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Utilization of Brewer's Spent Grains and Agricultural Residues in Pig Feed Formation

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Abstract: In this study, brewer's spent grains (BSG)-raw matrix was technologically and functionally improved by adding natural active ingredient carriers (crushed wheat, rapeseed, and pumpkin seed press cake) and using planetary roller extrusion and used as feed additive for pigs. Feeding trials were run for 189 days using 60 pigs with an age of 28 days. Pigs were grouped in a control group (fed with organic basic feed) and two experimental groups (fed with BSG 1 or BSG 2 in addition to organic basic feed). The 20 animals per group gained similar weight in the control group (306 g day^{-1} and 725 g day^{-1}) and in the group fed with BSG 1 (282 g day^{-1} and 627 g day^{-1}) or BSG 2 (250 g day^{-1} 598 g day^{-1}) in addition during rearing and fattening phases, respectively. Carcass evaluation revealed that meat quality did not differ between control and experimental groups. The BSG-based feed formulations tested seem to not result in negative effects on weight gain nor on meat quality. Animals were generally of good health and marketable quality, and thus the outcomes of this study are expected to contribute to an improved utilization strategy of brewer's spent grains from breweries.

Keywords: extrusion; feed; animal husbandry; side-stream valorization

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1. Introduction

In Germany, 93 million hectoliters of beer were produced in 2017. This resulted in approximately 1860 metric kt of brewer's spent grains (BSGs), when 20 kg hectoliter^{-1} [1,2] on average is produced as food-grade byproduct. BSGs are solids that are separated after soaking and boiling the previously cleaned, malted, and milled grains. In the mashing process, starch and proteins are broken down by malt enzymes [3]. At a temperature of 75–78 °C, BSGs are discharged from the beer-making process directly into silos. In small and medium breweries, they are often given away to local farmers. Due to a water content of approx. 80% (*w*/*w*) and the presence of nutrients, it is a rapidly perishable product [3,4]. Inoculating BSG with lactic acid bacteria creates more scope for microbiologically safe processing of BSG [5]. The method of ensiling, for instance, in fermentation barrels with lactic acid bacteria is thereby an easily applicable method which even allows longer storage and processing as feed for organic animal husbandry since no chemical ensiling agents are needed. Furthermore, fermentation with a specific microorganism such as *Bacillus velenzensis* can result in a degradation of lignocellulose and in an increase in soluble sugar and protein contents [6], thus increasing the nutritional value of BSG. Up to now, chemical ensiling agents have usually been used, which are easier to handle due to their heat resistance. Ensiling with lactic acid bacteria opens a use as organic feed.

Generally, BSGs are rich in valuable nutrients and proteins as well as neutral detergent fibers but fat and carbohydrates can also be found [7]. Particularly, the enrichment in essential amino acids such as lysine [3] may result in improved weight gains during breeding [7]. Due to their beneficial biochemical composition, BSGs have been used as feed for various animals such as pigs, chicken, lambs, and cows [8–13]. When dried BSGs were fed to slow-growing broiler chicken, no change in carcass yield and an increase in relative weight of gizzard and pancreas as well as a reduced growth performance were found [8]. Due to the high fiber content of BSGs, their use as feed for pigs is challenging. Pigs have a minimum requirement for fibers and are unable to digest fiber-rich (>6%, *w*/*w*) feeds [14] However, the high protein content of BSGs may counterbalance negative nutritional effects. Mukasafari et al. have shown that BSGs can replace 50% (*w*/*w*) of sow and weaner meal [13]. Ngodigha et al. found that including 20% (*w*/*w*) BSG in growing pig diets is cost-effective without negatively affecting blood metabolites [9]. Preparing the diets of weaned pigs with 20% (*w*/*w*) BSG and 0.1% (*w*/*w*) multienzymes was also found by Boontiam et al. to be an effective approach to improve growth, nutrient digestion, and absorption as well as immunity and antioxidant capacity [12]. Lee et al. treated cereal-based diets with a carbohydrase complex. They found, for instance, that arabinoxylan was partly degraded as well as higher AID high-molecular weight compounds (starch, non-cellulosic polysaccharides) [15]. Liu et al. found that the supplementation of diets with wheat bran fiber improves the growth performance and gut health in Xiangcun pigs. They concluded that this might be due to "improved antioxidative capacity and intestinal epithelium functions, as well as microbial fermentation in the intestine". They further concluded that wheat bran fibers are an attractive source of dietary fibers [16]. However, it was also concluded earlier that the performance effect is also dependent on the management practices on the farm [13]. Thus, more feeding experiments are needed considering individual management practices to develop BSG-based feeds.

