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Supplementary information

Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply

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SUPPLEMENTARY INFORMATION

Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply

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1. Current uses and feed use potential of food system by-products and residues

The food system by-products and residues include all the non-food parts produced in the crop, livestock and fish production and processing stages. In crop production there are two kinds of leftovers: crop residues and crop processing by-products. Crop residues refer to the plant material remaining after harvesting, including parts such as straw, leaves, stalks, roots and stover. Crop residues are typically high in fibre but with limited other important nutritional components and can cause digestibility problems. They are often used as basic caloric and fibre supplements, mostly in ruminant diets that add value to residues converting them to useful food and non-food goods and services. The use of crop residues as feed is most common in farming systems that produce both crops and livestock, especially in tropical semiarid and subhumid environments where most of the world's poor smallholders are located. Their actual use varies greatly. They provide a buffer for periods with droughts and other disturbances and contribute importantly to soil organic matter and therefore the sustainable removal rates should be based on the quantities of crop residues that must be left on field to maintain soil quality and reduce erosion (Scarlat et al., 2010; Monforti et al., 2013). The removal of nutrients when harvesting the crop residues can be compensated by conservation tillage, adequate crop rotation or adding manure (Scarlat et al., 2010). Despite their local importance in smallholder agriculture, their use as feed has been decreasing because of agricultural intensification mainly related to less residues being available and of less nutritious quality due to genetic selection and intensive livestock production requiring higher quality feed (Steinfeld et al. 2006).

Crop processing by-products refer to the side/co-products produced in food processing such as cereal by-products, oilseed by-products, tuber peels, molasses and pulps that are not used directly as human food. They are produced as by-products of food processing so their collection and further processing to feed is common and they are widely used as livestock and aquaculture feed ingredients.

Livestock by-products include all other parts of the animal when meat is extracted, such as offal, fat, skin, feet, bones, feathers and blood processed. Up to one half of the livestock biomass produced in meat, dairy and egg industries is not consumed by humans (Meeker & Hamilton, 2006). They can be converted to processed animal protein such as protein meals, blood meal, hydrolysed feather meal and to rendered animal fat and oil products. These livestock by-products include high amounts of important nutrients that can be converted to human edible food by circulating them through feed in livestock and aquaculture production. Their feed use is controlled by food safety regulations to avoid spreading of diseases, such as bovine spongiform encephalopathy (BSE) through feed. Currently, in the EU the high-risk by-products (categories 1 and 2 in the EU legislation), including e.g., bovine spinal cord and fallen stock, are mainly used as fuel or fertilizer (EFPRA, 2019; EC, 2009; EC, 2011). The main markets for the low-risk protein products (category 3), such as materials from slaughterhouse that have been passed fit for human consumption but are not intended to be consumed directly, are used as fertilizers and pet food, while the fat products are commonly used as feed and in oleochemistry (EFPRA, 2019).

Fish by-products refer to all other parts of fish and seafood when meat is extracted. Through a reduction process to fish meal and fish oil, they can be converted to valuable by-products that are widely used in aquaculture as well as in livestock (pig and poultry) feed. Approximately 25-35% of current fishmeal and fish oil used in animal feed comes from fish by-products (FAO 2020), with approximately two thirds derived from fishery by-products and one third from aquaculture by-products (Jackson and Newton 2016; Ytrestøl et al. 2016). The rest (65-75%) is produced from whole fish. Provided that a potential increase of raw materials from capture fisheries is very limited, any increase in fishmeal and fish oil production will have to be derived from aquaculture by-products or other protein alternatives (Hua et al. 2019; FAO 2020). Even though fish meal produced from by-products has lower protein and higher ash content (Hua et al. 2019), it nevertheless contains sufficient nutritional value to produce high quality feeds (Newton et al. 2014). The use of fish by-products is not limited to use in animal feeds. Certain by-products such as heads, frames, offcuts or derivatives such as hydrolysates can be used for human consumption either directly or as parts of products such as fish surimi and different sauces (Jayathilakan et al. 2012; Newton et al. 2014; Olsen et al. 2014; Stevens et al. 2018; FAO 2020). Other uses include the pet food industry, nutraceuticals, cosmetics, fuels, fertilizers, leather, natural pigments, and alternatives to plastic and constituents in other industrial processes (Stevens et al. 2018; FAO 2020).

2. Supplementary methods for aquafeeds calculations

Diet composition in Tacon et al. (2011) survey data are provided in ranges of inclusion for each ingredient (min, max, average) for specific species in the main fed aquaculture groups. In order to estimate a diet composition that sums up to 100%, the proportion of each ingredient for the average diet composition was used to scale the diet to it. If the maximum reported inclusion rate was below 100%, no extrapolation was performed, and this lower inclusion range was used instead. If the average or minimum was above 100% then it was scaled to 100%.

Examples for all three cases: a) average inclusion in the diet for five ingredients is A:20%, B:30%, C:10%, D:20% and E:10%. This sums up to a total of 90%, which cannot be as the diet needs to sum up to 100%. Each ingredient % is then divided by the 90% to get the proportion of the ingredient in the diet. Then the estimated proportion is multiplied with 100% to get the new diet composition that sums up to 100% while retaining the same proportions of the ingredients. b) the maximum inclusion rate in the diet for five hypothetical ingredients is A:10%, B:20%, C:20%, D:10% and E:5%. This sums up to a total 65% of the total diet. Given that we have no information on other ingredients in the diet we calculate the ingredients used only for this 65% of the diet. c) average inclusion in the diet for five ingredients is A:20%, B:40%, C:10%, D:20% and E:20%. This sums up to a total of 110%, which cannot be as the diet needs to sum up to 100%. Each ingredient % is then divided by the 110% to get the proportion of the ingredient in the diet. Then the estimated proportion is multiplied with 100% to get the new diet composition that sums up to 100% while retaining the proportions of the ingredients.

After the diet for each fed aquaculture group was scaled to the 100% inclusion, for the countries represented in the survey in Tacon et al. (2011), the scaled survey data were assigned to them but for the rest countries, the inclusion rate was estimated based on the weighted average global production for each aquaculture group. In order to compare our estimates to published data on feed use, we used the production data of 2010, the above procedure and group specific FCRs to estimate total feed and specific ingredients use. FCRs for commercial feeds for 2010 were taken from Tacon & Metian. (2015) and FCRs for farm-made feeds were calculated to be 50% higher than commercial ones based on Hasan et al. (2013). For highly carnivorous high value groups (other marine fishes and shrimps), the share of global production not fed on commercial feeds, was assumed to feed on whole fish ("trash" fish) and their FCRs were estimated according to reported conversion factors for these groups (Funge-Smith et al. 2005; De Silva & Turchini 2009; Hasan 2012; Cashion et al. 2016).

Our estimation for fishmeal use was at 4.25 million tons and for fish oil 0.79 million tons for commercial feeds only. Tacon et al. (2011) estimated the fishmeal and fish oil use in commercial feeds at 3.67 million tons and 0.764 million tons respectively. Our estimate of fish meal use is higher than reported for year 2010 and this is due to the fact that the countries represented in the survey data that were used to extrapolate diet composition globally, included also countries in which the use of fish meal is notably higher than the global average as reported in Tacon et al. (2015). To overcome this issue, for the further estimation of feed for the years of interest (2016-2018), we recalculated country specific diet inclusion rates for the years 2016-2018, by a) first assigning in the diet composition the global average use of fishmeal and fish oil for each aquaculture group for year 2015 for all countries and then b) rescaling the diet composition to 100% according to the proportions of the other protein rich and oil ingredients in the diet. After that, we estimated the feed use with FCRs for 2015 as described above.

3. Supplementary methods for calculating the replacement potential

The maximum and minimum replacement potential was calculated considering both the availability of replacement materials as well as the replacement constraints (table S5). First, the feed use of each of the food-competing feedstuff selected was multiplied with the replacement constraints to estimate the maximum and minimum replacement potential for each livestock group and replacement material individually (Eq 1).

$$(1)\ Repl_{f,ap,r,reg} = Feed_{f,ap,reg} * Constr_{ap,r}$$

where Repl is the replacement potential for each food-competing feedstuff (f,) animal (livestock or aquaculture) production group (ap) (including cattle meat, dairy cattle, poultry meat, poultry eggs, pork and aquaculture), the replacement material selected (r) and for each region (reg) (table S4). Feed is the feed use for each feedstuff (f), animal production group (ap) and region (reg) and Constr are the replacement constraints (table S5) for each animal production group (ap) and replacement material (r).

Second, the maximum and minimum replacement potentials were corrected with the availability of the selected replacement material in the region. If the sum of replacement potentials of the different animal production groups of one replacement material exceeded its regional availability, it was normalised to match the regional availability (Eq 2).

$$(2)\ If\ \sum \quad Repl_{f,r,reg} > Avail_{r,reg}$$

$$then\ \ Repl_{f,ap,r,reg} = (Feed_{f,ap,reg} * Constr_{ap,r}) * \frac{Avail_{r,reg}}{\sum \quad Repl_{r,reg}}$$

Third, the combined replacement potential of the different replacement materials was estimated by adjusting the maximum replacement potential for an animal production group to not exceed the feed use of the food-competing feedstuff of the same animal production group. If the sum of the replacement potential of the different replacement materials exceeded the feed use of the animal group, the individual replacement potentials of the different replacement materials were normalised to match the maximum feed use of the animal production group (Eq 3).

$$(3)\ If\ \sum \quad Repl_{f,ap,reg} > Feed_{f,ap,reg}$$

$$then\ \ Repl_{f,ap,r,reg} = (Feed_{f,ap,reg} * Constr_{ap,r}) * \frac{Feed_{f,ap,reg}}{\sum \quad Repl_{r,reg}}$$

Finally, the combined potential of the different replacement materials and animal production groups were summed to derive the total replacement potential (Eq 4).

$$(4)\ Repl_{total,f} = \sum \quad Repl_{f,ap,r,reg}$$

The increased food supply was estimated by multiplying the replaced food-competing feedstuff amounts with their energy (kcal), protein and fat contents (FAO, 2001).

Example: This is a hypothetical example to illustrate the calculations of the replacement potential.

There are 100 units of feed use of the food-competing feedstuff A, divided into feed use of cattle meat production (30), pig (10) and poultry (60) that can be replaced with replacement materials X, Y and Z. The replacement constraints (the max feed use of the feed A that can be replaced with X, Y and Z) for cattle meat are 0.3 (X), 0.5 (Y) and 0.9 (Z).

Replacement constraints:

- cattle: 0.3 (X), 0.5 (Y) and 0.9 (Z)
- pig: 1 (X), 0.3 (Y) and 0.9 (Z)
- poultry: 0 (X), 0 (Y) and 0.9 (Z)

Table S1a. Replacement potential taking into account the replacement constraints for individual replacement materials.

Animal production group	Feed use	Replacement potential with X	Replacement potential with Y	Replacement potential with Z
Cattle	30	0.3*30 = 9	0.5*30 = 15	0.9*30 = 27
Pig	10	1*10 = 10	0.3*10 = 3	0.9*10 = 9
Poultry	60	0*60 = 0	0*60 = 0	0.9*60 =54
Total	**100**	**19**	**18**	**90**

Second, the replacement potential is corrected with the availability. Here, the availability of the replacement materials in the region is 100 units of X, 0 units of Y and 50 units of Z.
Availability of the replacement material in a region:

- 100 (X)
- 0 (Y)
- 50 (Z)

Table S1b. Replacement potential taking into account the replacement constraints as well as the regional availability of the replacement material for individual replacement materials.

Animal productio n group	Feed use	Replacement potential with X	Replacement potential with Y	Replacement potential with Z
Cattle	30	9	15 * 0/18 = 0	27 * 50/90 = 15
Pig	10	10	3 * 0/18 = 0	9 * 50/90 = 5
Poultry	60	0	0 * 0/18 = 0	54 * 50/90 = 30
Total	**100**	**19**	**0**	**50**
		19 < 100, so no need to change these	18 > 0, so we need to adjust the potential here	90 > 50, so we need to adjust the potential here

Third, the combined replacement potential is estimated by not allowing the max replacement potential to exceed the feed use of the animal production group.

