{-14}	9.46×10^{-14}	8.83×10^{-14}	1.26×10^{-14}
Sodium chloride	1.37×10^{-12}	1.37×10^{-12}	1.37×10^{-12}	1.37×10^{-12}	3.04×10^{-13}
Soybean oil	3.15×10^{-7}	3.39×10^{-7}	4.84×10^{-7}	7.27×10^{-7}	4.84×10^{-8}
Feed additives	9.71×10^{-8}	9.71×10^{-8}	9.71×10^{-8}	9.71×10^{-8}	4.86×10^{-9}
Grid Electricity Use Feed Mill	2.70×10^{-13}	2.70×10^{-13}	2.70×10^{-13}	2.70×10^{-13}	2.70×10^{-16}
Total	8.02×10^{-6}	7.49×10^{-6}	6.99×10^{-6}	6.22×10^{-6}	

3.3.2. Performance-Based Impacts

The highest performance-based impact on ozone depletion could be found in diet I for both runs (run 1: 1.28×10^{-8} kg CFC-11 eq·kg^{-1}, run 2: 1.30×10^{-8} kg CFC-11 eq·kg^{-1}). In both runs, the relative impact decreased between diets I and IV, and the latter showed the lowest value (run 1: 1.05×10^{-8} kg CFC-11 eq·kg^{-1}, run 2: 1.11×10^{-8} kg CFC-11 eq·kg^{-1}). Run 1 showed significant differences between diet I, diet III, and diet IV. Diet II was similar to diet I and diet III. In run 2, the mean of diet IV was different from all other groups.

All values and significances regarding the performance-based impacts on ozone depletion can be found in Table 7.

Table 7. Mean performance-based impact on ozone depletion per run and diet (kg CFC-11 eq·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (kg CFC-11 eq·kg^{-1})	Performance-Based Impact at Run 2 (kg CFC-11 eq·kg^{-1})
I	$1.28 \times 10^{-8} \pm 5.6 \times 10^{-10\,a}$	$1.30 \times 10^{-8} \pm 6.6 \times 10^{-10\,a}$
II	$1.24 \times 10^{-8} \pm 5.2 \times 10^{-10\,a,b}$	$1.28 \times 10^{-8} \pm 6.6 \times 10^{-10\,a}$
III	$1.15 \times 10^{-8} \pm 6.3 \times 10^{-10\,b}$	$1.27 \times 10^{-8} \pm 7.2 \times 10^{-10\,a}$
IV	$1.05 \times 10^{-8} \pm 4.8 \times 10^{-10\,c}$	$1.11 \times 10^{-8} \pm 7.3 \times 10^{-10\,b}$

[a–c] significant differences between the groups in each run ($p < 0.05$).

3.4. *Acidification*

3.4.1. Impacts of the Feedstuffs

The highest total impact on acidification could be found in diet IV (10.54 mol H+ eq per t), followed by diet III (10.04 mol H+ eq per t), diet II (9.72 mol H+ eq per t), and diet I (9.46 mol H+ eq per t). The relative impact varied between 0.00004 mol H+ eq per kg feedstuff for calcium carbonate and 0.017 mol H+ eq per kg feedstuff for soybean oil. The relative impact of SBM (0.006 mol H+ eq per kg feedstuff) was lower than the relative impact of RSM (0.011 mol H+ eq per kg feedstuff). All values and the relative impact per ingredient can be found in Table 8.

Table 8. Impact of 1 t feed on acidification per ingredient (mol H+ eq per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (mol H+ eq per kg Feedstuff)
Rye	6.24	6.24	6.24	6.24	0.010
Barley	1.63	1.46	1.08	0.70	0.011
Soybean meal	1.07	0.80	0.48	0	0.006
Rapeseed meal	0	0.73	1.75	3.09	0.011
Ligonocellulose	0.08	0.06	0.04	0	0.004
Monocalcium phosphate	0.14	0.13	0.10	0.07	0.016
Calcium carbonate	0.0003	0.0003	0.0003	0.0003	0.00004
Sodium chloride	0.004	0.004	0.004	0.004	0.001
Soybean oil	0.11	0.12	0.17	0.25	0.017
Feed additives	0.18	0.18	0.18	0.18	0.009
Grid Electricity Use Feed Mill	0.01	0.01	0.01	0.01	0.00001
Total	9.46	9.72	10.04	10.54	

3.4.2. Performance-Based Impacts

The highest mean performance-based impact on acidification could be found in diet IV for both runs (run 1: 0.018 mol H+·kg^{-1}, run 2: 0.019 mol H+·kg^{-1}). In these, the relative impact increased between diet I and diet IV, showing the lowest value in diet I (0.015 mol H+ eq·kg^{-1} for both runs). Run 1 showed significant differences between diet I and diet III/IV. Diets III and IV were similar to each other, and diet II was similar to diet I and diet III/IV. Run 2 showed significant differences between diet I and diet IV, while diet II was similar to diets I and III, and diet III was similar to diets II and IV. All values and significances concerning the performance-based impacts on acidification can be found in Table 9.

