The protein challenge

Sari, Yessie W.; Widyarani, Y. W.; Sanders, Johan P. M.; Heeres, Hero J.

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Perspective

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The protein challenge: matching future demand and supply in Indonesia

Yessie W Sari†, Biophysics Division, Department of Physics, IPB University, Bogor, Indonesia
Widyarani †, Research Unit for Clean Technology, Indonesian Institute of Sciences, Bandung, Indonesia
Johan P M Sanders, Biobased Chemistry and Technology, Wageningen University, Wageningen, The Netherlands
Hero J Heeres, Department of Chemical Engineering, ENTEG, Rijksuniversiteit Groningen, Groningen, The Netherlands

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Abstract: Indonesia has the fourth largest population in the world and in the coming years food production will need to catch up with its growth. To fulfill the protein demand of this growing population, the productivity of the Indonesian agricultural sector should be increased. This can be achieved either by expanding the agricultural land or by increasing the productivity of existing agricultural land and protein use efficiency. An expansion of agricultural land is not always possible or desirable: large parts of Indonesia comprise forest areas, including tropical rain forests. Consequently, the optimization of the use of existing agricultural land is inevitable. The present manuscript describes and discusses the current protein consumption and production in Indonesia. It presents the levels predicted for 2035, which would imply a strong gap between consumption and production. Alternatives therefore need to be considered to avoid protein shortage in the future. These would include the use of new biomass resources, utilization of agricultural residues as alternative protein sources for feed and other nonfood applications, and biorefining of biomass sources. © 2021 Society of Chemical Industry and John Wiley & Sons, Ltd

Key words: Indonesia; agricultural residues; proteins; food; animal feed; biorefinery

Introduction

The world's population is expected to reach 9–10 billion people in 2050,[1] causing major impacts on our planet. To explore the anthropogenic effects on the Earth system, a new approach was proposed: 'planetary boundaries'. In this approach, several limits have been determined to indicate whether humans can operate safely. According to Rockström *et al.*[2] and Steffen *et al.*,[3] three planetary boundaries were overstepped in 2009: climate change, the rate of biodiversity loss, and the nitrogen cycle. Through extrapolations, it has been predicted that, from 2009 to 2050, the annual greenhouse gas emissions from food production may increase from 2.3 to 4.1 Gt CO_2 equivalents and that one of the main contributors may be land clearing for agriculture.[4] All of this would have severe impacts on biodiversity and the biogeochemical cycles, including the phosphorus and nitrogen cycles. Conijn *et al.*[5] and Springmann *et al.*[6] showed that diet change, waste reduction in households, increased feed efficiency, and increased field yields are required for staying within planetary boundaries. Notably, the application of only one of these measures will

†Both authors contributed equally to this work and should be considered co-main authors.

Correspondence to: Widyarani, Research Unit for Clean Technology, Indonesian Institute of Sciences, Kampus LIPI Jl Cisitu 21/154D, Bandung 40135, Indonesia. E-mail: widyarani@lipi.go.id

not suffice, and their combination will lead to the desired result only by overcoming major challenges. Besides the population, the average welfare level and per capita income are also expected to increase worldwide, leading to a higher proportion of animal products in human diets. To feed people and animals in 2050, about twice the current amount of protein will be required.[7] Already, two-thirds of the available agricultural land on Earth has been used to provide animal feed.[8] As such, the global future production of protein for food and feed applications is a major challenge.

Indonesia has the fourth largest population in the world, with 267 million people in 2019. This population is expected to grow to 304 million by 2035,[9] so food production needs to catch up. This would be particularly challenging for protein production, considering that Indonesia already imports 69% of the proteins used for commercial feed.[10] Hence, domestic sources should be identified to prevent extremely high dependence on imported proteins. Currently, arable land (14%) and permanent crops (19%) already occupy a considerable portion of the total 191 million ha of land area in Indonesia.[8] Expansion of agricultural land is not always possible or desirable as this might lead to extensive deforestation, also affecting tropical rain forests.