Table S1c. Combined replacement potential of the different replacement materials for individual animal production groups taking into account the replacement constraints as well as the regional availability of the replacement material.

The combined replacement potentials for feed A is then 15.7 + 0 + 48.3 =64 units, which is equivalent to 64/100 = 64% of the total A feed use in a region. These calculations would then be repeated with all the regions to come up with the global replacement potential.

Animal production group	**Feed use**	**Replacement potential with X**	**Replacement potential with Y**	**Replacement potential with Z**	**Combined replacement potential**	
Cattle	30	9	0	15	9 + 0 + 15 = 24 24/30 = 0.8 ~80% of the cattle feed A use	24 < 30 (cattle feed use of A) so no need to adjust here
Pig	10	~~10~~ 10 * 10/15 =6.7	~~0~~ 0 * 10/15 = 0	~~5~~ 5 * 10/15 =3.3	~~10 + 0 + 5 = 15~~ 6.7 + 0 + 3.3 =10 10/10 = 1 ~100% of the pig feed A use	15 > 10 (pig feed use of A) so the potential needs to be adjusted here
Poultry	60	0	0	54 * 50/90 = 30	0 + 0 + 30 = 30 30/60 = 0.5 ~50% of the cattle feed A use	30 < 60 (poultry feed use of A) so no need to adjust here
Total	**100**	**15.7**	**0**	**48.3**		

4. Comparison with previous global assessments of feed use and by-product availability

The results of this study for livestock and aquaculture feed use as well as the availability of by-products were compared to previous studies, and they were found to be in line and in accordance with their assessments. Our total estimate for livestock feed flows, 6026 million tons (dry matter), for 2016-2018 is well in line with the estimates of Mottet et al. (2017) and Herrero et al. (2013) that estimated the total livestock feed use to be 5996 million tons (dm) for 2010 and 4693 million tons for 2000, respectively. Mottet et al. (2017) showed that 14% of the feedstuff used consists of food-competing feedstuff, compared to our estimate of 15%. The difference here can be a result of the categorization of the food-competing feedstuff applied: Mottet et al. (2017) included also unprocessed soybeans in their category of human edible feed use, while in this study all the soybean use as feed was divided into soybean meals and oils and all the meals were assigned to the non-food competing feed category.

In order to compare our estimates for aquaculture feed use to published data, we used the production data of 2010. For year 2010, we estimated the total use of commercial feeds at 35.4 million tons tones and the total use of farm-made feeds at 32.65 million tons that is in accordance with Tacon et al. (2011) and Tacon and Metian (2015). Furthermore, we estimated the use of soymeal in commercial aquafeeds at 7.3 million tons and Tacon et al. (2011) estimated the use of soymeal in commercial aquafeeds for 2008 at 6.8 million tons thus, this estimate is also in accordance with the literature. We estimated the use of "trash" fish at 8.85 million tons and Tacon et al. (2011) estimated trash fish use for 2006 at 5.6-8.8 million tons thus, our estimates are in accordance with this earlier estimate as well.

For years 2016-2018 we estimated a total use of commercial aquafeeds of 53.8 million tons, while Tacon (2019) estimated commercial feed use of 51.5 million tons for 2017 therefore, our estimate is in accordance. In addition, we have estimated the use of fishmeal and fish oil in commercial feeds at 3.56 million tons and 0.78 million tons respectively. According to a recent IFFO report (SEAFISH), global production of fishmeal and fish oil since 2010 has stagnated at around 5 million tons and 1 million tons respectively. Tacon and Metian (2015) estimated that the aquaculture commercial feeds used 68% and 74% of the global fishmeal and fish oil production in 2012. Based on the above two sources, and assuming that the use of fishmeal and fish oil from the aquaculture sector remains approximately the same, then our estimates are in agreement with the literature.

The comparison of our results of the potential by-product production is challenging since global or even regional level estimates of the different by-product flows are scarce. Our estimate of potential crop residue production at the global level without removing the crop residues left on field, was 1976 million tons (uncertainty range 1775 – 2191 million tons) only considering crop residues from rice, cereals, sugar cane and pulses. Wirsenius (2000) estimated a production of cereal and sugar residues to be 2900 million tons in 1992-1994. The amounts of production of cereal bran and molasses were adopted from FAO Supply and Utilization accounts (FAO, 2021) and therefore those were in line with the FAO statistics. Wirsenius (2000) estimated the livestock by-products generated globally from other than ruminant origin to be 78.2 million tons for 1992-1994, compared to the estimate from this study of 62 million tons (52-73 million tons) for 2016-2018. The amounts of livestock by-products produced in Europe estimated in this study was 11.3 million tons (uncertainty range 9.5-13.2 million tons), without by-products from ruminant origin, compared to the amounts of livestock by-product processed in EU (17 million tons in 2017 including also by-products from ruminant origin) reported by the European Fat Processors and Renderers Association (EFPRA, 2019). Here, however, EFPRA reports the actual amounts processed, while we estimate the potential in processing, which may explain the difference in the numbers. More detailed numbers of the processing of the different livestock by-products in the EU were not available. In this study the total potential for fishmeal made from fish by-products was estimated to be 9.6 million tons (uncertainty range 8.4-10.9 million tons), compared to the estimates from Jackson & Newton (2016) that had estimated the full processing potential for fishmeal from fish by-products to be 9.5 million tons for 2009-2013.

5. Supplementary tables

Table S2. Description of the data used in this study.

Data	Description	Reference year	Spatial coverage	Source
Livestock and crop production	National level yearly livestock and crop production data. Three-year average between 2016-2018 was applied in this study.	2016-2018 applied here; Data available 1961-2020 *	All countries of the world and geographical aggregates according to the United Nations M-49 list.	FAOSTAT, FAO, 2021
Livestock feed composition	Composition of feed used in different livestock production groups for four different production systems.	2010	Feed ratios for ten world regions of the world.	Global Livestock Environmental Assessment Model FAO GLEAM 2.0 (FAO, 2017)
Livestock feed conversion ratios	Regional feed conversion ratios (kg dry matter feed/kg output)	2000	Ten world regions	Mekonnen and Hoekstra, 2012
Livestock feed conversion ratios	Regional feed conversion ratios (kg dry matter feed/kg prot)	2010	FCRs presented for two groups: Non-OECD and OECD countries	Mottet et al., 2017
Livestock feed conversion ratios	Regional feed conversion ratios (kg dry matter feed/kg prot)	2000	Nine world regions	Herrero et al., 2013
Aquaculture and capture fisheries production	Statistics of yearly national aquaculture and capture fish production	2016-2018 applied here; Data available 1950-2019 *	237 world countries and administrative regions	FishStatJ, 2020
Aquaculture feed composition	Diet composition for the major fed aquaculture groups based on country-specific survey on aquaculture feed use	2010	187 world countries and administrative regions	Tacon et al. 2011
Aquaculture feed conversion ratios	Regional feed conversion ratios (kg dry matter feed/kg output)	2010	Global	Tacon & Metian 2015
Residues-to-production ratios	Ratios showing the quantities of residues produced	2020	Eight world regions	Wirsenius (in prep), Garcia-Condado et al., 2019
Crop processing and Production of crop processing by-products	National level data of crop processing and Production of crop processing by-products FAO	2016-2018 applied here; Data available 2010-2019 *	All countries of the world and geographical aggregates according to the United Nations M-49 list.	FAOSTAT Supply and Utilization Accounts, FAO 2021
Technical conversion factors of crops and livestock products	Technical conversion factors applied for estimating the amounts of sugar beet pulp and oilseed meals produced	1992-1996	Global	FAO, 1996
Waste and losses in food supply chains	Weight percentages of food loss and waste for five steps of the food supply chains	2007	Seven world regions	FAO, 2011
Ratios of human consumption and non-food use of fish	Yearly ratios of human consumption and non-food use of fish	2016-2017 applied here; Data available 1995-2017 *	Ratios presented for two groups: developed and developing countries	FAO Fisheries yearbooks, FAO 2010; FAO, 2019

* Sources accessed 10/2021

Table S3. Food-competing feedstuff included in this study

Feedstuff	Group
Barley	Cereals
Cassava	Cereals
Maize	Cereals
Millet	Cereals
Rice	Cereals
Sorghum	Cereals
Wheat	Cereals
Fish oil made from whole fish	Fish oil
Fishmeal made from whole fish	Fishmeal
Groundnut oil	Oilseed oils
Oil from palm kernels	Oilseed oils
Sunflower seed oil	Oilseed oils
Rapeseed oil	Oilseed oils
Soy lecithin	Oilseed oils
Soy protein concentrate	Oilseed oils
Soybean oil	Oilseed oils
Faba bean meal	Pulses
Field pea protein	Pulses
Field pea meal	Pulses
Lupin meal	Pulses
Peas	Pulses
Pulses	Pulses

Table S4. Non-food competing feedstuff included in this study

Feedstuff	Group
Blood meal	Livestock by-product
Hydrolyzed feather meal	Livestock by-product
Meat and bone meal	Livestock by-product
Meat meal (pig)	Livestock by-product
Poultry oil	Livestock by-product
Poultry by-product meal	Livestock by-product
Fish oil from fish by-products	Fish by-product
Fishmeal from fish by-products	Fish by-product
Corn gluten meal	Cereal by-product
Wheat gluten meal	Cereal by-product
Sorghum meal	Cereal by-product
Bran	Cereal by-product
Barley bran	Cereal by-product
Barley hulls	Cereal by-product
Maize bran	Cereal by-product
Millet bran	Cereal by-product
Oat bran	Cereal by-product
Rye bran	Cereal by-product
Bran sorghum	Cereal by-product
Wheat germ	Cereal by-product
Rice bran	Cereal by-product
Wheat bran	Cereal by-product
Corn by-products	Cereal by-product
Distiller’s grains	Cereal by-product
Dry by-products from grain industries	Cereal by-product
Wet distilleries grains	Cereal by-product
Banana residues	Crop residues
Crop residues	Crop residues
Pulses straw	Crop residues
Sugarcane tops	Crop residues
Cottonseed meal	Oilseed meal
Groundnut meal	Oilseed meal
Oilseed meal, other	Oilseed meal
Rapeseed meal	Oilseed meal
Soybean meal	Oilseed meal
Sunflower seed meal	Oilseed meal
Palm kernel cake	Oilseed meal
Citrus pulp	Other

Feedstuff	Group
Complements (amino acids, minerals)	Other
Limestone	Other
Swill	Other
Krill meal	Other seafood
Squid meal	Other seafood
Squid oil	Other seafood
Fodder beet	Roughages
Fresh grass	Roughages
Grass and leaves	Roughages
Hay	Roughages
Leaves	Roughages
Legumes and silage	Roughages
Molasses	Sugar by-products
Sugarbeet pulp	Sugar by-products

Table S5. Countries and administrative regions included in the analysis and the division to subregions following the division in FAO (2021). *The data coverage of the livestock and aquaculture feed use and the availability of food systems' by-products and residues varies between countries.*