Table 9. Mean performance-based impact on acidification per run and diet (mol H+ eq·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (mol H+ eq·kg^{-1})	Performance-Based Impact at Run 2 (mol H+ eq·kg^{-1})
I	0.015 ± 0.0007 [a]	0.015 ± 0.0008 [a]
II	0.016 ± 0.0007 [a,b]	0.017 ± 0.0009 [a,b]
III	0.017 ± 0.0009 [b]	0.018 ± 0.0010 [b,c]
IV	0.018 ± 0.0008 [b]	0.019 ± 0.0012 [c]

[a–c] significant differences between the groups in each run ($p < 0.05$).

3.5. Eutrophication, Terrestrial

3.5.1. Impacts of the Feedstuffs

The lowest level for the total impact on terrestrial eutrophication was shown for diet I (40.22 mol N eq per t), and this level increased for diet II (41.55 mol N eq per t) and diet III (43.17 mol N eq per t), with diet IV showing the highest level (45.63 mol N eq per t). The relative impact per ingredient varied between 0.0002 mol N eq per kg feedstuff (calcium carbonate) and 0.063 mol N eq per kg feedstuff (soybean oil). The relative impact of SBM (0.023 mol N eq per kg feedstuff) was lower than that of RSM (0.048 mol N eq per kg feedstuff). All values and the relative impact per ingredient can be found in Table 10.

Table 10. Impact of 1 t feed on terrestrial eutrophication per ingredient (mol N eq per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (mol N eq per kg Feedstuff)
Rye	27.65	27.65	27.65	27.65	0.046
Barley	7.25	6.48	4.80	3.12	0.048
Soybean meal	4.18	3.14	1.87	0	0.023
Rapeseed meal	0	3.20	7.68	13.55	0.048
Ligonocellulose	0.32	0.24	0.16	0	0.016
Monocalcium phosphate	0.08	0.07	0.05	0.04	0.008
Calcium carbonate	0.0016	0.0015	0.0015	0.0014	0.0002
Sodium chloride	0.022	0.022	0.022	0.022	0.005
Soybean oil	0.41	0.44	0.63	0.94	0.063
Feed additives	0.27	0.27	0.27	0.27	0.014
Grid Electricity Use Feed Mill	0.04	0.04	0.04	0.04	0.00004
Total	40.22	41.55	43.17	45.63	

3.5.2. Performance-Based Impacts

The lowest mean performance-based impact on terrestrial eutrophication could be found in diet I for both runs (run 1: 0.064 mol N eq·kg^{-1}, run 2: 0.067 mol N eq·kg^{-1}). In both runs, the relative impact increased between diet I and diet IV, showing the highest value in diet IV (run 1: 0.077 mol N eq·kg^{-1}, run 2: 0.057 mol N eq·kg^{-1}). Run 1 showed significant differences between diet I and diet III/IV. Diets I and II and diets III and IV were similar to each other, and diet II was also similar to diet III. Run 1 showed significant differences between diets I/II and diets III/IV, while diets I and II and diets III and IV were similar to each other.

All values and significances for the performance-based effects on terrestrial eutrophication are shown in Table 11.

Table 11. Mean performance-based impact on terrestrial eutrophication per run and diet (mol N eq·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (mol N eq·kg^{-1})	Performance-Based Impact at Run 2 (mol N eq·kg^{-1})
I	0.064 ± 0.003 [a]	0.065 ± 0.003 [a]
II	0.069 ± 0.003 [a,b]	0.071 ± 0.004 [a]
III	0.071 ± 0.004 [b,c]	0.079 ± 0.004 [b]
IV	0.077 ± 0.004 [c]	0.081 ± 0.005 [b]

[a–c] significant differences between the groups in each run ($p < 0.05$).

3.6. Eutrophication, Marine

3.6.1. Impacts of the Feedstuffs

The total impact on marine eutrophication increased from diet I (8.12 kg N eq per t) to diet II (8.29 kg N eq per t) and diet III (8.49 kg N eq per t) up to diet IV (8.82 kg N eq per t). The relative impact varied between 0.00002 kg N eq per kg feedstuff (calcium carbonate) and 0.017 kg N eq per kg feedstuff (soybean oil). The relative impact of SBM (0.006 kg N eq per kg feedstuff) was lower than the relative impact of RSM (0.009 kg N eq per kg feedstuff). All values and the relative impact per ingredient can be found in Table 12.