To further foster the use of BSGs and agricultural residues in feed formation, this study aimed at characterizing their potential as ingredients for animal nutrition. The BSG-raw matrix was technologically and functionally improved by adding other natural active ingredient carriers (crushed wheat, rapeseed, and pumpkin seed press cake) to improve the nutritional and energetic values of feed and using the possibilities of planetary roller extrusion as a technique to produce feed blends. Finally, the developed formulations were provided to pigs in addition to organic quality basic feed. The outcomes of this study are expected to contribute to an improved utilization strategy of BSGs from breweries and agricultural residues and to a reduction of waste streams. This study further contributes to strategies for the use of residues with high fiber contents, and thus paves the way to novel future feed preparations.

2. Material and Methods

2.1. Material for Feed Preparation

In this study, BSGs, crushed wheat, rapeseed, and pumpkin seed press cake as well as organic quality basic feed were investigated. Residues from rapeseed and pumpkin seed oil production were selected due to their nutritional quality and performance in a previously carried out acceptance test with pigs. Wheat was obtained freshly crushed and served as a technological aid in extrusion. All materials were of organic quality and sourced regionally except organic rapeseed press cake, which was regionally not available at the time.

2.2. Ensiling of Prepared Feed

About 50 kg of hot BSG (approx. 78 °C) was taken from the brewing process and filled directly into a fermentation barrel. After a cooling period of 24 h, the ensiling process was started. At a temperature of about 32 °C, 10 mg of ensiling aid (Bio-Sil, Dr. Pieper GmbH, Wuthenow, Germany) was added per kg of BSG and ensiling was carried out for 14 days at room temperature. After 14 days, the ensiled BSGs were used for extrusion.

2.3. Extrusion of Ensiled Feed

Extrusion of the ensiled BSG was carried out using a planetary roller extruder (L-WE50/800-M3, Entex GmbH, Bochum, Germany). About 10 kg of ensiled BSG per hour were fed to the extruder via a continuously operating feeder (DDW-M-DSR28, Brabender, Duisburg, Germany) and processed via two roller section modules at about 65 °C and 2 bar. The temperature was chosen to maintain the nutritional quality. Two BSG-extrudates containing (*w*/*w*) 30% BSG silage, 55% crushed wheat, and 15% rapeseed press cake (BSG 1), or 15% pumpkin seed press cake (BSG 2) were produced. Crushed wheat and press cakes were used to improve the taste as pure BSGs were not accepted by pigs in a preliminary study. The moisture content was at least 31% (*w*/*w*).

2.4. Feeding Trial

The basic questions of the feed acceptance and feeding trials were whether the provided BSG-based feed would be accepted and eaten by the pigs, and in what quantity it would be consumed, as well as what effects would be seen on the increase in live weight during piglet rearing compared to a control group. The feeding trials were performed at the Teaching and Research Station for Animal Breeding and Husbandry (LVAT).