Eastern Africa	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mayotte, Mozambique, Rwanda, Seychelles, Somalia, Tanzania United Rep. of, Uganda, Zambia, Zimbabwe
Middle Africa	Angola, Cameroon, Central African Republic, Chad, Congo, Congo Dem. Rep. of the, Equatorial Guinea, Gabon, Sao Tome and Principe
Southern Africa	Botswana, Lesotho, Namibia, South Africa
Western Africa	Benin, Burkina Faso, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Niger, Nigeria, Senegal. Sierra Leone, Togo
Northern Africa	Algeria, Egypt, Libya, Morocco, Sudan, Tunisia
Western Asia	Armenia, Azerbaijan, Bahrain, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen
Eastern Asia	China, China, Hong Kong SAR, Japan, Korea, Dem. People's Rep, Korea, Republic of, Mongolia
South-Eastern Asia	Brunei Darussalam, Cambodia, Indonesia, Lao People's Dem. Rep., Malaysia, Myanmar, Philippines, Singapore, Thailand, Timor-Leste, Viet Nam
Southern Asia	Afghanistan, Bangladesh, Bhutan, India, Iran (Islamic Republic of), Nepal, Pakistan, Sri Lanka
Central Asia	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan,
Eastern Europe	Belarus, Bulgaria, Czech Republic, Hungary, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Ukraine
Northern Europe	Denmark, Estonia, Faroe Islands, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, United Kingdom
Southern Europe	Albania, Croatia, Cyprus, Greece, Italy, Malta, Montenegro, Portugal, Serbia, Slovenia, Spain
Western Europe	Austria, Belgium, France, Germany, Luxembourg, Netherlands, Switzerland
Oceania	Australia, Cook Islands, Fiji, French Polynesia, Kiribati, Marshall Islands, Micronesia (Federated States of), New Caledonia, New Zealand, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, Wallis and Futuna Islands
North America	Bermuda, Canada, Saint Pierre and Miquelon, United States of America
Caribbean	Antigua and Barbuda, Aruba, Bahamas, Barbados, British Virgin Islands, Cayman Islands, Cuba, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Is., US Virgin Islands
Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
South America	Argentina, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela (Bolivarian Republic of)

Table S6. Replacement constraints of fishmeal, fish oil, cereals, oilseed oils and pulses with food system by-products considering the nutritional needs in livestock and aquaculture production

Feedstuff	**Replacement material**		**Dairy cattle**	**Beef cattle[1]**	**Pigs**	**Poultry**	**Aquaculture**
Fishmeal	Livestock by-products *		-	-	75 - 100%	75 - 100%	27-79%
	Oilseed meals		-	-	75 - 100%	75-100%	30-80%
	Fishmeal from fisheries by-products		-	-	75 - 100%	31-40%	75 - 100%
Fish oil	Poultry oil		-	-	-	-	51-79%
	Fish oil from fisheries by-products		-	-	-	-	75-100%
Cereals	Crop residues		100% but production decreased 40-80%	100% but production decreased 40-80%	2% piglets 13% sows	2%	0%
	Cereal bran, hulls	Wheat bran	45-55%	45-55%	16%	15-39%	0%
		Oat hulls	45-55%	45-55%	5-10%	5-37%	0%
	Distiller's grains and brewers' grains		26-100%	26-100%	10-43%	4-40%	0%
	Sugar beet pulp		70-100%	70-100%	10-25% (up to 70% on sows)	2-18%	0%
	Molasses		17-30%	17-30%	5-10%	0%	0%
	Citrus pulp		34-100%	34-100%	13-40%	0-15%	0%
Oilseed oils	Poultry oil		-	-	100%	100%	75-100%
	Fish oil from fisheries by-products		-	-	100%	100%	75-100%
Pulses	Oilseed meals		75-100%	75-100%	75-100%	75-100%	75-100%
	Livestock by-products[2] *	Meat and bone meal, pig	-	-	0%	9-56%	75-100%
		Poultry meal			75-100%	0%	75-100%
		Feather meal	-	-	12-43%	0%	75-100%
		Fishmeal from fish by-products	-	-	100%	24-75%	75-100%
		Blood meal	-	-	50%	10%	75-100%

The rows without a number refer to not including the feed in their current diet.

Replacement constraints derived from literature review detailed in tables S6 (aquaculture) and S7 (ruminants, pig and poultry production).

* Only from non-ruminant origin and intra-species recycling not allowed.

[1] Assumed similar replacement potential as on dairy cows if scarce literature indicated lower substitution rates, as the nutrient and energy requirements of animals with identical liveweight for growth are usually lower than for milk production (Luke, 2021).

[2] Due to lack of literature, it was assumed that the results of substituting soybean meal with processed animal protein are also applicable to other leguminous feed resources.

Table S7. Review of studies addressing the replacement of fishmeal (FM) /fish oil (FO) with livestock by-products.

Ingredient	Species	substitution (%)	substitution details	reference	Limitations	Benefits
Feather meal	European seabass	76%	In the diets explored, FM decreased, feather meal increased and so did corn meal and very little FO. Crude protein was kept at approximately the same levels.	Campos et al. (2017)	Palatability but when mixed with other proteins it's ok	decrease feed price, environmental impact and carbon footprint when local feather meal is used
feather meal/poultry meal/meat meal	malabar grouper	25%	In the diets explored, FM was replaced with the alternative meals and the wheat flour amount changed in the different diets. As a result, the protein content fluctuated a bit between the different diets.	Li et al. (2009)		
feather meal/meat meal	rainbow trout	30%		cited results from another article in Li et al. (2009)		
feather meal	Japanese flounder	40%		cited results from another article in Campos et al. (2017)		
feather meal	major carp	50%		cited results from another article in Campos et al. (2017)		
feather meal	Nile tilapia	66%		cited results from another article in Campos et al. (2017)		
blood meal and fish-offal meal blend	rohu	21%	Fermented anima and fish by-products for substituting FM	Dawood & Koshio (2019) fermented products for aquafeeds		Fermentation increases digestibility and crude protein content, and can be used for producing unconventional feedstuffs to replace FM and FO. Animal by-products have high digestibility and lack anti-nutrients that crops do have.
fish-offal meal	catfish	50%		table in Dawood & Koshio (2019)		
fish-offal meal	Indian major carp, rohu	50%	while 30% is fermented	table in Dawood & Koshio (2019)		

Ingredient	Species	substitution (%)	substitution details	reference	Limitations	Benefits
feather meal	catla catla	75%	30% feather meal and 10% FM if feather meal processed right with fermentation	table in Dawood & Koshio (2019)		
poultry meal	sea bream	50%	with supplementation of lysine & methionine (because these two miss from poultry meal)	Karapanagiotidis et al. (2018)		The use of non-ruminant by-products could enhance aquaculture's sustainability and eco-efficiency, as these feedstuffs provide a valuable means of animal by-products utilization and have in general a more favourable carbon footprint when compared with fishmeal and plant alternatives
pet-grade poultry meal or pork meat meal	fingerling Nile tilapia	100%	diet was supplemented with FO and wheat was decreased in the different diets	Hernandez et al. (2014)	The 100% substitution might not be possible in other species that have lower digestive capacity	As efficient as FM based diets. Protein digestibility and nutritional composition depends on the quality of the animal by-products and the processing technology. Nile tilapia is a species with high digestive capacity
average all alternatives		53%				

Table S8. Review of studies using food system by-products and residues (column 1) to replace food-competing feedstuff (column 3) through feeding experiments involving various farm animal species (column 2). *DM dry matter, OM organic matter, NDF neutral detergent fibre, ADF acid detergent fibre, CP crude protein, ECM energy corrected milk yield, BW body weight, ADG average daily gain, FCR feed conversion ratio (feed input/production output).*

Ingredient	**Species**	**substitution (%)**	**substitution details**	**Results**	**Optimal substitution rate**	**reference**
Sugar beet pulp	Dairy cows, 37 days in milk, milk yield 36-37 kg/d	70% of corn grain in dry matter	Isonitrogenous diets, dietary starch concentration was decreased, milk yield 36-37 kg/d, cows 37 days in milk	No impact on feed intake, milk yield, milk fat or protein concentration, milk lactose concentration was decreased 2,5%, no impact on plasma energy metabolites	70%	Münnich et al., 2018
	Dairy cows, 85 days in milk, milk yield 39 kg/d	100% of small-grain cereals (1:1:1 mixture of wheat, barley and oats)	Simultaneously, soybean meal was substituted with rapeseed meal and 72 g/kg DM of wheat bran added to the diet, milk yield 38,6 kg/d, cows 85 days in milk	No impact on feed intake, no impact on milk yield, ECM, milk fat or protein concentration, milk lactose concentration was decreased 1%, no effect on FCR	100%	Karlsson et al., 2018
	Dairy cows		A meta-analysis, sugar beet pulp intake 0-5,56 kg/d, milk yield 14,3-44,1 kg/d	Effect of sugar beet pulp on feed intake depends on the feed intake level of the cow: at low intake levels (≤3,5% BW) sugar beet pulp is more likely to increase feed intake but at high intake levels (>3,5% BW) sugar beet pulp is more likely to decrease feed intake. Thus, the effect of sugar beet pulp on feed intake depends on the cows' potential to increase their feed intake. The effects did not differ between the types of feeds (maize or barley) that were substituted by sugar beet pulp. Sugar beet pulp has no impact on milk yield.		Münnich et al., 2017
	Beef cattle, steers, BW 368 kg	100% of barley	Isonitrogenous diets, forage-concentrate ratio 35:65, dietary starch concentration was decreased and ADF concentration increased, BW of steers 368 kg and age 420d	Quadratic response on DM and NDF digestibility with highest digestibility on moderate substitution rates, substitution of barley with sugar beet pulp may reduce the risk of rumen abnormality when low-forage diets are fed, ADG not reported.		Mojtahedi & Mesgaran, 2011
	Beef cattle, steers, BW 314 kg	34% of corn	Feedlot system, isonitrogenous diets, forage: concentrate ratio 15:85	The substitution of corn with sugar beet pulp decreased feed intake (-7,1%), ADG (-6,7%) and final BW (-3,2%)		Nichols et al., 2014
	Beef cattle, bulls, BW 322 kg	30% of barley		Substitution of barley with sugar beet pulp increased silage intake (+10,3%), feed intake (+4,8%), final BW (+2,4%) and carcass weight (+2,5%). The substitution had no impact on FCR.	30%	Pesonen et al., 2014
	Beef cattle, steers, BW 187 kg	100% of barley	Separate feeding of forage and concentrate, forage:concentrate ratio varied from 42:58 to 51:49	The substitution of barley with sugar beet pulp decreased silage intake (-19%) and body condition score (-8,7%) but had no effect on ADG or BW.	≤100%	Keane 2005

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Beef cattle, steers, BW 54 kg	20% or 39% of corn	Isonitrogenous diets, steers were grown until reached the same BW	Quadratic response on feed intake with highest levels on lower substitution rate, the substitution of corn with sugar beet pulp linearly increased days on feed (+5,7%) and decreased ADG (-5,7%)	20%	Chester-Jones et al., 1991
	Beef cattle, bulls, BW 140kg	25% or 50% of barley	Separate feeding or forage and concentrate, forage:concentrate ratio varied from 57:43 to 59:41	No impact on silage, feed intake, final BW, ADG, carcass weight or FCR	50%	Jaakkola & Huhtanen, 1990
	Pigs, finishing barrows , BW 106 kg	25% or 50% of maize	All diets contained equal amounts of barley	BW at slaughter (-4,1%) and carcass weight (-9,2%) were decreased with the substitution rate of 50% but not with 25%. Both substitution rates decreased dressing percentage (up to -5,0%).	25%	Magistrelli et al., 2009
	Pigs, gestating and lactating sows, 2nd parity	10% of small-grain cereals in fresh matter (mix of wheat and barley)	Simultaneously, the proportion of soybean meal was decreased by 3,9%	The substitution of cereals with sugar beet pulp had no impact on sow BW, weight loss from gestation to weaning of litter, litter size or piglet weight. Litter gain and sow feed intake was decreased at peak lactation when 10% of cereals were substituted with sugar beet pulp.	10%	Krogh et al., 2017
	Pigs, gestating and lactating sows)	70% of small-grain cereals (100% of wheat and 4,5% of barley)	Simultaneously, the proportion of soybean meal was increased by 79%. Isonitrogenous diets.	The substitution of cereals with sugar beet pulp had no impact on sow BW or body weight gain, backfat thickness, feed intake, amount of piglets born at least in short-term.	70%	Philippe et al., 2015
	Pigs, gestating and lactating sows	64% of barley	Simultaneously, the proportion of soybean meal was increased from 50 to 120 g/kg	The substitution of cereals with sugar beet pulp increased feed intake (+3,1% during pregnancy and +5,4% during lactation) and decreased the weight of piglets at birth (-9,3%), but had no impact on litter size at birth or at weaning or weight of piglets at weaning	64%	Danielsen & Vestergaard, 2001
	Pigs, fattening , BW 35 kg	48% of small-grain cereal (71% of wheat and 0% of barley)	Isonitrogenous diets. Simultaneously, the proportion of soybean meal was increased by 32%.	The substitution of cereals with sugar beet pulp decreased the finalBW (-7,3%), carcass weight (-11%) and ADG (-10%) of fattening pigs, but it had no impact on feed intake.	<48%	Philippe et al., 2015
	Pigs, weaned, BW 8 kg	11 to 43% of wheat in phase 1, 10 to 40% of wheat in phase 2	Simultaneously, the proportion of canola oil was increased from 5 to 50 g/kg DM in both growth phases and dietary CP concentration was decreased 6,8% in phase 1 and 7,1% in phase 2, dietary starch concentration was decreased	The substitution of cereals with sugar beet pulp decreased feed intake (-5,6%) and ADG (-8,1%). The lowest inclusion level (60 g/kg diet) had no effect on growth.	11%	Wang et al., 2016