Table 12. Impact of 1 t feed on marine eutrophication per ingredient (kg N eq per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (kg N eq per kg Feedstuff)
Rye	5.37	5.37	5.37	5.37	0.009
Barley	1.50	1.34	1.00	0.65	0.010
Soybean meal	1.04	0.78	0.46	0	0.006
Rapeseed meal	0	0.59	1.42	2.50	0.009
Ligonocellulose	0.06	0.04	0.03	0	0.003
Monocalcium phosphate	0.007	0.007	0.005	0.004	0.001
Calcium carbonate	0.0002	0.0001	0.0001	0.0001	0.00002
Sodium chloride	0.002	0.002	0.002	0.002	0.0004
Soybean oil	0.11	0.12	0.17	0.26	0.017
Feed additives	0.03	0.03	0.03	0.03	0.001
Grid Electricity Use Feed Mill	0.003	0.003	0.003	0.003	3.47×10^{-6}
Total	8.12	8.29	8.49	8.82	

3.6.2. Performance-Based Impacts

The lowest mean performance-based impact on marine eutrophication could be found in diet I for run 1 (0.013 kg N eq·kg^{-1}) and diet IV for run 2 (0.011 kg N eq·kg^{-1}). In run 1, the highest value could be found for diet IV (0.015 kg N eq·kg^{-1}. Run 2 showed the highest vale for diet III (0.016 kg N eq·kg^{-1}). In run 1, diets I and IV showed a significant difference, while both diet II and diet III were similar to diets I and IV. Run 2 showed significant differences between diet I and diet IV, while diet II was similar to diets I and III, and diet III was similar to diets II and IV.

All values and significances concerning the performance-based impacts on marine eutrophication can be found in Table 13.

Table 13. Mean performance-based impact on marine eutrophication per run and diet (kg N eq·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (kg N eq·kg^{-1})	Performance-Based Impact at Run 2 (kg N eq·kg^{-1})
I	0.013 ± 0.0006 [a]	0.013 ± 0.0007 [a]
II	0.014 ± 0.0006 [a,b]	0.014 ± 0.0007 [a,b]
III	0.014 ± 0.0008 [a,b]	0.015 ± 0.0009 [b,c]
IV	0.015 ± 0.0007 [b]	0.016 ± 0.0010 [c]

[a–c] significant differences between the groups in each run (p < 0.05).

3.7. Eutrophication, Freshwater

3.7.1. Impacts of the Feedstuffs

The highest level for the total impact on the eutrophication was shown for diet I (0.200 kg P eq per t), and this level decreased for diet II (0.185 kg P eq per t) and diet III (0.170 kg P eq per t), with diet IV showing the lowest level (0.146 kg P eq per t). The relative impact per ingredient varied between 5.04 × 10^{-8} kg P eq per kg feedstuff (calcium carbonate) and 0.00075 kg P eq per kg feedstuff (soybean oil). The relative impact of SBM (0.00051 kg P eq per kg feedstuff) was higher than the relative impact of RSM (0.00015 kg P eq per kg feedstuff). All values and the relative impact per ingredient can be found in Table 14.

Table 14. Impact of 1 t feed on freshwater eutrophication per ingredient (kg P eq per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (kg P eq per kg Feedstuff)
Rye	0.075	0.075	0.075	0.075	0.00013
Barley	0.017	0.015	0.011	0.007	0.00011
Soybean meal	0.091	0.069	0.041	0	0.00051
Rapeseed meal	0	0.010	0.024	0.042	0.00015
Ligonocellulose	0.0009	0.0007	0.0005	0	0.00005
Monocalcium phosphate	8.04 × 10^{-5}	7.15 × 10^{-5}	5.36 × 10^{-5}	4.02 × 10^{-5}	8.94 × 10^{-6}
Calcium carbonate	4.04 × 10^{-7}	3.78 × 10^{-7}	3.78 × 10^{-7}	3.53 × 10^{-7}	5.04 × 10^{-8}
Sodium chloride	1.72 × 10^{-6}	1.72 × 10^{-6}	1.72 × 10^{-6}	1.72 × 10^{-6}	3.82 × 10^{-7}
Soybean oil	0.005	0.005	0.008	0.011	0.00075
Feed additives	0.010	0.010	0.010	0.010	0.00052
Grid Electricity Use Feed Mill	3.43 × 10^{-5}	3.43 × 10^{-5}	3.43 × 10^{-5}	3.43 × 10^{-5}	3.43 × 10^{-8}
Total	0.200	0.185	0.170	0.146	

3.7.2. Performance-Based Impacts

The highest mean performance-based impact on freshwater eutrophication could be found for diet I in both runs (run 1: 3.19 × 10^{-4} kg P eq·kg^{-1}, run 2: 3.00 × 10^{-4} kg P eq·kg^{-1}). In run 1, the lowest value could be found for diet IV (2.46 × 10^{-4} kg P eq·kg^{-1}). Run 2 showed the lowest value for diet III (2.82 × 10^{-4} kg P eq·kg^{-1}). Significant differences could be observed for run 1 between the mean values of diet I/II and diets III and IV. Diets III and IV also showed a significant difference, while diets I and II were similar. In run 2, the mean of diet IV was different from all other groups.

All values and significances regarding the performance-based impacts on freshwater eutrophication can be found in Table 15.