For the feeding trial, 60 pigs with an age of 28 days, consisting of 31 animals (crossbreds from Pietrain and German Landrace breeds), and 29 animals (crossbreds from German Landrace and German Edelschwein breeds), including 13 females and 47 castrated males, were used. The pigs were purchased from the farm pig breeding facility in Grießen (Bauern AG Neißetal, Schenkendöbern, Germany), and weighed on delivery. The pigs with live weights between 6.3 kg and 12.3 kg were distributed so that the groups had similar mean weights. Worming and treatment with a preparation of colistin sulfate and zinc oxide were carried out immediately after housing. Until 30 kg live weight, rearing fodder was used. From about 30 kg live weight pre-fattening fodder and from about 75 kg live weight final-fattening fodder were used (Table 1). The feeding experiment started at an age of 42 days and was conducted in a conventional barn with slatted floors with separate lying area. Straw was offered for occupation. The control group (CG) as well as the experimental groups 1 (G 1) and 2 (G 2) consisted of 20 pigs each. Organic quality basic feed was offered ad libitum in feed troughs with several feeding places for all three groups. The BSG-based extrudates were offered to G1 and 2 as additional feed in troughs at a ratio of 1:10 (*w*/*w*, basic feed/BSG-based extrudates); CG was only fed with basic feed. The feed quantity of additional feed was calculated according to theoretical feed consumption. The amount of BSG-based feed offered was increased by 10 g per animal on a weekly basis from 40 g at week 1 to 100 g at week 7 and remained constant afterwards until the end of the 189-days-long feeding trial. Uneaten residues were balanced the following day and fresh feed was weighed in again. Furthermore, live weight gain was determined and health status assessment was carried out.

Table 1. Organic quality feed mixtures for piglet rearing, pre-fattening, and final-fattening phases.

	Rearing [%, *w*/*w*]	**Pre-Fattening [%, *w*/*w*]**	**Final-Fattening [%, *w*/*w*]**
Mineral feed	2.5	2.5	1.7
Wheat	25.0	10.0	0
Rye	10.0	23.3	73.3
Triticale	22.5	30.0	0
Barley	0	0	10.0
Oat	10.0	0	0
Corn	10.0	16.7	0
Soybean cake	20.0	7.5	5.0
Pea	0	10.0	10.0

2.5. (Bio)Chemical Analysis

2.5.1. Analysis of Feed Composition

The nutritional values and amino acid contents in feed materials were determined by near infrared (NIR) spectroscopy and analyzed by the AgroLab LUFA GmbH (Kiel, Germany) according to VO(EG) 152/2009 III, respectively.

The ADF value (acid detergent fiber) includes the indigestible part of the cell wall components such as cellulose and lignin. The NDF value (neutral detergent fiber) indicates the plant cell wall components in a feed such as cellulose, hemicellulose, pectin, and lignin. Subtracting the ADF from the NDF value gives the fermentable fiber content of the feed, which nurtures the microflora in the animal's intestine.

2.5.2. Evaluation of the Carcass and Meat Quality

Due to the different growth of the pigs, the slaughter of the individual animals took place gradually. A total of 46 out of 60 animals were slaughtered until the end of the feeding trial. Animals that had not reached a slaughtering weight of at least 120 kg by then were no longer included in the evaluation. Carcass evaluation was performed directly. The analysis of the meat samples was done randomly.

The following parameters were determined as slaughter performance data according to the guideline of the German Federal Association of Cattle and Pig (2019): carcass length (cm), back fat thickness (cm), mean of measuring points at loin, middle and ridge, side fat thickness (cm), fat area, chop area (cm^2) at the chop cut between 13th/14th rib, and lean meat area (cm^2) at the chop cut between 13th/14th rib (cm^2). Furthermore, rib, lean meat percentage (%), pH value 45 min after slaughter on the chop/ham, conductivity 45 min after slaughter on the chop, and marbling were assessed. Visual assessment of meat was carried out on a 1–6-point scale and included color brightness after 24 h using an optoelectronic measuring probe to differentiate between light and dark meat. Furthermore, organs were visually assessed, and drip juice loss was determined. To determine drip juice loss 24 h after slaughter, 2 cm thick slices were cut from the chop, weighed, and stored hanging in a waterproof bag at 4 °C. After 24 h, the sample was weighed back.

2.5.3. Fecal Analysis

To investigate worm infestation, fecal samples were collected, pooled, and examined microscopically after preparing a suspension.

2.5.4. Determination of Trolox Equivalent Antioxidant Capacity

Pool samples of different meat parts or fat were extracted with methanol. These extracts were used for the determination of the trolox equivalent antioxidant capacity (TEAC) as described recently [17].