The objective of this paper is to provide an overview of the existing and new potential protein resources that might supply Indonesia's growing demand for proteins in the future. Additional protein supply may be derived from the use of new biomass resources and residues, such as agricultural leftovers or by-products of biomass processing from the food industry. Biorefinery,[11] a concept that involves the fractionation of primary crops and residues, might also contribute to higher protein-use efficiency. Our review first provides an overview of the applications of proteins in the food and feed industry. Subsequently, the current food and feed consumption of proteins estimated for Indonesia is presented together with predictions of future demand and consumption. Finally, possible solutions to close the gap between future demand and supply are presented together with an outlook on the relative challenges.

Methods

The current food and feed consumption of proteins in Indonesia was estimated using available statistics and used to project their future demand and consumption. The details regarding these calculations are provided in the supplementary information.

Data on the daily average protein consumption from 182 food items were obtained from the Indonesian Central Bureau of Statistics.[12] Food items were grouped into the following categories: (1) rice, (2) corn, (3) other cereals and tubers, (4) fish, shrimp, and other aquatic products, (5) meat (including processed meats), (6) eggs and milk, (7) vegetables and fruits, (8) tofu and tempeh, and (9) others (e.g., legumes, beverages, and mixed processed food). The annual protein consumption for each group of food items, and the total is calculated using Eqn (1):

$$C_{na} = C_{pd} \cdot population \cdot 365 \cdot 10^{-12} \quad (1)$$

where

C_{na} = annual national consumption (Mt proteins · year^{-1})

C_{pd} = daily consumption *per capita* (g proteins · person^{-1} · day^{-1})

Animal feed consumption is estimated using Eqns (2)–(4). Here, the feed–weight conversion ratio (X_{fw}) and protein–feed conversion efficiency (E_{pp}) are intended as described by Alexander *et al.*[13] and Tacon and Metian:[14]

$$X_{fp} = \frac{X_{fw}}{P} \quad (2)$$

$$C_{ft} = C_{na} \cdot X_{fp} \quad (3)$$

$$C_{fp} = \frac{C_{na}}{E_{pp}} \quad (4)$$

where

X_{fp} = feed conversion ratio (t feed · t proteins^{-1})

X_{fw} = feed–weight conversion ratio (t feed · t edible weight^{-1})

P = protein content (t proteins · t food^{-1})

C_{ft} = (total) feed consumption (Mt feed · year^{-1})

C_{fp} = feed–protein consumption (Mt feed proteins · year^{-1})

E_{pp} = protein–feed conversion efficiency (t proteins · t feed proteins^{-1})

The values of all of these parameters refer to dry matter (DM).

The protein demand in Indonesia in 2035 was estimated under two scenarios. Scenario 1 assumed that the daily *per capita* consumption would not change in the future. In this case, the annual protein consumption was calculated using Eqn (1) and the estimated population in 2035 (304 million).[1] Scenario 2 assumed, instead, that the daily consumption of total food proteins and animal-based proteins *per capita* would increase in 2035. For this purpose, we used a projection of the total protein consumption in 2050 (by Tilman *et al.*[7]), which correlates protein consumption with gross domestic product (GDP). On the basis of the projections obtained for countries in Economic Group D (with an annual GDP of 1000–4000 in 1990$), it was estimated that the protein consumption in Indonesia in

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2035 will be 31% higher than that in 2019. Notably, meat consumption was used as a proxy for animal protein consumption. According to Vranken *et al.*,[15] for countries that had an annual GDP < 35 035 in 2005$, a 1% rise in GDP would result in a 0.5% rise in meat consumption. The Indonesian GDPs in 2019 and 2035 were calculated using a projection from the Organization for Economic Co-operation and Development (OECD),[16] estimating an 82% increase in GDP between these 2 years. On the basis of this information, the Indonesian animal protein consumption in 2035 can be expected to be 41% higher than that in 2019. Using these data, we applied Eqns (1)–(4) to project the food and feed protein demands in 2035 under Scenario 2.

Data on protein production were obtained from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT),[8] the Indonesian Central Bureau of Statistics,[17] and the United States Department of Agriculture (USDA).[10,18] To estimate the production in 2035, 10 years (2009–2018) of production data from FAOSTAT were analyzed by linear regression.