Table 15. Mean performance-based impact on freshwater eutrophication per run and diet (kg P eq·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (kg P eq·kg^{-1})	Performance-Based Impact at Run 2 (kg P eq·kg^{-1})
I	$3.19 \times 10^{-4} \pm 1.4 \times 10^{-5\,a}$	$3.23 \times 10^{-4} \pm 1.6 \times 10^{-5\,a}$
II	$3.06 \times 10^{-4} \pm 1.3 \times 10^{-5\,a}$	$3.16 \times 10^{-4} \pm 1.6 \times 10^{-5\,a}$
III	$2.79 \times 10^{-4} \pm 1.5 \times 10^{-5\,b}$	$3.09 \times 10^{-4} \pm 1.8 \times 10^{-5\,a}$
IV	$2.46 \times 10^{-4} \pm 1.1 \times 10^{-5\,c}$	$2.61 \times 10^{-4} \pm 1.7 \times 10^{-4\,b}$

$^{a–c}$ significant differences between the groups in each run ($p < 0.05$).

3.8. Particulate Matter

3.8.1. Impacts of the Feedstuffs

The total impact on the emission of particulate matter showed a slight increase, starting with diet I (7.10×10^{-5} disease incidence per t), followed by diet II (7.27×10^{-5} disease incidence per t) and diet III (7.47×10^{-5} disease incidence per t), with the highest value being shown in diet IV (7.80×10^{-5} disease incidence per t). The relative impact varied between 8.09×10^{-10} disease incidence per kg feedstuff and 1.36×10^{-7} disease incidence per kg feedstuff. The relative impact of SBM (4.73×10^{-8} disease incidence per kg feedstuff) was lower than the relative impact of RSM (7.84×10^{-8} disease incidence per kg feedstuff). All values and the relative impact per ingredient can be found in Table 16.

Table 16. Impact of 1 t feed on the emission of particulate matter per ingredient (disease incidences per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (Disease Incidence per kg Feedstuff)
Rye	4.64×10^{-5}	4.64×10^{-5}	4.64×10^{-5}	4.64×10^{-5}	7.74×10^{-8}
Barley	1.19×10^{-5}	1.06×10^{-5}	7.87×10^{-6}	5.12×10^{-6}	7.87×10^{-8}
Soybean meal	8.56×10^{-6}	6.43×10^{-6}	3.83×10^{-6}	0	4.73×10^{-8}
Rapeseed meal	0	5.25×10^{-6}	1.26×10^{-5}	2.23×10^{-5}	7.84×10^{-8}
Ligonocellulose	6.09×10^{-7}	4.57×10^{-7}	3.05×10^{-7}	0	3.05×10^{-8}
Monocalcium phosphate	9.26×10^{-7}	8.23×10^{-7}	6.17×10^{-7}	4.63×10^{-7}	1.03×10^{-7}
Calcium carbonate	6.48×10^{-9}	6.07×10^{-9}	6.07×10^{-9}	5.67×10^{-9}	8.09×10^{-10}
Sodium chloride	9.18×10^{-8}	9.18×10^{-8}	9.18×10^{-8}	9.18×10^{-8}	2.04×10^{-8}
Soybean oil	8.87×10^{-7}	9.55×10^{-7}	1.36×10^{-6}	2.05×10^{-6}	1.36×10^{-7}
Feed additives	1.49×10^{-6}	1.49×10^{-6}	1.49×10^{-6}	1.49×10^{-6}	7.46×10^{-8}
Grid Electricity Use Feed Mill	9.32×10^{-8}	9.32×10^{-8}	9.32×10^{-8}	9.32×10^{-8}	9.32×10^{-11}
Total	7.10×10^{-5}	7.27×10^{-5}	7.47×10^{-5}	7.80×10^{-5}	

3.8.2. Performance-Based Impacts

The lowest mean performance-based impact on the emission of particulate matter could be found in diet I for run 1 (1.13×10^{-7} disease incidences·kg^{-1}) and diet IV for run 2 (1.00×10^{-7} disease incidences·kg^{-1}). In run 1, the highest value could be found for diet IV (1.31×10^{-7} disease incidences·kg^{-1}), while run 2 showed the highest value for diet III (1.42×10^{-7} disease incidences·kg^{-1}). Run 1 showed significant differences between diets I and III/IV. Diets III and IV were similar to each other, and diet II was similar to diet I and diet III/IV. Run 2 showed significant differences between diets I and IV, while diet II was similar to diets I and III, and diet III was similar to diets II and IV.

All values and significances concerning the performance-based impacts on particulate matter can be found in Table 17.

Table 17. Mean performance-based impact on the emission of particulate matter per run and diet (disease incidence from humans·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (disease incidence·kg^{-1})	Performance-Based Impact at Run 2 (disease incidence·kg^{-1})
I	$1.13 \times 10^{-7} \pm 4.9 \times 10^{-9}$ [a]	$1.15 \times 10^{-7} \pm 5.9 \times 10^{-9}$ [a]
II	$1.20 \times 10^{-7} \pm 5.1 \times 10^{-9}$ [a,b]	$1.24 \times 10^{-7} \pm 6.4 \times 10^{-9}$ [a,b]
III	$1.23 \times 10^{-7} \pm 6.8 \times 10^{-9}$ [b]	$1.36 \times 10^{-7} \pm 7.7 \times 10^{-9}$ [b,c]
IV	$1.31 \times 10^{-7} \pm 6.1 \times 10^{-9}$ [b]	$1.39 \times 10^{-7} \pm 9.1 \times 10^{-9}$ [c]

[a–c] significant differences between the groups in each run ($p < 0.05$).