2.5.5. Determination of Dry Matter

The dry matter of the pool samples was determined using a moisture analyzer MA 150 (Sartorius, Goettingen, Germany).

2.5.6. Analysis for Tocopherol

The extracted fat was diluted in isooctane and analyzed by high-performance liquid chromatography. Separation of tocopherols (α-, γ-, and δ-tocopherol) was performed on a Zorbax Sil column (5 µm, 4.6 × 250 mm, Knauer, Berlin, Germany) using isocratic isooctane/ethyl acetate 96/4 (*v*/*v*). Fluorescence detection was performed using a Merck-Hitachi F 1000 fluorescence spectrophotometer (Extinction 296 nm; Emission 330 nm). External calibration was performed by dissolving the standards in isooctane in the concentration range of 2.5 and 20 µg mL^{-1}.

2.5.7. Stability Index Determination Using Rancimat Method

As a criterion for the oxidative stability of the fat, the induction time was determined using the rancimat method. In this process, a constant flow of air is passed through 5 g of sample heated to 110 °C. The sample was then subjected to an oxidation process. The volatile decomposition products formed during the oxidation process were transferred in a measuring cell using deionized water and measured conductometrically. The induction time was determined by continuously recording the conductivity–time curve and results from the specific point in time at which the slope of the conductivity changes.

2.5.8. Peroxide Value Determination

Peroxide value was determined according to Wheeler in a microanalysis approach [18]. One hundred milligrams of extracted fat were weighed into an Erlenmeyer flask. A total of 30 mL of solvent (acetic acid/chloroform 3:2, *v*/*v*) and 0.5 mL of saturated potassium iodide solution were added. After stirring for 60 s, 30 mL of distilled water was added and titrated potentiometrically (TitroLine® 7000, Pt 61 electrode, Xylem Analytics Germany Sales GmbH & Co. KG, Weilheim, Germany) with sodium thiosulfate (0.001 N). The end point of the titration was detected by automatic titration based on the strong change of the electrochemical potential.

2.6. Statistical Analysis

Statistically significant difference of feed compositions was determined using *t*-test and the software SigmaPlot version 11.

3. Results and Discussion

3.1. Analysis of Feed Composition

The composition of the organic quality feed, which was used as basic feed for rearing, pre-, and final-fattening, is shown in Table 1. The feed was mixed by a farm in Brandenburg (Germany), the soya and mineral feed contained was bought in, and all other components came from the farm's own production. The organic mill Gut Rosenkrantz is subject to the requirements and controls of the "Bioland" guidelines.

The listed nine constituents varied in their weight-specific contents based on the nutritional requirements of the pigs in the different breeding stages. One of the objectives of this study was to assure that the extruded feeds (BSG 1 and BSG 2) had a similar metabolizable energy content of 13–15 MJ kg^{-1} as found in the organic quality basic feed. This expectation could be met with values for BSG 1 of 13.9 MJ kg^{-1} and for BSG 2 of 14.7 MJ kg^{-1} (Table 2). Contrarily, the protein contents (*w*/*w*) of the extruded feeds were higher (BSG 1: 14.7%, BSG 2: 20.8%). The starch content was 43% (*w*/*w*) in BSG 1 and BSG 2, and comparable to rearing fodder but 8% (*w*/*w*) less than the content in pre-fattening fodder (Table 2). Fat analysis revealed a higher fat content in BSG 1 and BSG 2 than in rearing and pre-fattening fodder.

The crude fiber content, which plays an important role in satiety and intestinal health, but also the contents of ADF and NDF were increased in BSG 1 compared with BSG 2 (Table 2). However, both BSG 1 and 2 contained only half of the ADF content of the organic quality basic feed. Contrarily, BSG 1 had a NDF content which was comparable to the organic quality basic feed, while the content in BSG 2 was reduced. Nevertheless, the compositions of BSG 1 and 2 were not statistically different to the organic basic feed applied.