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Pigs, weaned piglets, BW 6 kg	5% or 11% of corn	Isonitrogenous and isocaloric diets	The substitution of corn with sugar beet pulp decreased feed intake (-9,8%) and ADG (-14%) at both substitution rates in optimum hygienic conditions, but no differences were reported on poor hygienic conditions.	<5%	Berrocoso et al., 2015
	Poultry, growing egg-laying pullets	2% or 4% of cereal (mix of barley, corn and wheat)	Simultaneously, the proportion of soybean meal was decreased by 0% to 4% depending on growth stage	The substitution of cereals with sugar beet pulp (4%) decreased average daily gain (-4,2%) and resulted in poorer FCR (+4,4%), these negative effects started to take place after the age of 5 weeks.	2%	Guzmán et al., 2015
	Poultry, broilers (Ross 308)	18 to 55% of cereals (mix of maize and wheat)	Diets were formulated to have energy as the first limiting nutrient resource. Slightly decreasing CP concentration with increasing sugar beet pulp dose.	Quadratic response on feed intake and ADG with highest levels on small doses of sugar beet pulp (150 g/kg diet). Sugar beet pulp resulted in poorer FCR than cereals (+42%)	18%	Taylor et al., 2021
	Poultry, broilers (Ross 308)	18% of corn in started diet, 13% of corn in grower diets	Isonitrogenous diets	The substitution of corn with sugar beet pulp decreased OM digestibility (-4,5%), but this was prevented with enzyme addition. ADG not reported.	13-18% with enzyme addition	Abdel-Daim et al., 2020
	Poultry, broilers (Ross 308)	up to 7,5% of rice	Slightly decreasing CP concentration with increasing sugar beet pulp dose.	No effect on feed intake or ADG from 1 to 18d of age. Quadratic response on FCR with lowest levels on low-moderate doses of sugar beet pulp (25-50 g/kg)	5%	Jiménez-Moreno et al., 2013
Molasses	Dairy cows, 182 days in milk, milk yield 21kg/d	17% of cereal (wheat)	Forage:concentrate ratio 50:50, CP concentration was increased from 144 to 151 g/kg DM	No impact on feed intake, milk yield or milk fat or protein concentration	17%	Hindrichsen et al., 2006
	Dairy cows, milk yield 18-19 kg/d	30% of barley	Forage:concentrate ratio 50:50	No impact on OM intake, milk yield or milk fat or protein concentration	30%	Murphy et al.,
	Dairy cows, 41 days in milk, milk yield 23-24 kg/d	33% of barley	Forage:concentrate ratio 58:42 to 56:44	No impact on feed intake or milk fat or protein concentration. The substitution of barley with molasses decreased milk yield.	<33%	Huhtanen, 1987
	Beef cattle, growing bulls, BW 268 kg	11% or 23% of barley and molassed sugar beet pulp (1:1)		No impact on feed intake and final BW, the substitution of barley and sugar beet pulp decreased ADG (-9,6%) and resulted in poorer FCR (+1%)	<11%	Huhtanen & Hissa, 1996
	Pigs			A review	5-10%	Mordenti et al., 2021

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
Wheat bran	Dairy cows, 47-57 days in milk, milk yield 24-25 kg/d	50% and 100% of barley	Forage:concentrate ratio 58:42 to 60:40	No impact on feed intake, milk fat or protein concentration or BWof cows. The substitution of barley with wheat bran linearly decreased milk yield (-6,0%).	50%	Huhtanen, 1991
	Beef cattle, heifers , BW 584 kg	22% to 84% of barley	Isonitrogenous diets	No impact on feed intake, the substitution of barley with wheat bran decreased linearly the digestibility of DM (up to -7,0%) and OM (-6,9%). Quadratic responses on NDF, ADF and gross energy digestibility with lowest levels on moderate doses of wheat bran. No impact on apparent N retention. ADG not reported.		Friedt et al., 2014
	Beef cattle, steers, BW 335 kg	100% of corn	CP concentration was increased from 126,6 to 131 g/kg DM, steers were grown until reached the same BW	No impact on feed intake, the substitution of corn decreased ADG (-18%) and resulted in poorer FCR (+19%).	<100%	Freitas et al., 2013
	Pigs, weaned piglets, BW 9 kg	16% of maize and 25% of dehulled soybean meal	Isonitrogenous and isocaloric diets	No impact on feed intake and ADG.	16%	Yu et al., 2016
	Poultry, broilers (Ross)	35-39% of corn depending on growth phase	CP concentration was decreased from 22 to 19%	No impact on ADG, FCR or carcass %.	35-39%	Ali et al., 2008
	Poultry, broilers (Ross 308)	15-21% of corn (grain and starch) depending on growth phase	CP concentration was decreased from 22,1 to 21,2% on starter and 20,0 to 19,4% on grower and increased from 18,1 to 19,0% on finisher diets	No impact on feed intake or ADG. The use of wheat bran during the whole production period resulted in similar FCR as in control, whereas the temporal use of wheat bran during starter period improved FCR (-15%)	15-21%	Li et al., 2019
	Poultry, broilers (Ross 208)	19% or 37% of cereals (mix of barley and wheat starch)	CP concentration was increased with wheat bran from 157 to 171 and 184 g/kg DM	The substitution of cereals with wheat bran increased feed intake (+49%), final BW (+29%). The higher substitution rate resulted in poorer FCR than control and lower substitution rate (+11%)	19%	Jørgensen et al., 1996
Wheat bran, oat hulls and green grass meal	Pigs, gestating sows	53% of barley	Concentration of green grass meal 150 g/kg, wheat bran 150 g/kg and oat hulls 200 g/kg in diet. Simultaneously, the proportion of soybean meal was decreased from 50 to 30 g/kg	The substitution of cereals with sugar beet pulp increased feed intake during pregnancy (+31%), but had no impact on the weight of piglets at birth, litter size at birth or at weaning or weight of piglets at weaning	53%	Danielsen & Vestergaard, 2001

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
Oat hulls	Dairy cows, 182 days in milk, milk yield 21 kg/d	57% of cereal (wheat)	Simultaneously, quality of cereals was changed from wheat (223 g/kg DM on control) to oats (97 g/kg DM on oat hulls diet), forage:concentrate ratio 50:50, CP concentration was slightly decreased from 144 to 139 g/kg DM	No impact on feed intake, no statistically significant impact on milk yield or milk fat or protein concentration, although milk yield numerically decreased (-9,6%)	<57%	Hindrichsen et al., 2006
	Pigs, weaned piglets, BW 9 kg	11% of maize and 21% of dehulled soybean meal	Isonitrogenous and isocaloric diets	No statistically significant impact on feed intake and ADG, although numerically decreased (-5,3% and -8,6%)	<11%	Yu et al., 2016
	Pigs, weaned piglets, BW 6 kg	7% or 14% of corn	Isonitrogenous and isocaloric diets	The substitution of corn with oat hulls decreased feed intake (-10%) and ADG (-12%) at both substitution rates in optimum hygienic conditions, but no differences were reported on poor hygienic conditions	<7%	Berrocoso et al., 2015
	Pigs, growing barrows, BW 25kg	18% of corn	Isonitrogenous and isoenergetic diets	The substitution of corn with oat hulls decreased feed intake (-0,5%), ADG (-8,8%) and final BW (-5,0%)	<18%	Ndou et al., 2017
	Poultry, broilers (Ross 308)	18 to 55% of cereals (mix of maize and wheat)	Diets were formulated to have energy as the first limiting nutrient resource. Slightly decreasing CP concentration with increasing oat hulls dose.	Quadratic response on feed intake and ADG with highest levels on moderate doses of oat hulls (300 g/kg diet). Oat hulls resulted in poorer FCR than cereals (+30%).	37%	Taylor et al., 2021
	Poultry, broilers (Ross 308)	up to 7,5% of rice	Slightly decreasing CP concentration with increasing oat hulls dose.	No effect on feed intake or ADG from 1 to 18d of age. Quadratic response on FCR with best performance on moderate doses of oat hulls (25-50 g/kg).	5%	Jiménez-Moreno et al., 2013
Distillers' grains	Beef cattle, heifers , BW 323 kg	8% to 15% of corn (high moisture)	Dried corn distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 29 to 0 g/kg DM. CP concentration of the diet was increased with increasing proportion of distillers' grain. Diets included also ground corn. Forage:concentrate ratio 13:87.	The substitution of corn with distillers' grains had no impact on BW, ADG, feed intake or FCR.	15%	Huizenga and McCann, 2021

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Beef cattle, heifers, BW 347 kg	12% of corn (steam flaked)	Dried corn distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 29 to 0 g/kg DM. CP concentration of the diet was decreased with increasing proportion of distillers' grains. Forage:concentrate ratio 6:94.	The substitution of corn with distillers' grains decreased feed intake, if distillers' grains originated from dry-grind ethanol process. No impact on final BW, ADG or FCR.	12%	Depenbusch et al., 2008
	Beef cattle, steers, BW 306 kg	12% to 48% of corn (dry rolled and fine ground)	Dried corn distillers' grains with solubles. Dietary CP concentration 130 g/kg DM. Forage:concentrate ratio 13:87.	The substitution of corn with distillers' grain had no impact on feed intake. Quadratic response on final BW with highest levels on 20% substitution rate. However, the final BW on diet with 48% substitution rate was still higher than on control without distillers' grains. Tendency for highest ADG and best FCR on diet with 20% substitution rate.	48%	Buckner et al., 2007
	Beef cattle, steers, BW 375 kg	17% to 41% of corn (dry rolled)	Dried corn distillers' grains with solubles. CP concentration of the diet was increased from 114 to 165 g/kg DM with increasing proportion of distillers' grains. Diets included also ground corn. Forage:concentrate ratio 10:90.	The substitution of corn with distillers' grains had no impact on final BW, ADG or FCR. Quadratic response on feed intake with highest levels on 29% substitution rate.	41%	Benson et al., 2005
	Beef cattle, steers, BW 289 kg	43% of barley	Dried wheat distillers' grains with solubles. CP concentration of the diet was increased from 125 to 172 g/kg DM with increasing proportion of distillers' grains. Forage:concentrate ratio 60:40.	The substitution of barley with distillers' grains increased final BW (+5%), ADG (+15%), feed intake (+6%) and resulted in improved FCR (-12%)	43%	He et al., 2015
	Beef cattle, heifers, BW 301 kg	100% of barley	Dried corn distillers' grains with solubles or dried wheat distillers' grains with solubles. CP concentration of the diets varied from 100 to 212 g/kg DM. Forage:concentrate ratio 55:45.	The substitution of barley with distillers' grains increased DMI (+17%). No impacts on final BW, ADG or FCR.	100%	Holtshausen et al., 2011