3.9. Water Use

3.9.1. Impacts of the Feedstuffs

The total impact on water use was 53.81 m^3 water eq deprived per t for diet I, 52.56 m^3 water eq deprived per t for diet II, 58.91 m^3 water eq deprived per t for diet III, and 69.26 m^3 water eq deprived per t for diet IV. The relative impact varied between 0.0001 m^3 water eq deprived per kg feedstuff (calcium carbonate) and 3.169 m^3 water eq deprived per kg feedstuff (soybean oil). The relative impact of SBM (0.026 m^3 water eq deprived per kg feedstuff) was higher than the relative impact of RSM (0.009 m^3 water eq deprived per kg feedstuff). All values and the relative impact per ingredient can be found in Table 18.

Table 18. Impact of 1 t feed on water use per ingredient (m^3 water eq deprived per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (m^3 water eq deprived per kg Feedstuff)
Rye	9.01	9.01	9.01	9.01	0.015
Barley	1.41	1.26	0.93	0.61	0.009
Soybean meal	4.72	3.55	2.11	0	0.026
Rapeseed meal	0	0.64	1.53	2.70	0.009
Ligonocellulose	8.04	6.03	4.02	0	0.402
Monocalcium phosphate	1.25	1.11	0.84	0.63	0.139
Calcium carbonate	0.001	0.001	0.001	0.001	0.0001
Sodium chloride	0.02	0.02	0.02	0.02	0.005
Soybean oil	20.60	22.18	31.69	47.53	3.169
Feed additives	8.58	8.58	8.58	8.58	0.429
Grid Electricity Use Feed Mill	0.17	0.17	0.17	0.17	0.0002
Total	53.81	52.56	58.91	69.26	

3.9.2. Performance-Based Impacts

The lowest mean performance-based impact on water use could be found for diets I and II in run 1 (0.09 m^3 water eq. deprived·kg^{-1}) and for diets I and IV in run 2 (0.80 m^3 water eq. deprived·kg^{-1}). In run 1, the highest value could be found for diet IV (0.12 m^3 water eq. deprived·kg^{-1}), while run 2 showed the highest vale for diet III (0.13 m^3 water eq. deprived·kg^{-1}). Run 1 showed significant differences between diets I and III/IV and diets II and II/IV. Diets III and IV were similar to each other, while diets I and II also showed a significant difference. Run 2 showed significant differences between diets I and III/IV and between diets II and III/IV. Diets III and IV were similar to each other.

All values and significances concerning the performance-based impacts on water use can be found in Table 19.

Table 19. Mean performance-based impact on water use per run and diet (m^3 water eq. deprived·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (m^3 water eq. deprived·kg^{-1})	Performance-Based Impact at Run 2 (m^3 water eq. deprived·kg^{-1})
I	0.09 ± 0.004 ^{a}	0.09 ± 0.004 ^{a}
II	0.09 ± 0.004 ^{b}	0.09 ± 0.005 ^{b}
III	0.10 ± 0.005 ^{c}	0.11 ± 0.006 ^{c}
IV	0.12 ± 0.005 ^{c}	0.12 ± 0.008 ^{c}

$^{a–c}$ significant differences between the groups in each run ($p < 0.05$).

3.10. Resource Use, Fossils

3.10.1. Impacts of the Feedstuffs

In total, the highest use of fossil resource could be found for diet I (4452 MJ per t), followed by diet II (4259 MJ per t), diet III (4046 MJ per t), and diet IV (3772 MJ per t). The relative impact per ingredient varied between 0.09 MJ per kg feedstuff (calcium carbonate) and 34.60 MJ per kg feedstuff (monocalcium phosphate). The relative impact of SBM (7.73 MJ per kg feedstuff) was higher than the relative impact of RSM (3.43 MJ per kg feedstuff). All values and the relative impact per ingredient can be found in Table 20.