The fermentable fiber content forms the basis for the microflora in the intestine. It contributes to intestinal health when the colon is supplied with enough bacterial fermentable substances. The hard-to-digest carbohydrates such as cellulose, hemicellulose, beta-glucans, pentosans, pectins, and inulins promote the establishment of beneficial bacteria (lactic acid bacteria/bifidobacteria), and thus intestinal health. As the largest immune organ, a healthy intestine ensures a high level of immune competence. However, a high fiber content also contradicts a complete digestion by pigs [14,19]. Thus, replacing parts of the rapeseed and pumpkin seed press cakes with BSGs resulted in a lowered fiber content of the final feed (Table 2).

It was of interest that the amino acid contents (lysine, methionine, cysteine, threonine, valine, isoleucine, leucine, glutamic acid, and tyrosine) were similar or even higher in the extrudates BSG 1 and 2 compared to the initial organic quality basic feed for rearing and pre-fattening (Table 3). All components of the basic feed are organic, including the mineral feed, which means it contains no free amino acids or enzymes. Therefore, there is less than in conventional feed. The amino acids recommended for pig feed are lysine, methionine, cysteine, threonine, valine, isoleucine, leucine, and tyrosine, which were all found in this study. Furthermore, the amino acids tryptophan, arginine, histidine, and phenylalanine are recommended [20] but were not detected. Thus, it was to be shown that amino acids present in extruded feeds promote live weight gain and overall well-being of the animals in this stage.

3.2. Feed Acceptance Test and Feeding Trials

3.2.1. Feeding Trial

Due to the promising composition of the produced extrudates BSG 1 and 2, both were used for feeding trial. Furthermore, both extrudates were not statistically different from organic basic feed. The two extrudates were supplied together with the organic quality basic feed in a weight-based ratio of 1:10. Due to the limited ability of pigs to digest fibers, the ratio was not further increased. The feed with BSG 1 was always completely eaten by the animals after a habituation period of 10 days, during which feed residues could still be found in the trough. Every day, the animals demanded the food expectantly and loudly. After a short time, the trough was eaten empty. At the beginning, the 20 animals fed with BSG 2 did not finish their daily portion. However, this behavior changed and after 12 weeks pigs started to finish the daily portion. In total, the group with BSG 1 ate 299 kg and the group with BSG 2 216 kg of additional feed throughout the feeding period.

For occupation, straw was provided to the control and experimental groups. However, for pigs, occupation with forage is also a welcome change. Due to this lack of opportunities in conventional pig farming, behavioral disorders such as tail biting or chewing of conspecifics develop in some cases [21]. Such behavior was not observed in the feeding trial. Animals were predominantly of good health. Only 5 of 60 animals in CG had to be treated with antibiotics.

In the 189-days-long feeding trial, different amounts of feed were consumed between the groups. The 20 animals in the CG consumed 5559 kg organic quality basic feed, the 20 animals in G 1 4630 kg, and the animals in G 2 3883 kg. At the same time, the 20 animals in G 1 and 2 consumed additionally 299 and 216 kg of BSG 1 and BSG 2, respectively. Reasons for the reduced feed consumption could be that the BSG-based extrudates provided distraction and occupation, and thus the animals spent less time consuming it. It is, however, more likely that the fiber content was still high in the BSG-based feed which resulted in a greater satiation. Mateos et al. and Yaakugh et al. found a similar result. Their experiments with BSG supplied at different ratios revealed that feed intake and consequently weight gain were reduced with increasing fraction of BSG [14,19]. However, no effect on weight gain and feed conversion was observed when pigs were fed up to 20% (w/w) with BSG [9].

The different consumption behaviors between all groups resulted in an unequally weight gain (Figure 1). The daily weight gain (Table 4) revealed that, on mean, the 20 animals per group gained more in CG (306 g day^{-1} and 725 g day^{-1}) than in G 1 (282 g day^{-1} and 627 g day^{-1}) and G 2 (250 g day^{-1} 598 g day^{-1}) during rearing and fattening phases, respectively. A difference was found between the minimum and maximum weight gain (Table 4) among all groups irrespective of whether organic quality basic feed or additional BSG-based feed was used. For instance, those pigs which were fed with BSG 1 during rearing gained weight at 476 g day^{-1}, which was 160 g day^{-1} more than pigs fed with BSG 2. Also, for those animals which gained minimum weight, BSG 1 was superior to

BSG 2. However, BSG 1 seems not necessarily to be the better feed as pigs which show a maximum weight gain and were fed with BSG 2 during fattening phase gained 120 g more per day than pigs fed with BSG 1. The metabolizable energy in BSG-based feeds (Table 2) is slightly higher than those in the basic feed, but at the same time the protein and amino acid contents are low.