General features of proteins

Proteins are macromolecules based on monomers known as 'amino acids'. Although a large number of amino acids are synthetically available, only 20 are present in proteins. Protein properties are defined by the type and arrangement of amino acids in the molecules. Proteins are present in biomass alongside other components such as lipids and carbohydrates. In many types of biomass, proteins are encapsulated in cell walls that are built up from cellulose, hemicellulose, and lignin. The presence of (residual) amounts of these biopolymers has a major effect on product properties (e.g., solubility, extractability, and digestibility), which, in turn, determine the suitability of a product for processing and different applications.[19] Among the 20 proteinaceous amino acids, nine (i.e., isoleucine, leucine, valine, phenylalanine, tryptophan, methionine, histidine, lysine, and threonine) are considered essential for humans and most farm animals because they cannot be synthesized by humans and most farm animals: they need to be supplied externally. Several amino acids are considered semi-essential because they are required under special circumstances (e.g., during illness and certain growth stages).

Protein applications

Proteins are important constituents of our daily food and are essential for the growth, maintenance, and metabolism of both humans and animals. Notably, proteins also have many other applications. For example, they are used to modify material properties (e.g., as emulsifiers, foaming agents, and adhesives).[20] Some purified, high-quality proteins or peptides are used as building blocks in the preparation of personal care products or pharmaceuticals.[21] Amino acids are also of potential interest for the production of nitrogen-containing base chemicals (e.g., acrylonitrile, ethanolamine, and 1,4-butanediamine),[22] although investigations of this type of application are still at an early stage. In the following subsections we will describe protein properties relevant for food, feed, and other applications.

Food products

Protein content and structure determine the texture and palatability of food products.[23] Notably, the nutritional qualities of proteins are mainly determined by their amino acid compositions, particularly the fraction of essential to total amino acids. The protein digestibility corrected amino acid score (PDCAAS), which indicates the digestible quality of proteins and the amino acid requirements for humans, is another important parameter to consider.[24]

Animal feed

For animal feed applications, the protein content, amino acid composition, and digestibility should also be considered in a similar way to the approach taken for human food applications. Amino acid requirements are animal specific and depend on the animal growth stage. This is particularly important for essential amino acids because they cannot be synthesized by most farm animals and should be assimilated from feed. A sample comparison between the amino acid composition of several protein sources and amino acid requirements for a 6–8 weeks broiler is presented in Table 1. Notably, cows are less dependent on essential amino acids because the microorganisms present in their first stomachs are able to synthesize essential amino acids from any type of protein.

Functional properties of proteins

Proteins are also used in food products to tailor their properties (e.g., they can serve as emulsifiers, foaming agents, and film-forming agents). Not all proteins are suitable for a certain application, and their functional properties (e.g., solubility and emulsifying capacity) need to be considered to assess their suitability. Table 2 shows the functional properties of some relevant protein sources.

Notably, corn protein concentrate and soybean protein isolate are commercial products, and cassava leaf protein concentrate is not yet produced commercially.[34] Moreover, palm kernel meal is available on the market in the form of an unprocessed product.[18]

Table 1. Essential and semi-essential amino acid content of selected protein sources (% of crude protein) and requirements for broiler feed.

Amino acid (AA)	Corn[25]	Soybean meal[26]	Palm kernel meal[27]	Cassava leaves[28]	AA requirements in feed[a]
Essential:					
Histidine	3.3	2.7	2–3	1–4	1.5
Isoleucine	2.9	4.6	3–5	6–8	3.4
Leucine	10.7	7.7	6–7	9–12	5.2
Lysine	3.4	6.3	3–4	7–8	4.7
Methionine	2.2	1.4	2–4	1–3	1.8
Methionine + cysteine	4.5	2.9	3–5	2–4	3.3
Phenylalanine	4.0	5.1	4–5	4–7	3.1
Phenylalanine + tyrosine	7.6	8.6	7–9	8–13	5.8
Threonine	3.6	4.0	4	4–6	3.8
Tryptophan	0.7	1.4	1	1–4	0.9
Valine	4.2	4.8	5–6	4–8	3.9
Semi-essential:					
Arginine	4.3	7.5	10–15	4–6	5.6
Glycine + serine	8.5	9.4	9–10	7–14	5.4
Crude protein (% of DM)	8.6	53.5	15–19	29–39	18.0

[a]Amino acid requirements in feed for a 6–8 week-old broiler[29].

Table 2. Functional properties of selected protein sources.