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Beef cattle, heifers, BW 312 kg	50% to 100% and 24% to 71% of barley, depending on growth stage	Dried wheat distillers' grains with solubles. CP concentration of the diets was increased from 136 to 329 g/kg DM with increasing proportion of distillers' grains. Forage concentrate ratio on backgrounding diets (55 d) 55:45, on finishing diets (118 d) 10:90.	The substitution of barley with distillers' grains increased feed intake (+12%) but resulted in poorer FCR (+6%) during the finishing period. No impact on feed intake, ADG or FCR during backgrounding period.	71-100%	Gibb et al., 2009
	Dairy cows, 23 days in milk, milk yield 31 kg/d	45% of corn (rolled)	Wet corn distillers' grain. Simultaneously, the proportion of soybean meal was decreased from 167 to 0 g/kg DM. CP concentration of the diet was increased from 180 to 210 g/kg DM with increasing proportion of distillers' grains. Forage:concentrate ratio 50:50.	The substitution of corn with distillers' grains decreased feed intake (-11%) and milk protein concentration (-7%) but had no impact on milk yield or ECM yield.	45%	Schingoethe et al., 1999
	Dairy cows, 76/244 days in milk, milk yield 33-36 kg/d	57% of barley	Dried corn-wheat distillers' grains with solubles. Simultaneously, the proportion of canola meal was decreased from 31 to 0 g/kg DM and corn gluten meal from 56 to 5 g/kg DM and beet pulp was increased from 25 to 111 g/kg DM. Forage:concentrate ratio 50:50.	The substitution of barley with distillers' grains increased energy corrected milk yield (+6%), but had no impact on feed intake, milk yield or milk composition.	57%	Zhang et al., 2010
	Dairy cows, 78 days in milk, milk yield 41 kg/d	16% to 49% of corn (ground)	Dried distillers' grains with solubles. Simultaneously, the proportion of soybean hulls was increased from 0 to 96 g/kg DM and soybean meal was decreased from 130 to 6 g/kg DM. Forage:concentrate ratio 49:51. Isonitrogenous diets.	The substitution of corn with distillers' grains decreased feed intake (-11%) and tended to improve FCR (-10%) but had no impact on milk yield, ECM yield or milk protein or fat concentration or yield.	49%	Ranathunga et al., 2010
	Dairy cows, 73 days in milk, milk yield 40-44 kg/d	12% to 25% of corn (ground)	Dried or wet distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 125 to 16 g/kg DM. Forage:concentrate ratio 50:50. CP concentration of the diets varied from 163 to 176 g/kg DM.	The substitution of corn with distillers' grains tended to decrease feed intake (-4%) but increased milk yield (+6%), fat yield (+9%), protein yield (+7%) and ECM yield (+7%) and improved FCR (-9%). Higher substitution rate (25%) tended to result in better FCR (-4%) than lower substitution rate (12%).	25%	Anderson et al., 2006

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Dairy cows, 144 days in milk, milk yield 36-38 kg/d	15% to 29% of corn (dry ground)	Modified wet distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 100 to 38 g/kg DM, cottonseeds 50 to 0 g/kg DM and soyhulls from 51 to 20 g/kg DM. Forage:concentrate ratio 47:53. Isonitrogenous diets.	The substitution of corn with distillers' grain tended to decrease ECM (-6%) and decreased milk fat concentration (-14%) and yield (-12%) and resulted in poorer FCR (+7%).	<15%	Boerman et al., 2021
	Dairy cows, 99 days in milk, milk yield 40 kg/d	34% to 100% of corn (flaked)	Dried corn distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 132 to 0 g/kg DM. CP concentration of the diets increased from 162 to 168 with increasing proportion of distillers' grains. Forage:concentrate ratio 60:40.	The substitution of corn with distillers' grains increased feed intake (+8%) and milk yield (+12%) but decreased milk fat (-12%) and protein concentration (-5%). No impact on FCR.	100%	Benchaar et al., 2013
	Pigs, gestating sows, 2nd and 3rd parity	9% to 16% of corn	Dried corn distillers' grain with solubles. Simultaneously, the proportion of soybean meal was decreased from 160 to 0 g/kg. Isonitrogenous diets.	The substitution of corn with distillers' grains increased feed intake during lactation (+10%), shortened the time from weaning to oestrus (-20%) and increased ADG of piglets (+15%). No impact on sow BW, piglets born, piglet BW or piglet survival.	16%	Shi et al., 2014
	Pigs, gestating sows, 2nd and 3rd parity	11% to 20% of corn	Dried corn distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 320 to 50 g/kg DM. Isonitrogenous diets.	The substitution of corn with distillers' grains had no impact on sow BW, feed intake, time from weaning to oestrus, piglets born or weaned, piglet BW or piglet survival.	20%	Wang et al., 2013
	Pigs, gestating sows, 1st and 2nd parity	16% and 27% of corn depending on production stage	Dried distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 188 or 300 to 0 g/kg. CP concentration was decreased from 162 to 149 g/kg during gestation and from 189 to 183 g/kg during lactation with increasing proportion of distillers' grains.	The substitution of corn with distillers' grains decreased litter size at birth (-5%) and weaning (-4%) and sows gained less weight during nursing (-4%). No impact on sow feed intake, time from weaning to oestrus or longevity.	<16-27%	Li et al., 2014

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Pigs, finishing, BW 107 kg	27% of corn	Dried distillers' grain with solubles. Simultaneously, the proportion of soybean meal was decreased from 123 to 58 g/kg. CP concentration was increased from 114 to 144 g/kg with increasing proportion of distillers' grains.	The substitution of corn with distillers' grains decreased final BW (-2%), ADG (-11%), feed intake (-12%) but had no impact on FCR.	<27%	Pilcher et al., 2015
	Pigs, growing-finishing, BW 30 kg	14% to 29% of corn in phase 1, 13% to 25% in phase 2, 12% to 24% in phase 3	Dried distillers' grains with solubles. 3-phase feeding. Simultaneously, the proportion of soybean meal was decreased from 239/165/108 to 151/73/20 g/kg. CP concentration was increased with increasing proportion of distillers' grains.	The substitution of corn with distillers' grains had no impact on final BW, ADG, feed intake or FCR.	12-29%	Xu et al., 2010
	Pigs, growing-finishing, BW 48 kg	18% to 20% of corn, depending on the amount of fat in the diet	Dried distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 252 to 233 g/kg. CP concentration was increased from 179 to 201 g/kg with increasing proportion of distillers' grains.	The substitution of corn with distillers' grains had no impact on ADG, feed intake or FCR.	18-20%	Linneen et al., 2008
	Pigs, growing-finishing, BW 46 kg	14% to 43% of corn in phase 1, 13% to 39% in phase 2	Dried distillers' grains with solubles. 2-phase feeding. Simultaneously, the proportion of soybean meal was decreased from 273/213 to 253/193 g/kg in phase 1 and 2, respectively. CP concentration was increased from 183/160 to 233/210 g/kg with increasing proportion of distillers' grains in phase 1 and 2, respectively.	The substitution of corn with distillers' grains decreased feed intake (-2%), tended to decrease ADG (-2%) and had no impact on FCR.	13-14%	Linneen et al., 2008

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Pigs, growing-finishing, BW 50 kg	7% to 27% of corn in phase 1, 6% to 24% in phase 2, 6% to 23% in phase 3, 6% to 22% in phase 4	Dried distillers' grains with solubles. 4-phase feeding. Simultaneously, the proportion of soybean meal was decreased from 269/209/169/142 to 246/187/147/119 g/kg in phase 1, 2, 3 and 4 respectively. CP concentration was increased from 182/159/144/133 to 212/189/174/164 g/kg with increasing proportion of distillers' grains in phase 1, 2, 3 and 4, respectively.	The substitution of corn with distillers' grains decreased feed intake (-4%), ADG (-4%), carcass weight (-2%) but had no impact on slaughter weight or FCR.	11-13%	Linneen et al., 2008
	Poultry, broilers (Cobb 500)	4% to 13% of corn	Dried distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 277 to 212 g/kg. Isonitrogenous diets.	The substitution of corn with distillers' grains decreased BW (-7%) at the highest substitution rate but had no impact on FCR	4-9%	Campasino et al., 2015
	Poultry, broilers (Arbor Acres)	7% to 9% depending on growth stage	Dried distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 245/132 to 178/67 g/kg depending on growth stage. Isonitrogenous diets.	The substitution of corn with distillers' grains had no impact on BW, ADG, feed intake or FCR	7-9%	Shalash et al., 2009
	Poultry, broilers (Ross 308)	4% to 17% of wheat	Dried wheat distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 283 to 180 g/kg. Isonitrogenous diets. CP concentration was decreased from 254 to 247 g/kg with increasing proportion of distillers' grains.	The substitution of corn with distillers' grains had no impact on BW, ADG, feed intake, FCR or mortality	13%	Thacker and Widyaratne, 2007
	Poultry, pullets (Single Comb White Leghorn)	2% to 10% of corn in phase 1, 2% to 9% in phase 2, 2% to 8% in phase 3, 2% to 10% in phase 4	Simultaneously, the proportion of soybean meal was decreased from 323/271/217/263 to 259/206/152/199 g/kg in phase 1, 2, 3 and 4 respectively. Isonitrogenous diets.	The substitution of corn with distillers' grains increased BW on highest substitution rate (+%) but had no impact on feed intake or FCR	8-10%	Masa'deh et al., 2012

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Poultry, laying hens (White Leghorn)	18% of corn	Dried corn distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 295 to 191 g/kg. Isonitrogenous diets.	The substitution of corn with distillers' grains had no impact on feed intake, laying rate, egg weight or FCR	18%	Purdum et al., 2014
	Poultry, laying hens (Single Comb White Leghorn)	4% to 18% of corn in phase 1, 4% to 22% in phase 2	Dried corn distillers' grains with solubles. Simultaneously, the proportion of soybean meal was decreased from 244/236 to 106/110 g/kg in phase 1 and 2, respectively. Isonitrogenous diets.	The substitution of corn with distillers' grains tended to decrease egg weight in phase 1 (-2%) but had no impact on egg weight in phase 2, feed intake, weight gain or laying rate	18-22%	Masa'deh et al., 2011
Brewers' grains	Dairy cows, 247 days in milk, milk yield 21-22 kg/d	23% of corn	Dried brewers' grains. Simultaneously, the proportion of soybean meal was decreased from 125 to 87 g/kg with increasing proportion of brewers' grains. Isonitrogenous diets. Forage:concentrate ratio 50:50.	The substitution of corn with brewers' grains decreased DMI (-9%) and milk fat concentration (-4%) but had no impact on milk yield, milk fat or protein yield or FCR.	23%	Younker et al., 1998
	Dairy cows, 145 days in milk, milk yield 14-15 kg/d	32% to 65% of corn	Wet brewers' grains. Simultaneously, the proportion of soybean meal was decreased from 115 to 0 g/kg DM and CP concentration was increased from 177 to 191 g/kg DM with increasing proportion of brewers' grains. Forage:concentrate ratio 50:50.	The substitution of corn with brewers' grains had no impact on feed intake, milk yield, milk fat or protein concentration or FCR	65%	West et al., 1994
	Dairy cows, milk yield 22-26/18-22 kg/d	26% to 51% of corn	Pressed brewers' grains. Simultaneously, the proportion of soybean meal was decreased from 200 to 0 g/kg DM and CP concentration was increased from 167 to 153 g/kg DM with increasing proportion of brewers' grains. Forage:concentrate ratio 40:60.	Trial 1: The substitution of corn with brewers' grains decreased feed intake (-25%), milk yield (-13%) and protein concentration (-6%) were decreased only with the highest substitution rate. Trial 2: Trial 1: The substitution of corn with brewers' grains decreased feed intake (-36%), milk yield was decreased (-%17 and -22%) with two highest substitution rates and milk protein concentration with highest substitution rate (-5%). Milk fat concentration was increased with brewers' grain inclusion in the diets (+17%).	26-39%	Davis et al., 1983