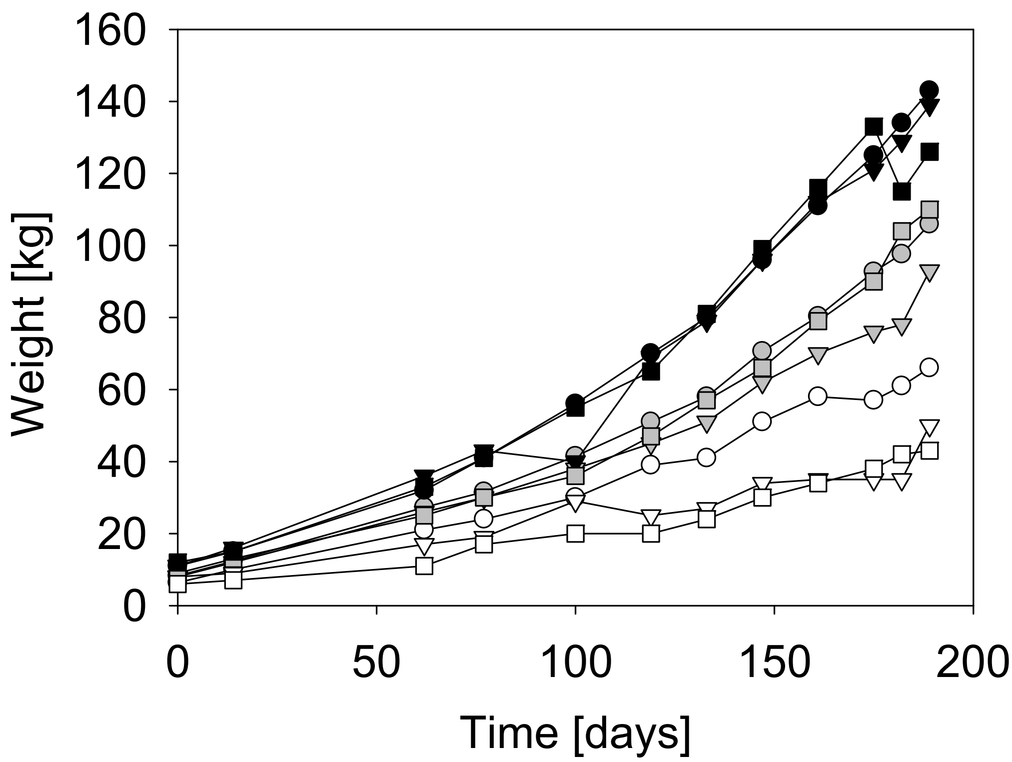

Figure 1. Mean (gray symbol), minimum (white symbol), and maximum (black symbol) individual weight gain of the 20 pigs within control group (CG, circle) as well as within experimental groups G 1 (triangle) and G 2 (quadrate) during feeding experiment.

The pigs eat according to their energy needs. With the amount of feed they eat, they can cover their energy requirements, but not the amino acid requirements for growth and meat production. From the weight gains reported earlier, it can be seen that the values found in the rearing and fattening phases (Table 4) are comparable with the weight gain found earlier [9,14,22]. Ikurior reported a gain of around 400 g per day when BSGs were supplied at different ratios with ground maize grain of around 1 kg per day [22]. Ngodigha et al. found a gain of 440 g per day when 10% (*w*/*w*) of maize–soybean was replaced with BSG to which 0.5% lysine-hydrochloride was added [9]. Mukasafari et al. found a mean daily weight gain of 308 g, 317 g, 266 g, 125 g, and −153 g when (*w*/*w*) 0%, 25%, 50%, 75%, or 100% BSGs were supplied, respectively [13].