Table 20. Impact of 1 t feed on fossil resource use per ingredient (MJ per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (MJ per kg Feedstuff)
Rye	1683	1683	1683	1683	2.81
Barley	357	319	236	154	2.36
Soybean meal	1399	1051	626	0	7.73
Rapeseed meal	0	230	552	973	3.43
Ligonocellulose	42.5	31.9	21.3	0	2.12
Monocalcium phosphate	311	277	208	156	34.60
Calcium carbonate	0.75	0.71	0.71	0.66	0.09
Sodium chloride	5.59	5.59	5.59	5.59	1.24
Soybean oil	112	121	172	259	17.24
Feed additives	446	446	446	446	22.31
Grid Electricity Use Feed Mill	94.9	94.9	94.9	94.9	0.09
Total	4452	4259	4046	3772	

3.10.2. Performance-Based Impacts

The lowest mean performance-based impact on resource use could be found in diet III for both runs (run 1: 6.34 MJ·kg^{-1}, run 2: 6.28 MJ·kg^{-1}). The highest value could be found for diet I in run 1 (7.11 MJ·kg^{-1}) and for diet II in run 2 (6.90 MJ·kg^{-1}). Run 1 showed significant differences between diet I/II and diet IV. Diet I and II were similar to each other, and diet III was similar to diet I/II and diet IV. In run 2, no significant differences could be observed.

All values and significances regarding the performance-based impacts on resource use can be found in Table 21.

Table 21. Mean performance-based impact on water use per run and diet (MJ·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (MJ·kg^{-1})	Performance-Based Impact at Run 2 (MJ·kg^{-1})
I	7.11 ± 0.31 ^{a}	7.20 ± 0.37 ^{a}
II	7.03 ± 0.30 ^{a}	7.26 ± 0.37 ^{a}
III	6.66 ± 0.37 ^{a,b}	7.37 ± 0.42 ^{a}
IV	6.34 ± 0.29 ^{b}	6.37 ± 0.44 ^{a}

^{a,b} significant differences between the groups in each run ($p < 0.05$).

3.11. Land Use

3.11.1. Impacts of the Feedstuffs

In total, the highest soil quality index could be found for diet I (87,344), followed by diet II (83,893), diet III (80,753), and diet IV (76,305). The relative impact per ingredient expressed as soil quality index varied between 0.13 (calcium carbonate) and 487.3 (soybean oil.) The relative soil quality index of SBM (162.1) was higher than that of RSM (70.1) All values and the relative impact per ingredient can be found in Table 22.

Table 22. Impact of 1 t feed on land use per ingredient (soil quality index points per t).

Ingredients	Diet I	Diet II	Diet III	Diet IV	Impact per Ingredient (Soil Quality Index Points per kg Feedstuff)
Rye	44,836	44,836	44,836	44,836	74.7
Barley	9356	8365	6196	4028	62.0
Soybean meal	29,344	22,049	13,132	0	162.1
Rapeseed meal	0	4694	11,280	19,898	70.1
Ligonocellulose	396	297	198	0	19.8
Monocalcium phosphate	18.0	16.0	12.0	9.0	2.0
Calcium carbonate	1.1	1.0	1.0	0.9	0.13
Sodium chloride	4.2	4.2	4.2	4.2	0.93
Soybean oil	3167	3411	4873	7309	487.3
Feed additives	110	110	110	110	5.5
Grid Electricity Use Feed Mill	110	110	110	110	0.11
Total	87,344	83,893	80,753	76,305	

3.11.2. Performance-Based Impacts

The lowest mean performance-based impact on land use could be found in diet IV for both runs (run 1: 128.21 soil quality index points·kg^{-1}, run 2: 123.18 soil quality index points·kg^{-1}). In run 1, the highest value could be found for diet I (132.93 soil quality index points·kg^{-1}), while run 2 showed the highest value in diet III (138.93 soil quality index points·kg^{-1}). No significant differences were observed.

All values and significances concerning the performance-based impacts on land use can be found in Table 23.

Table 23. Mean performance-based impact on water use per run and diet (soil quality index points·kg weight gain^{-1}).

Diet	Performance-Based Impact at Run 1 (soil quality index points·kg^{-1})	Performance-Based Impact at Run 2 (soil quality index points·kg^{-1})
I	139.43 ± 6.1 [a]	135.62 ± 7.2 [a]
II	138.42 ± 5.9 [a]	137.67 ± 7.3 [a]
III	132.93 ± 7.3 [a]	138.93 ± 8.3 [a]
IV	128.21 ± 5.9 [a]	123.18 ± 8.9 [a]

[a] significant differences between the groups in each run ($p < 0.05$).

4. Discussion

4.1. Evaluation of the Used Methods

The calculation of the impact focused on the feed only. It excluded all emissions of the animal husbandry and the transport emissions of feed and pigs to the run location. As all housing conditions were equal for all pigs in both runs, no differences were expected. The origin of the feedstuffs was used by the online software application Opteinics® (BASF Lampertsheim GmbH, Lampertsheim, Germany) to refer to the correct way of production only. Therefore, average default values from the GFLI database were extracted for each country. Advantages/disadvantages that may exist due to a special way of the production of the feedstuffs are not included in the database.