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Poultry, broilers (Hubbard)	11% to 41% of wheat in phase 1, 12% to 43% of wheat in phase 2 and 3	Dried brewers' grains. Simultaneously, the proportion of soybean meal was decreased from 285/265 to 124/107 g/kg. Isonitrogenous diets.	Phase 1: The substitution of wheat with brewers' grains decreased ADG (-23%), final BW (-23%) with three highest substitution rates and resulted in poorer FCR (+21%) with two highest substitution rates. No impact on feed intake. Phase 2: The substitution of wheat with brewers' grains decreased ADG (-12%) and resulted in poorer FCR (+13%) with three highest substitution rates. No impact on feed intake or final BW. Phase 3: The substitution of wheat with brewers' grains decreased ADG (-10%) and resulted in poorer FCR (+10%) with two highest substitution rates. No impact on feed intake or final BW.	11-23%	López and Carmona, 1981
	Poultry, broilers (Abor-Acre)	10% to 44% of corn	Enzyme supplemented dried brewers' grains. Simultaneously, the proportion of groundnut cake was decreased from 270 to 0 g/kg. Isonitrogenous diets.	The substitution of corn with brewers' grains decreased final BW (-25%), feed intake (-17%) and ADG (-38%) and resulted in poorer FCR (+34%) with two highest substitution rates	20%	Isikwenu et al., 2012
	Poultry, broilers (Ross 308)	10% to 17% of corn in phase 1, 2% to 11% in phase 2	Dried brewers' grains. Simultaneously, the proportion of soybean meal was decreased from 340/26 to 252/0 g/kg and fish meal was increased from 10/0 to 34/10 g/kg in phase 1 and 2, respectively.	The substitution of corn with brewers' grains decreased ADG (-7%) and resulted in poorer FCR (+7%) during phase 1 with highest substitution rate. Lowest substitution rate resulted in poorest FCR during phase 2. No impacts on feed intake during phase 1 or 2.	10-17%	Hussaini et al., 2010
	Poultry, laying hens (Rhode Island Red)	10% to 100% of grains (mix of wheat, sorghum and barley)	Dried brewers' grains. Simultaneously, the proportion of protein feeds (mix of soybean meal, alfalfa meal, fish meal and meat meal) was decreased from 269 to 0 g/kg with increasing proportion of brewers' grains. CP concentration of the diets increased from 174 to 202 with increasing proportion of brewers' grains.	The highest substitution rate was removed from the analysis due to severe impacts on animal performance. The substitution of grains with brewers' grains decreased feed intake (-6%) and egg production (-8%) with the second highest substitution rate. No impact on FCR.	40%	Lopéz et al., 1981
	Pigs, growing-finishing, BW 52 kg	15% to 45% of corn	Dried brewers' grains. Equal amount of protein feed between diets. CP concentration of diets was increased from 149 to 187 g/kg with increasing proportion of brewers' grains.	The substitution of corn with brewers' grains increased the days to slaughter (+54%), decreased ADG (-38%) but had no impact on FCR.	<15%	Yaakugh et al., 1994

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Pigs, weaned, BW 6 kg	29% to 57% of corn	Dried brewers' grain. Simultaneously, the proportion of groundnut cake was decreased from 200 to 100 g/kg. CP concentration of diets varied from 204 to 228 g/kg DM.	The substitution of corn with brewers' grains had no impact on final BW, ADG or FCR during weaner phase (~20 kg BW). During grower phase, lowest and highest substitution rate resulted in lower ADG and poorer FCR than zero and medium substitution rate.	43%	Amaefule et al., 2006
	Pigs, weaned, BW 8 kg	10% to 30% of corn	Dried brewers' grains. Equal amount of protein feed between diets. CP concentration of diets was increased from 201 to 221 g/kg with increasing proportion of brewers' grains.	The substitution of corn with brewers' grain decreased final BW, weight gain and feed intake with highest substitution rate. No impact on FCR.	20%	Imonikebe et al., 2009
Brewers' grains and distillers' grains	Beef cattle, steers, BW 311 kg	Wet brewers' grains substituted 10%/5% and wet distillers' grains 5%/7% of barley in DM basis in growing and finishing period, respectively.	During growing period, simultaneously, the proportion of canola was decreased from 91 to 0 g/kg DM. No protein feed during finishing period. Forage:concentrate ratio 41:59 to 39:61 and 7:93 during growing and finishing period, respectively.	The substitution of barley with brewers' grains or distillers' grains had no impact on final BW, DMI or ADG during growing period, but they tended to result in improved FCR (-7%). During finishing period, brewers' grain or distillers' grain had no impact on final BW, feed intakeor FCR but resulted in decreased ADG (-8%). No difference between brewers' grain or distillers' grain, but they were not fed with equal portions in the diet.		Ojowi et al., 1997
Citrus pulp	Beef cattle, steers, BW 384 kg	23% to 41% of corn (grain and steam flaked corn)	Simultaneously, the proportion of corn silage was decreased from 400 to 210 g/kg DM. DM concentration of the diet was decreased from 519 to 324 g/kg and CP concentration increased from 143 to 149 g/kg DM with increasing proportion of citrus pulp. Dietary NDF was 312 to 322 g/kg DM on all diets. Forage:concentrate ratio 40:60 to 21:79	Feed intakewas decreased (-13%) with increasing proportion of fresh citrus pulp. No impact on final BW or ADG. The substitution of corn with fresh citrus pulp improved FCR (-7%).	41%	Luzardo et al., 2021
	Beef cattle, heifers, BW 220 kg	15% to 43% of corn depending on growth stage	CP concentration of the diets was slightly decreased with increasing proportion of dehydrated citrus pulp (up to 8 g/kg DM). Forage:concentrate ratio 24:76 to 11:89 depending on growth stage.	The substitution of corn with dehydrated citrus pulp decreased linearly BW (-7%), ADG (-25%), feed intake (-11%) and resulted in poorer FCR (+15%). Dehydrated citrus pulp was not palatable for animals.	<15%	Cribbs et al., 2015

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Beef cattle, heifers, BW 257 kg	73% of corn	CP concentration of citrus pulp diets was 7g/kg DM lower than corn diet	The substitution of corn with citrus pulp decreased final BW (-2%), ADG (-5%), feed intake (-12%) and resulted in poorer FCR (+21%).	<73%	Sousa et al., 2020
	Beef cattle, steers, BW 365 kg	70% of corn	CP concentration of citrus pulp diet was 5 g/kg DM higher or 2 g/kg DM lower than ground corn diet, depending on forage:concentrate ratio of the diet. Forage:concentrate ratio 40:60 or 20:80. The experiment compared steam-rolled corn and pelleted citrus pulp to ground corn.	Selected contrasts do not allow the comparison between citrus pulp and corn diets. Therefore, only numerical differences are described here, when P-values for contrast comparing ground corn vs. steam-rolled corn and citrus pulp P<0.05. Citrus pulp diets resulted in numerically lower feed intake than corn diets (-10% or -3%, depending on dietary concentrate proportion). Also final BW (-3% or -2%) and ADG (-14% or -10%) were numerically lower for citrus pulp diet than corn diets. Citrus pulp resulted in numerically poorer FCR than corn diets (+4% or +16%).	<70%	Ferrari et al., 2019
	Beef cattle, steers, BW 354 kg	79% to 82% of corn	CP concentration of the diets varied from 120 to 135 g/kg DM. Forage:concentrate ratio 25:75 to 38:62 depending on the diet.	The substitution of ground or steam-flaked corn with citrus pulp had no impact on feed intake, final BW or carcass weight. Citrus pulp resulted in lower ADG than steam-flaked corn (-14%).	79-82%	Maia Filho et al., 2016
	Dairy cows, 130 days in milk, milk yield 28 kg/d	34% of corn	Isonitrogenous diets. Forage:concentrate ratio 40:60	The substitution of corn with pelleted citrus pulp decreased feed intake (-6%) and improved FCR (-8%). No impact on milk yield or milk fat concentration. Citrus pulp diets with buffer inclusion resulted in lower milk protein concentration than diets without buffer or supplemented with corn.	34%	Martins et al., 2021
	Dairy cows, 133 days in milk, milk yield 35 kg/d	54% to 60% of corn	Dietary CP concentration varied from 157 to 179 g/kg DM depending on diet. Forage:concentrate ratio 48:52	The substitution of corn with dry citrus pulp pellets decreased feed intake (-4%) and milk protein concentration (-%2). No impact on milk yield.	54-60%	Solomon et al., 2000
	Dairy cows, 164 days in milk, milk yield 23-25 kg/d	66% to 100% of corn	Dietary CP concentration varied from 154 to 160 g/kg DM. Forage:concentrate ratio 60:40.	The complete substitution of corn with citrus pulp decreased numerically feed intake (-12%). Diets had no impact on milk yield, although numerically highest milk yields were achieved with 100% citrus pulp diet (+9% compared to 100% corn)	100%	Santos et al., 2014

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Dairy cows, 99 days in milk, milk yield 31-33 kg/d	85% of corn hominy (NaOH treated corn)	Citrus pulp diet had 2-8 g/kg DM higher CP concentration than corn hominy diet. Forage:concentrate ratio 33:67.	The substitution of corn hominy with citrus pulp had no impact on feed intake, milk yield or milk composition.	85%	Leiva et al., 2000
	Dairy cows, 228-266 days in milk, milk yield 28-31 kg/d	53% of cornmeal	Isonitrogenous diets. Forage:concentrate ratio 45:65.	The substitution of cornmeal with citrus pulp decreased milk yield (-12%) and milk protein yield (-8%), but increased fat concentration (+6%).	<53%	Leiva et al., 2000
	Dairy cows, 85 days in milk, milk yield 20 kg/d	33% to 100% of corn	Pasture grazing experiment. Estimated pasture intake 10.6 kg DM/cow/d. CP concentration of concentrates 117-121 kg/kg DM.	The substitution of corn with dried citrus pulp linearly decreased milk (-15%), milk fat (-14%) and protein yield (-16%). No impact BW change or body condition score.	<33%	Steyn et al., 2017
	Poultry, broilers (Cobb 500)	15% of grain	Isonitrogenous diets. Orange pulp partially substituted grains during the finisher phase (d 23-42 of production). Grain in control diet constituted of 100% wheat, in orange pulp diet corn and wheat with 35:65 ratio.	The substitution of grains with orange pulp had no impact on finishing BW, carcass weight, cumulative feed intake or FCR.	15%	Zoidis et al., 2022
	Poultry, broilers (Ross 350)	5% or 10% of corn	CP concentration of diets varied 215-229 g/kg DM.	The substitution of corn with citrus pulp decreased BW at the age of 34d (-24%), ADG (-26%) and carcass weight (-28%), increased feed intake (+32%) and resulted in poorer FCR (+75%).	<5%	Mourao et al., 2008
	Poultry, laying hens (Lohmann Brown-Classic)	6% of corn	Simultaneously, the concentration of brans (wheat and rice) was decreased from 64 to 0 g/kg and concentration of soybean meal was increased from 230 to 256 g/kg. CP concentration of diets was 172 to 174 g/kg.	The substitution of corn with orange pulp decreased laying rate (-30%), feed intake (-20%) and resulted in poorer FCR (+22%)	<6%	Gliomytis et al., 2018
	Poultry, laying hens (Hy-line W-36 strain)	8% to 33% of corn	Simultaneously, the proportion of soybean meal was increased from 287 to 312 g/kg. Isonitrogenous diets.	The highest substitution rate of corn with orange pulp decreased laying rate (-5%) and resulted in poorer FCR (+3%), no impacts on lower substitution rates (8-25%). Egg weight was increased when the substitution rate was 17% of corn or higher.	≤25%	Nazok et al., 2010