Fecal analysis revealed that none of the samples contained roundworm eggs. Possible infestation would also have been apparent when the organs were inspected after slaughter. Milky spots would have been visible in the liver, caused by the migratory larvae of *Ascaris suum*. Thus, low weight gain may therefore not be a consequence of an infection.

3.2.2. Evaluation of Carcass and Meat Quality

The carcass evaluation revealed only slight differences between control and experimental groups (Table 5) and the meat quality did not differ between control and experimental groups.

Higher TEAC values were found in the meat than in the fat and the highest values were detected in the control group. In the experimental group fed with BSG 1, the TEAC was somewhat higher than in the group fed with BSG 2 (Table 6). Compared to the pure fat phase, meat also contains other antioxidant substances such as proteins, peptides (e.g., glutathione), and enzymes (e.g., catalase) [23]. It is therefore reasonable that higher TEAC values were determined in the meat.

It was to be investigated to what extent a possible tocopherol content in the oil press residues (rapeseed and pumpkin seed) could have an influence on well-being. For this, the sum of α-, γ-, and δ-tocopherol for the different samples was determined. Samples of rapeseed press cake (66.9 mg per 100 g fat) and pumpkin seed press cake (47.0 mg per 100 g fat) had elevated levels. However, this was not reflected in fat samples of G 1 (0.6 mg per 100 g fat) and 2 (0.5 mg per 100 g fat), as they were below the CG value (0.9 mg per 100 g fat). Similarly, no effect of antioxidant-rich feeding on the content of tocopherols in muscle meat was observed in previous studies [24].

The peroxide value in all meat and fat samples was so low that oxidation was not advanced. Furthermore, the values of the stability index showed only minor deviations and values between 0.92 and 1.18 were found. Consequently, the BSG-based feed had no negative influence on the quality of meat and fat.

The term bioeconomy stands for various sectors and combines activities in agri- and aquaculture, forestry, production of food and feed, production of bio-based chemicals, and so on [25]. It is commonly accepted that biomass should be holistically used. However, often the properties of the biogenic resources do not allow, for instance, the production of feed from fiber-rich materials. Thus, the aim of the current work was to make use of unconventional materials and to guide to a cascading use [26].

A constant growth of pigs during feeding trials using the prepared formulations has been achieved and the meat quality was not negatively impacted. Thus, it might be concluded that fiber-rich materials can be used to a larger extend for feed preparation. However, we should clearly admit that further health parameters of the pigs should have been determined and blood samples should have been analyzed to clearly indicate the condition of the animals. Furthermore, feeding trials were carried out with only one animal species. This limits the application of the results and further research should be carried out to investigate the use of fiber-rich biogenic resources in feed formulation, which would certainly contribute to a cascading use and a sustainable bioeconomy.

Table 2. Composition of rapeseed press cake, pumpkin seed press cake, brewer's spent grains-based extrudates (BSG 1, BSG 2) as well as feed for rearing, pre- and final-fattening (ADF = acid detergent fibers; NDF = neutral detergent fibers; n. a. = not available).

Material	Ash [%, *w*/*w*]	ADF [%, *w*/*w*]	NDF [%, *w*/*w*]	Fiber [%, *w*/*w*]	Protein [%, *w*/*w*]	Starch [%, *w*/*w*]	Fat [%, *w*/*w*]	Metabolizable Energy * [MJ kg^{-1}]
Rapeseed press cake	2.2	14.6	20.8	11.9	27.0	n. a.	n. a.	n. a.
Pumpkin seed press cake	0.9	1.9	0	6.3	52.1	n. a.	n. a.	n. a.
BSG 1	0.5	4.4	16.8	4.2	14.7	42.7	5.7	13.9
BSG 2	3.0	3.9	9.6	2.3	20.8	43.0	5.2	14.7
Rearing	1.4	7.0	12.7	3.7	13.0	42.4	3.5	13.4
Pre-fattening	0	7.9	14.6	3.2	12.8	51.2	2.7	13.6
Final-fattening	0.3	8.1	18.2	3.7	11.8	n. a.	n. a.	n. a.