4.2. Impacts of the Feedstuff on the Environment

The impact on climate change in soybean oil (7.35 kg CO_2 eq per kg feedstuff) and SBM (4.42 kg CO_2 eq per kg feedstuff) was extremely high when compared with the other ingredients in these diets. For SBM, however, Dalgaard et al. (2007) determined a lower impact, with 721 g CO_2 eq per kg SBM, which corresponds to 0.721 kg CO_2 eq per kg feedstuff [40]. The higher value in our study may be related to a special (eco-friendly) way of production. The origin of the soybean meal in the study by Dalgaard et al. was Argentina, which has no rainforest and, therefore, does not emit emissions due to clearances. This results in a lower impact on climate change. However, with regard to GFLI 2022, the relative impact on climate change for soybean meal from Argentina was given as 4087 kg CO_2 eq per t, which equals 4.087 kg CO_2 eq per kg feedstuff. The highest relative impact on climate change was found for soybean oil (7.34 kg CO_2 eq per kg feedstuff), which was probably related to the production process to a large extent. RSM as a substitute for SBM showed a lower impact on climate change (0.59 kg CO_2 eq per kg feedstuff). A study by Svanes et al. (2020) showed similar values of 0.7 kg CO_2 eq per kg feedstuff for rapeseed press cake [41]. The impact of rapeseed oil was 2.04 kg CO_2 eq per kg feedstuff when produced in Germany. Therefore, the usage of rapeseed oil as a substitute for soybean oil would result in a greater reduction in the impact on climate change.

The ozone depletion impact of all ingredients was similar. This indicates that changing the ingredients does not affect the ozone depletion impact of the feed.

Because rapeseed is not a legume, unlike soybeans, it is well known that it has a relatively high impact on soil acidification through fertilization and nutrient leaching [42]. The effect of fertilizer regulations and improved methods of field work are not covered in this type of study. The study by Svanes et al. (2020) assessed the impact on acidification as g PO_4^{3-} per kg feedstuff, while our study used kg P per kg feedstuff. Therefore, the values of 0.011 kg P per kg feedstuff used in the present study and those of 8 g PO_4^{3-} per kg feedstuff (which equals 0.008 kg PO_4^{3-} per kg feedstuff) in the previously mentioned study cannot be compared directly but, nevertheless, turned out to be at a similar level [41].

The impact of the feed on eutrophication is split into terrestrial, marine, and freshwater eutrophication. The results for terrestrial and marine eutrophication show the same tendency: a substitution of SBM by RSM resulted in an increase in the impact. This could be mostly related to the higher relative impact of RSM when compared to SBM for both factors. The reason is probably that rapeseed is known to force high fertilization rates and nutrient leaching [42]. As mentioned above, the acidification effect of fertilizer regulations and/or improved field practices was not included in this study.

However, the impact on freshwater eutrophication decreased when SBM was replaced by RSM. In this case, the impact of RSM was lower than that of SBM. The different result may be related to the fact that freshwater eutrophication includes phosphates, phosphoric acids, and total phosphorus, while terrestrial and marine eutrophication could be attributed to the emission of nitrogen-containing compounds. [37].

For all three types of eutrophication, the highest relative impact could be found for soybean oil. This may be mostly related to the processing process. In total, especially a reduction in soybean oil, may reduce the impact on all categories of eutrophication. For the terrestrial and marine eutrophication, the usage of SBM has an advantage when compared to RSM. For the eutrophication of freshwater, however, RSM showed a lower impact. A comparison to other studies regarding eutrophication was not made because other studies used different methods for evaluating eutrophication (for example, not being split into categories, or different evaluating methods leading to different units).

The impact of the feed on particulate matter was nearly the same when gradually substituting SBM with RSM. The results showed a slight tendency towards a higher impact of the diets with a higher share of RSM (to the eighth decimal point). This could be probably traced back to the usage of soybean oil showing the highest relative impact in this study. It may be concluded that a change in ingredients hardly affects the impact on particulate matter.

Replacing SBM with RSM showed a significant reduction in water use. The relative water use of SBM in this study was 2.9 times that of RSM. Rittler and Bykova (2022), however, found out that the usage of water for the production of soybean was below that for the production of rapeseed [43]. In their study, the water usage of soybean oil was 122 times higher than that of SBM. The same trend was also described by Gerbens-Leenes et al. for the footprint of blue water [44]. The different results in that study may be related to the slightly different ways of production.

For the usage of fossil resources, SBM showed a 2.2 times higher relative impact than RSM. Only the relative impacts of soybean oil, feed additives, and monocalcium phosphate were higher. For feed additives and monocalcium phosphate, this might be related to the production process, which used high amounts of energy [45,46]. For soybean oil, the higher impact is probably related to the production process, as SBM had a much lower impact. Overall, a reduction in SBM, soybean oil, feed additives, and monocalcium phosphate would result in a lower use of fossil resources. However, reducing the use of feed additives and monocalcium phosphate in the diets may be difficult to realize with regards to given requirements of the animals.

Referring to the results, a reduction in both SBM and soybean oil would decrease the land use. This is related to the high land use in South America needed to cultivate the soybean [4]. However, RSM had a significantly lower impact on land use compared to SBM.