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Poultry, broilers (Ross 308)	1% to 13% of corn depending on growth stage and diet	Simultaneously, the proportion of soybean meal was increased with increasing proportion of citrus pulp. Isonitrogenous diets.	The substitution of corn with citrus pulp decreased BW (-21%), ADG (-25%) and resulted in poorer FCR (+31%).	<1-2%	Basir and Toghyani, 2017
	Pigs, growing-finishing, BW 62 kg	13% of corn	Isonitrogenous diets.	The substitution of corn with citrus pulp had no impact on feed intake, ADG or FCR.	13%	Lei et al., 2018
	Pigs, weaned piglets, BW 6 kg	18% of corn	Isonitrogenous diets	The substitution of corn with citrus pulp decreased feed intake (-20% to -32% depending on the growth stage), ADG (-44 to -49%) and resulted in poorer FCR (+23% to -45%).	<18%	Pascoal et al., 2015
	Pigs, finishing, BW 85 kg	18-19% of corn	Three different forms of citrus pulp (dried, ensiled and pressed). Isonitrogenous diets.	Dried citrus pulp resulted in similar feed intake and FCR to corn diet. Ensiled and pressed citrus pulp resulted in lower feed intake (-20%) and poorer FCR (+17%) than corn and dried citrus pulp. Diets had no impact on ADG.	18-19%	Crosswhite et al., 2013
	Pigs, finishing, BW 80 kg	13% to 40% of corn	Simultaneously, the proportion of soybean meal was increased from 164 to 188 g/kg. Isonitrogenous diets.	The substitution of corn with citrus pulp had no impact on feed intake, final BW or FCR. Highest ADG was achieved with 13% substitution rate.	40%	Watanabe et al., 2010
	Pigs, finishing, BW 73 kg	51% of corn	Simultaneously, the proportion of soybean meal was increased from 140 to 167 g/kg	The substitution of corn with citrus pulp decreased final BW (-17%), ADG (-59%), feed intake (-29%) and resulted in poorer FCR (+76%).	<51%	Berenchtein et al., 2019
Straw	Pigs, weaned piglets, BW 6 kg	7% or 14% of corn	Isonitrogenous and isocaloric diets	The substitution of corn with straw decreased feed intake (-9,5%) and ADG (-13%) at both substitution rates in optimum hygienic conditions, but no differences were reported on poor hygienic conditions.	<7%	Berroccoso et al., 2015
	Poultry, growing egg-laying pullets	2% or 4% of cereal (mix of barley, corn and wheat)	Simultaneously, the proportion of soybean meal was decreased by 0% to 4% depending on growth stage	The substitution of cereals with straw (4%) resulted in poorer FCR (+2,7%), these negative effects started to take place after the age of 10 weeks.	2%	Guzmán et al., 2015

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Pigs, gestating sows	13.35% of concentrate (mix of corn, soybean meal with hulls, soybean oil, minerals and vitamins)	The CP concentration of diet was decreased from 15% to 12.13%. Control diet without straw was fed at 1.95 kg/d and diet with straw at 2.25 kg/d.	The substitution of concentrates with straw increased the amount of farrowed live pigs, litter BW and the amount of weaned pigs per litter.	13%	Veum et al., 2009
	Beef cattle, steers, BW 608 kg	100% of barley or 100% of corn	Isonitrogenous diets	The substitution of both cereals with straw decreased feed intake (-7.2%). ADG or BW change not reported.		Reynolds et al., 1993
	Beef cattle, steers, BW 186	20% to 76% of barley	Isonitrogenous diets. Two diets with lowest barley proportion included also rapeseed meal (0.27 to 0.66 kg DM/d)	The substitution of barley with straw linearly decreased feed intake (-20%), final liveweight (-21%), ADG (-38%), carcass gain (-58%) and resulted in poorer FCR (+29%). Reconstructing regression equation for carcass gain based on data on Aronen et al. (1994) results in equation: $\hat{Y}$ = 819.89 – 0.5652x, where x= proportion of straw g/kg in diet DM. Extrapolating the diets of Aronen et al to complete substitution of barley with straw results in diet with straw concentration of 743 g/kg DM, rapeseed meal 208 g/kg DM, urea 20 g/kg DM and minerals 29 g/kg DM. Using the estimated regression equation above, the proportion of 743 g/kg DM of straw in the diet would result in carcass gain of 400 g/d, assuming linearity of response also on higher substitution rates. This would mean a 38% decrease in carcass gain compared to the diet with 302 g/kg DM straw in the diet.		Aronen et al., 1994
	Beef cattle, heifers, BW 205 kg	30% of barley		No statistically significant impact on feed intake. The substitution of barley with straw decreased ADG (-43%).		Ortigues et al., 1989
	Sheep, lambs, BW 11 kg	17% to 50% of corn	CP concentration linearly decreased with increasing proportion of sorghum straw	No statistically significant impact on BW, however, the highest substitution rate resulted in -25% lower BW compared to lowest substitution rate. The substitution of corn with sorghum straw decreased DMI (-18%)		Malisetty et al., 2014
	Sheep, rams, BW 18 kg	29% to 100% of concentrate supplement (2:1:1 mix of wheat bran, noug seed cake and sesame seed cake)		The substitution of concentrate with tef straw decreased feed intake (-29%), final BW (-24%) and ADG (-103%). Animals on the 100% straw diet lost BW -2g/d, the final BW being 0.2 kg lower than initial BW. However, higher animal performance might have been expected if the animals were supplemented with protein feed while substituting cereals with straw.		Hagos & Melaku, 2009

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Sheep, lambs, BW 11 kg	10% to 30% of concentrate (mix of corn, groundnut cake, sunflower cake, deoiled rice bran, molasses, urea and minerals)	CP concentration linearly decreased with increasing proportion of sorghum straw	The substitution of cereals with sorghum straw decreased feed intake (-24%), final BW (-29%), ADG (-41%) and resulted in poorer FCR (+29%). Reconstructing regression equation for carcass gain based on data on Vankateswarlu et al (2014) results in equation: $\hat{Y} = 28.927 – 0.0256x$, where x= proportion of straw g/kg in diet DM. Extrapolating the diets of Vankateswarlu et al. to complete substitution of concentrates with straw results in a diet with straw concentration of 1000 g/kg DM. Using the estimated regression equation above, the proportion of 1000 g/kg DM of straw in the diet would result in net gain of 3.3 kg, assuming linearity of response also on higher substitution rates. This would mean 82% decrease in carcass gain compared to the diet with 400 g/kg DM straw in the diet. However, the decrease in animal performance might be lower if animals are supplemented with protein feeds while cereals are substituted with straw.		Venkateswarlu et al., 2014
	Sheep, lambs, BW 18 kg	6% to 19% of cereals (mix of barley and corn)	Isonitrogenous diets	The substitution of cereals with wheat straw decreased feed intake (-29%), final BW (-19%), ADG (-34%) and resulted in poorer FCR (+23%)		Haddad & Ata, 2009
soybean meal	Pigs, piglets, BW 7 kg	50% or 100% of fishmeal	Isonitrogenous diets, proportion of fishmeal 0, 2,5 or 5% of diet, main protein feed soy (26 to 35% of diet)	The substitution of fishmeal with soy had no impact on feed intake or FCR. Quadratic response on ADG with highest levels on diet with 2,5% of fishmeal.	100%	Keegan et al., 2004
	Pigs, piglets, BW 9 kg	50% or 100% of fishmeal	Isonitrogenous diets, proportion of fishmeal 0, 2,5 or 5% of diet, main protein feed soy (29 to 37% of diet)	The substitution of fishmeal with soy had no impact on feed intake or ADG. The substitution of fishmeal with soy resulted in slightly poorer FCR.	100%	Keegan et al., 2004
	Pigs, piglets, BW 7 kg	100% of fishmeal	Isonitrogenous and isocaloric diets, proportion of fishmeal 0 or 7,4% of diet, main protein feed soy (12 to 24% of diet)	The substitution of fishmeal with soy decreased ADG and resulted in poorer FCR. No impacts on feed intake.	<100%	Ma et al., 2019
	Pigs, piglets, BW 7 kg	100% of fishmeal	Proportion fishmeal 0 or 6% of diet, main protein feed soy (23 to 33% of diet)	No impact on feed intake or ADG. The substitution of fishmeal with soy resulted in similar or poorer FCR, depending on the quality of substituted fishmeal.	100%	Jones et al., 2018
	Pigs, piglets, BW 7 kg	50% or 100% of fishmeal	Proportion fishmeal 0, 3 or 6% of diet, main protein feed soy (23 to 33% of diet)	The substitution of fishmeal with soy decreased linearly ADG and resulted in poorer FCR. No impacts on feed intake.	<100%	Jones et al., 2018

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Pigs, growing gilts and castrates, BW 25 kg	50%, 79% or 100% of fishmeal	Isonitrogenous diets. Proportion of fishmeal 0, 2.7, 6.5 or 13% of diet and soy 20, 16, 10 or 0% of diet, respectively	No impact on ADG or FCR	100%	Valaja et al., 1992
	Poultry, broilers (Cobb 500)	100% of fish meal	Isonitrogenous and isocaloric diets. Proportion of fish meal 78 g/kg in started diets and 72 g/kg in finisher diets, main protein feed soy (155 or 247 g/kg in starter diets and 144 or 225 g/kg in finisher diets)	No impact on feed intake. The substitution of fishmeal with soy decreased ADG and resulted in poorer FCR.	<100%	Hossain et al., 2013
	Poultry, broilers (384 Ross × Ross 308)	100% of fish meal	Isonitrogenous diets. Single protein source in the diet (soybean or fish), proportion of fishmeal in the diet 29%.	No impact on feed intake or BW	100%	Bryan et al., 2019
	Poultry, broilers (Hubbard × Hubbard)	100% of fish meal	Isonitrogenous diets. Three protein levels. Single protein source in the diet (soy protein concentrate or fishmeal), proportion of fishmeal in the diet 203, 329 or 457 g/kg. Diets were not formulated to ideal protein ratios.	The substitution of fishmeal with soy protein concentrate decreased BW.	<100%	Drew et al., 2004
	Poultry, broilers (Hubbard × Hubbard)	100% of fish meal	Isonitrogenous diets. Three protein levels. Single protein source in the diet (soy protein concentrate or fishmeal), proportion of fishmeal in the diet 203 or 457 g/kg. Diets were not formulated to ideal protein ratios.	The substitution of fishmeal with soy protein concentrate decreased BW.	<100%	Drew et al., 2004
	Poultry, broilers (Ross × Ross)	100% of fish meal	Isonitrogenous and isocaloric diets. Main protein feed soy (35% or 31% in starter diets, 32 or 28% in grower diets and 26 or 22% in finisher diets)	No impact on finishing BW, ADG or FCR	100%	Hess et al., 2009
	Poultry, broilers	25, 50, 75 or 100% of fish meal	Isonitrogenous and isocaloric diets. Maximum fishmeal proportion in the diet 25%.	The impacts on ADG and FCR depend on the quality of fishmeal. The replacement of 50% to 100% of fishmeal with soybean meal resulted in highest ADG and most efficient FCR.	50-100%	Waldroup et al., 1965
	Dairy cows, 85 days in milk, milk yield 24 kg/d	100% of faba bean and pea	Isonitrogenous concentrates. Ad libitum access to forage.	The substitution of faba beans and pea with soy had no impact on milk yield or milk composition but tended to increase milk fat yield (+14%).	100%	Volpelli et al., 2012

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Dairy cows, 139/150 days in milk, milk yield 34 kg/d	100% of faba bean and pea	Isonitrogenous concentrates. Ad libitum access to forage.	The substitution of faba beans and pea with soy had no impact on milk yield or milk composition	100%	Volpelli et al., 2012
	Beef cattle, heifers, BW 318 kg	100% of faba bean or lupin	Isonitrogenous concentrates. Ad libitum access to forage.	The substitution of faba beans or lupin with soy increased ADG (+11%) and resulted in improved FCR (-3%).	100%	Ragni et al., 2018
	Pigs, gestating and lactating sows	100% of peas	CP concentration of diets was increased from 135/156 to 144/170 g/kg with increasing proportion of soybean meal.	The substitution of faba beans with soy increased lactation length (+2%) and decreased litter growth rate (-4%) but had no impact on feed intake during gestation or lactation, number of piglets born or weaned, piglet mortality or annual productivity of sow	100%	Gatel et al., 1988
	Pigs, weaned piglets, BW 6 kg	100% of peas	CP concentration of diets varied from 210 to 216 g/kg	The substitution of peas with soy tended to increase ADG (+4%) and feed intake (+4%). No impact on FCR.	100%	Valencia et al., 2008
	Pigs, growing-finishing, BW 30 kg	100% of lupin	Isonitrogenous diets.	The substitution of lupin with soy decreased feed intake (-1%) but had no impact on ADG, FCR or length of the production period.	100%	Roth-Maier et al., 2004
	Poultry, laying hens (Lohmann Selected Leghorn, Lohmann brown)	100% of faba bean	Isonitrogenous diets.	The substitution of faba beans with soy increased laying rate (+14%) and egg mass (+17%) and resulted in improved FCR (-15%)	100%	Fru-Nji et al., 2007
	Poultry, laying hens (Lohmann Selected Leghorn)	100% of pea	CP concentration of diets varied from 193 to 203 g/kg.	The substitution of peas with soy tended to increase egg mass (+1%) and result in improved FCR (-3%). No impact on laying rate.	100%	Fru-Nji et al., 2007
	Poultry, broilers (Ross)	50% or 100% of pea, faba bean or lupin	Isonitrogenous diets during d 1-10, CP concentration of diets varied from 212 to 222 during d 11-28 and from 192 to 205 during d 29-42.	The substitution of peas or lupin with soy increased ADG (+5% / +7%) during d 1-42. No impacts on feed intake or FCR during d 1-42. Soy and faba beans resulted in similar SDG, feed intake and FCR during d 1-42.	100%	Moschini et al., 2005