* Metabolizable energy (ME) was calculated by AGROLAB LUFA GmbH using following equation: ME [MJ kg^{-1}] = 0.0205 × digestible crude protein [g kg^{-1}] + 0.0398 × digestible crude fat [g kg^{-1}] + 0.0173 × starch [g kg^{-1}] + 0.0160 × sugar [g kg^{-1}] + 0.0147 × digestible residue [g kg^{-1}]. The digestible residue is the digestible organic matter minus the sum of digestible crude protein, digestible crude fat, starch, and sugar [27].

Table 3. Composition of brewer's spent grains-based extrudates (BSG 1, BSG 2) as well as feed for rearing and pre-fattening. Cysteine was determined as cysteic acid. (Analysis in original substance.).

Material	Lysine [%, *w*/*w*]	Methionine [%, *w*/*w*]	Cysteine [%, *w*/*w*]	Threonine [%, *w*/*w*]	Valine [%, *w*/*w*]	Isoleucine [%, *w*/*w*]	Leucine [%, *w*/*w*]	Tyrosine [%, *w*/*w*]	Glutamic Acid [%, *w*/*w*]
BSG 1	0.7	0.3	0.3	0.6	0.8	0.6	1.1	0.5	3.8
BSG 2	0.7	0.4	0.4	0.6	1.0	0.8	1.5	0.7	5.0
Rearing	0.8	0.3	0.3	0.6	0.7	0.7	1.2	0.5	3.6
Pre-fattening	0.6	0.2	0.3	0.4	0.5	0.5	0.8	0.3	3.0

Table 4. Mean, minimum, and maximum daily gain in weight (CG = control group; G 1 and G 2 = experimental group).

	Rearing			Fattening		
	Mean [g Day^{-1}]	Min [g Day^{-1}]	Max [g Day^{-1}]	Mean [g Day^{-1}]	Min [g Day^{-1}]	Max [g Day^{-1}]
CG	306	222	444	725	407	1084
G 1	282	175	476	627	291	877
G 2	250	127	317	598	209	999

Table 5. Mean values of the most important parameters of carcass evaluation (CG = control group; G 1 and G 2 = experimental group; p.m. = *postmortem*).

Parameter	Unit	CG	G 1	G 2
Carcass mass	kg	100.6	101.1	99.5
Carcass length	cm	107.7	106.8	108.0
Back fat thickness	cm	2.9	2.9	3.0
Side fat thickness	cm	4.3	4.4	4.6
Fat area	cm^2	28.6	30.2	30.3
Chop area	cm^2	39.2	41.0	41.7
Lean meat content	% (*w*/*w*)	50.1	50.1	50.8
pH value in cutlet 45 min p.m.	-	6.3	6.2	6.3
Conductivity 45 min p.m. in cutlet	mS	3.5	3.6	3.4
Conductivity 24 h p.m. in cutlet	mS	5.5	5.5	5.5
Drip juice loss	% (*w*/*w*)	3.5	3.5	3.3
Marbling	Points	4.8	3.4	4.0
Color brightness	% (*w*/*w*)	70.2	72.1	67.4

Table 6. Mean trolox equivalent antioxidant capacity (TEAC) in piglets (CG = control group; G 1 and G 2 = experimental group).

Sample	Material	TEAC [μmol TE g^{-1} Dry Matter]
CG	Meat	518.9
	Fat	78.0
G 1 (BSG 1-based feed)	Meat	494.4
	Fat	107.2
G 2 (BSG 2-based feed)	Meat	387.8
	Fat	72.8

4. Conclusions

It was shown that processed BSG and agricultural residues can be used in pig feed formation. The use of residues is particularly interesting, as less feed is needed that would also be suitable for human nutrition. The BSG-based feed formulations did not result in negative effects on meat quality and the animals were generally of good health. Similar weight gains were obtained compared to the control. However, the high fiber content of the BSG-based feeds and consequently a faster saturation may potentially affect the weight gain. Nevertheless, it can be concluded that BSG- and agricultural residue-based feeds can be used to supplement parts of ground fodder, which will eventually result in reduced waste formation.

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