4.3. Performance of the Animals

Substituting SBM with RSM in the compound feeds did not influence the feed intake of the animals. The highest feed intakes tended to occur with the feed containing 16% RSM (Diet III). When feeding 28% RSM in the present study, the average daily gains were not negatively affected. Nonetheless, numerically, the lowest growth performance was measured in the groups fed the highest amounts of RSM. The use of up to 8% RSM (group: RSM8) did not result in any negative effects on feed intake and the performance in weaning pigs [47]. In growing pigs, a supplementation of 12% and 17% had no negative effects on feed intake. Nevertheless, daily weight gains were partly lower in the groups fed higher amounts of RSM [48,49]. Studies performed by Parr et al. (2015) showed no negative effects of diets containing 20% or 30% RSM compared to a control diet in young pigs [50]. In contrast, Lee and Woyengo (2018) found a negative correlation between the amounts of cold pressed canola cake (up to 40% in the diet) and the average daily feed intake [51]. Similar findings were published by Ellner (2021) after feeding high amounts of RSM to young animals [22]. Wheat- and rye-based diets containing either 20% SBM or 30% RSM were fed to piglets aged 28 days. Particularly, in the rye-based diets, the feed intake, as well as the daily weight gains, were affected negatively when 30% of RSM was used. Generally, it must be stated that studies focusing on the use of RSM (up to 15%) in the feed of weaned piglets showed that the increased use of RSM resulted in partly lower, but also higher, weight gains [52,53]. Feed intake is, among other things, affected by palatability of the feedstuffs [54]. Landero et al. (2018) showed a higher palatability for diets containing 20% SBM compared to diets with 20% RSM in a direct choice experiment with weaned piglets, although this did not result in generally lower feed intakes of the diets containing RSM in a subsequent study [55]. These deviating results may indicate that the individual composition or quality of the RSM might be different between the feedstuffs, as it is known that varieties do differ in the content of anti-nutritive substances having an impact on palatability and growth performance [56,57]. Moreover, the inclusion of 30% RSM in the study of Ellner (2021) increased the content of indigestible fiber, such as acid detergent lignin, significantly in the diets [22]. Generally, it can be assumed that RSM contains twice the fiber content in comparison to SBM [58]. It is known that high amounts of fiber in the diet can affect the feed intake, as well as the daily weight gains, especially in young pigs [59]. Substituting SBM with RSM resulted in higher feed conversion ratios when 16% or 28% RSM were used in the diets. Similar findings were published by Thacker (2001), where 15% SBM was substituted with 22% RSM [60]. Interestingly, the inclusion of increasing levels of RSM (up to 14% compared to an SBM diet) had no negative effect on the feed conversion ratio, whereas the highest level of RSM in this study (21%) had a negative effect on the feed conversion ratio [61]. A negative effect on the feed conversion ratio can be attributed to a reduced digestibility. A previous study by Mitaru (1984) showed reduced effects of rapeseed hulls on ileal digestibility [62]. A reduced protein digestibility when using higher amounts of RSM was already found by Keady and O'Doherty (2000). Ellner (2021), who found a lower digestibility due to the use of RSM, also determined a higher feed conversion ratio by very high contents of RSM in the diets [22].

4.4. Impacts of the Feedstuffs in Relation to Performance

Overall, for this type of calculation, the difference between the different diets turned out to be smaller than the total values from the feed, and the order (from high to low values) changed for some factors. This suggests that evaluating the environmental impact of different feeding systems only in terms of the impact of feed is an inappropriate method and should be reconsidered. The method presented in the current study seemed to be a good option to compare the results of a LCA with the performance of the animals.

The replacement of SBM with RSM resulted in an increase in the environmental effect (corrected to the weight gain) on acidification, terrestrial eutrophication, marine eutrophication, particulate matter, and water use. A decrease in the corrected environmental impacts could be found for climate change, freshwater eutrophication, and resource use. The impacts on ozone depletion and land use showed no clear results. Published studies regarding growing-finishing pigs often show the impact up to slaughter. This has the advantage that the influence up to the finished product that can be shown is usually calculated on the basis of the slaughter yield. This is not possible with the applied phase–by-phase approach (which only considers rearing). However, the method used makes it possible to evaluate individual phases. As to the authors' knowledge, there are currently no other studies using this method, and further studies would be desirable to generate a larger database of results for individual production phases.

5. Conclusions

Feeding diets containing increased amounts of RSM to weaned piglets showed no negative effects on feed intake and weight gains of the animals. Even though the feed conversion ratio was negatively affected by high amounts of RSM, a lower CO_2 footprint or a markedly lowered impact on climate change was achieved. In addition, the performance-based sustainability analyses showed a lower negative impact on freshwater eutrophication and resource use. On the other hand, the diets containing higher amounts of RSM showed negative influences on acidification, terrestrial eutrophication, marine eutrophication, and the emission of particulate matter. Since soybean oil has a high environmental impact as a feedstuff, the use of a regionally produced alternative should also be considered here. The shown influence of animal performance, affected by the feed on the environmental impact, indicates that the parameter performance should always be included and that a simple consideration of the feed is not sufficient.

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