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
Canola meal and cake, rapeseed meal and cake	Poultry, broilers (Cobb 500)	100% of fish meal	Isonitrogenous and isocaloric diets. Proportion of fish meal 84 g/kg in started diets and 70 g/kg in finisher, main protein feed canola meal (168 or 281 g/kg in starter diets and 140 or 243 g/kg in finisher diets)	No impact on feed intake. The substitution of fishmeal with canola decreased ADG and resulted in poorer FCR.	<100%	Hossain et al., 2013
	Poultry, broilers (384 Ross × Ross 308)	100% of fish meal	Isonitrogenous diets. Single protein source in the diet (canola or fish), proportion of fishmeal in the diet 29%.	No impact on BW, the substitution of fishmeal with soy increased feed intake.	100%	Bryan et al., 2019
	Dairy cows, 113 days in milk, milk yield 34 kg/d	100% of faba beans	Isonitrogenous diets. Forage:concentrate ratio 57:43.	The substitution of faba beans with rapeseed increased milk yield (+5%) and milk protein yield (+5%) and tended to increase fat yield (+4%). No impact on feed intake.	100%	Lamminen et al., 2019
	Dairy cows, 95 days in milk, milk yield 29 kg/d	100% of faba beans or pea	Isonitrogenous diets. Forage:concentrate ratio 60:40.	The substitution of faba beans or pea with rapeseed increased milk yield (+5%) and milk protein yield (+6%). No impact on feed intake.	100%	Ramin et al., 2017
	Dairy cows, 103-127 days in milk, milk yield 29-32 kg/d	100% of faba beans	Isonitrogenous diets. Forage:concentrate ratio 48:52 to 54:46.	The substitution of faba beans with rapeseed meal increased feed intake (+8%), milk yield (+8%), milk protein concentration (+4%), and protein yield (+11%) and tended to increase fat yield (+4%)	100%	Puhakka et al., 2016
	Pigs, fattening, BW 27 kg	100% of lupin	Isonitrogenous diets.	The substitution of lupin with rapeseed cake had no impact on final BW, ADG, feed intake or FCR.	100%	Partanen et al., 2006
Fish waste silage, ensiled fish by-products	Poultry, broilers (Cobb 500)	12% to 47% of soybean meal in starter phase, 14% to 56% in grower phase, 16% to 62% in finisher phase	Isonitrogenous and isoenergetic diets. Simultaneously, the proportion of corn was increased from 501 g/kg to 629 g/kg in starter phase, from 571 to 697 g/kg in grower phase and 609 to 735 g/kg in finisher phase	The substitution of soybean meal with fish waste silage increased BW (+7,5%), weight gain (+7,7%) and decreased feed conversion ratio (-3,9%)	47-62%	Shabani et al., 2021
	Poultry, broilers (Cobb 500)	25% to 75% of soybean meal	Isonitrogenous diets.	No impact on feed intake or FCR. Fish waste silage did not decrease average daily gain compared to control, and diets with 10 and 20% fish waste silage in DM resulted in highest ADG.	75%	Al-Marzooqi et al., 2010

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
	Poultry, broilers (Arbor-Acres)	8% to 24% of soybean meal	Isonitrogenous diets, only 14d long experiment	No statistically significant impact on feed intake, ADG or FCR, but highest substitution rate resulted in numerically poorest FCR (-8,9% compared to control)	24%	Vizcarra-Magaña et al., 1999
	Poultry, meat chickens (White Leghorn)	15% or 31% of fishmeal	Isonitrogenous and isocaloric diets	The substitution of fishmeal with fish silage resulted in similar or higher feed intake, ADG and FCR as fishmeal	31%	Espe et al., 1992
	Poultry, meat chickensbroilers (White Leghorn)	20% or 40% of fishmeal	Isonitrogenous and isocaloric diets. In addition, the supplementation of crystalline amino acids was studied	The substitution of fishmeal with fish silage resulted in similar or higher feed intake, ADG and FCR as fishmeal. The performance was not further improved by amino acid supplementation.	40%	Espe et al., 1992
	Poultry, meat chickensbroilers (White Leghorn)	6% to 39% of fishmeal	Isonitrogenous and isocaloric diets	No impacts on feed intake, ADG or FCR.	39%	Espe et al., 1992
	Pigs, growing, BW 45 kg	25% to 100% of fish meal	Isonitrogenous and isocaloric diets.	The substitution of fish meal with ensiled fish by-products increased feed intake (+4,9%), final BW (+5,2%), ADG (+11%) and improved FCR (-13%)	100%	Thi Thuy et al., 2011
Ensiled shrimp by-products	Pigs, growing, BW 19 kg	50% or 100% of fish meal	CP and gross energy concentration of 100% ensiled shrimp by-products diet was lower than the two other diets (CP 12,3 vs. 13%; GE 13,1 vs. 13,7 MJ/kg DM)	The complete substitution, but not 50% substitution rate, of fish meal with ensiled shrimp by-products decreased final BW (-7,2%) and ADG (-21%). The substitution linearly decreased feed intake (up to -24%) and linearly increased the length of growing period (+14%). No impact on FCR.	<50%	Ngoan et al., 2001
Fish by-product meal	Poultry, broilers (Arbor Acres × Arbor Acres)	12% to 53% of soybean meal in starter diets, 12% to 55% in grower diets, 12% to 56% in finisher diets	Isonitrogenous and isocaloric diets	No impact on the final BW or carcass weight. Diets with two highest substitution rates resulted in poorest FCR on weeks 2 to 4 of 6-week production period.	33-35%	Ponce and Gernat, 2002
Marine by-product meals	Poultry, laying hens (Bovans White)	5% of soybean meal	CP concentration varied but was higher for all experimental treatments (20,4-22,2%) than for control (18,6%)	No impact on egg weight. The impact of marine by-product meals on animal performance depended on the processing method. Dried mackerel, dried scallop viscera and dried shrimp heads resulted in similar egg production than soybean meal.	≥5%	Toyes-Vargas et al., 2018

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
Poultry meal	Pigs, piglets, BW 7 kg	100% of fishmeal	Isonitrogenous diets, proportion of fishmeal/poultry meal 0, 2,5 or 5% of diet, main protein feed soybean meal (26-30% of diet)	No impact on feed intake. The substitution of fishmeal with poultry meal decreased ADG and resulted in poorer FCR.	<100%	Keegan et al., 2004
	Pigs, piglets, BW 9 kg	100% of fishmeal	Isonitrogenous diets, proportion of fishmeal/poultry meal 0, 2,5 or 5% of diet, main protein feed soybean meal (29-33% of diet)	No impact on feed intake, ADG or FCR.	100%	Keegan et al., 2004
Meat and bone meal	Poultry, broilers (Ross 308)	6% to 15% of soybean meal	Isonitrogenous diets. Simultaneously, the proportion of corn was increased from 59% to 62%.	No impact on BW, weight gain or FCR.	15%	Bozkurt et al., 2004
	Poultry, broilers (Avian 48)	9 to 17% of soybean meal, depending on growth phase	Isonitrogenous and isoenergetic diets. Simultaneously, the proportion of corn was increased from 61/63/59 to 65/67/61%	No impact on feed intake, BW or FCR.	9-17%	Caires et al., 2010
	Poultry, broiler (Ross 308)	27% to 53% of soybean meal in starter diet, 44% to 82% in finisher diet	Isonitrogenous and isocaloric diets. Simultaneously, the proportion of corn was increased from 638/742 to 679/771 g/kg	The substitution of soybean meal decreased weight gain (-13%) and resulted in poorer FCR (+16%)	<27-82%	Liu et al., 2016
	Poultry, broiler	High-ash MBM 14% to 23% of soybean meal in starter diets, 15% to 24% in grower diets, 20% to 32% in grower diets Low-ash MBM 22% to 39% of soybean meal in starter diets, 23% to 43% in grower diets, 31% to 56% in grower diets	Simultaneously, the proportion of corn was changed and CP concentration slightly increased	No impact on BW or FCR.	14-32% for high-ash MBM 11-56% for low-ash MBM	Drewyor & Waldroup, 2000

Ingredient	Species	substitution (%)	substitution details	Results	Optimal substitution rate	reference
Blood meal	Poultry, broilers (Avian 48)	19% to 36% of soybean meal, depending on growth phase	Isonitrogenous and isocaloric diets. Simultaneously, the proportion of corn was increased from 61/63/59 to 62/68/67%	No impact on feed intake or FCR, the substitution of soybean meal with blood meal decreased final BW (-8,3%)	<19-36%	Caires et al., 2010
	Poultry, broilers (Ross)	5% or 10% of soybean meal	CP concentration was increased and energy concentration decreased with increasing proportion of blood meal	No impact on feed intake or weight gain. The substitution of soybean meal with blood meal improved FCR (-4,6%).	10%	Auh et al., 2010
	Poultry, broilers (Ross)	5% or 10% of commercial feed supplement (composition not mentioned)	Isonitrogenous and isocaloric diets	The substitution of commercial feed supplement decreased feed intake (-21%) and weight gain (-43%) and resulted in poorer FCR (+84%).	<5%	Auh et al., 2010
	Pigs, piglets, BW 7 kg	17% to 49% of soybean meal		No impact on feed intake. The substitution of soybean meal increased ADG, final BW and improved FCR.	49%	DeRouchey et al., 2002
Blood meal and bone flour	Pigs, growing, BW 18 kg	25% to 100% of soybean meal	Isonitrogenous and isocaloric diets. In addition, the supplementation with crystalline amino acids (Ile) was studied.	Moderate substitution rate (5,9% DM) resulted in best FCR. Complete replacement of soybean meal resulted in decreased feed intake and ADG compared to soy. Supplementation of Ile improved animal performance with 100% substitution rate, but did not perform as well as soy.	50%	King & Campbell, 1978
Feather meal	Pigs, growing, BW 23 kg	13% to 41% of soybean meal in grower phase, 17% to 48% in finisher phase	CP concentration was increased with increasing proportion of feather meal	Highest inclusion rate resulted in lower feed intake, final BW and ADG than diet with inclusion rate of 0 or 4% of DM. No impact on FCR.	34-43%	van Heugten & van Kempen, 2002
	Pigs, piglets, BW 11 kg	12% of soybean meal	Isonitrogenous and isocaloric diets	The substitution of soybean meal with feather meal increased feed intake (+6,7%), ADG (+15%) and final BW (+8,1%). No impact on FCR.	12%	Pan et al., 2016
	Pigs, growing, BW 50kg	100% of soybean meal	Isonitrogenous and isocaloric diets. In addition, the supplementation of feather meal diets with crystalline amino acids (Lys+Trp) was tested.	The substitution of soybean meal with feather meal decreased feed intake (-7,7%), ADG (-28%) and resulted in poorer FCR (-23%)	<100%	Brotzge et al., 2014

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