Functional properties	Unit	Corn protein concentrate[30]	Soybean protein isolate[31]	Palm kernel meal protein[27]	Cassava leaf protein concentrate[32,33]
Crude protein content	% of DM	83	92–95	69	42–47
Solubility (at pH = 7)	% of proteins	80	83–92	85	6–22
Water-holding capacity	g water · g sample^{-1}	NA	1.2–4.4	NA	3.5
Emulsifying capacity	g oil · g sample^{-1}	704–729	510–678	NA	NA
Emulsifying stability index	min	119–198	142–279	16	140
Foaming capacity	% of volume	98–107	96–104	22.5	12.5
Foaming stability	% (min)[a]	11–35 (150)	50 (8)	4 (30)	2 (80)

NA, data not available.
[a]Remaining foam after the time indicated within parentheses.

Current protein consumption in Indonesia

Estimations of the current food and feed protein consumption in Indonesia will be provided and discussed in the following paragraphs.

Human protein consumption in Indonesia

Human protein consumption in Indonesia ranged from 33 to 101 g · person^{-1} · day^{-1} in 2019, with a national average of 62 g · person^{-1} · day^{-1}.[12] This national average is lower than both the protein consumption in OECD countries (104 g · person^{-1} · day^{-1}) and worldwide (80 g · person^{-1} · day^{-1}). Moreover, it falls between the protein consumption of low-income (58 g · person^{-1} · day^{-1}) and lower middle-income countries (69 g · person^{-1} · day^{-1}).[35] Considering a population of 267 million, the annual total human protein consumption can be estimated to be 6.0 Mt.

Figure 1 shows various sources of proteins for human consumption: one-third of these proteins are derived from cereals, whereas 34% are derived from animals. The latter value is in line with the available data on animal protein consumption in lower middle-income countries (35%), and it is significantly lower than the value found for OECD countries (60%) and the worldwide average animal protein consumption (39%).[35] Overall, these data indicate that food crops currently represent an important source of proteins for humans in Indonesia.

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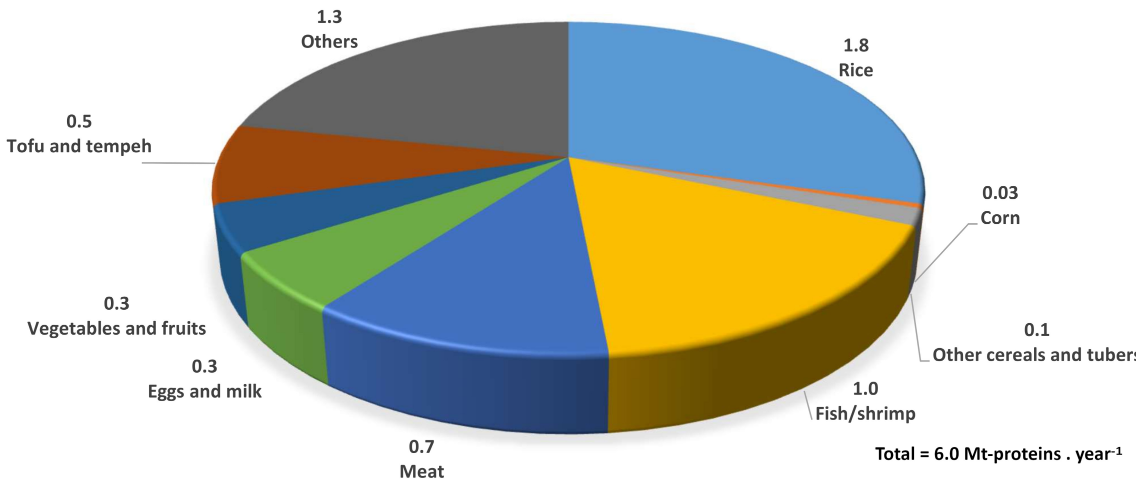

Figure 1. Protein consumption in Indonesia (Mt proteins · year^{-1}) in 2019 divided by food group.[12]

Table 3. Estimation of the animal feed consumption in 2019 based on the animal food protein consumption.

Food item	Animal food protein consumption[12] (Mt proteins · year^{-1})	Estimated feed consumption (Mt feed · year^{-1})	Estimated feed protein consumption (Mt feed proteins · year^{-1})
Fish and shrimp	0.69[a]	5.6	2.2
Beef	0.09	12.0	2.2
Chicken meat	0.61	11.1	3.1
Other meat	0.01	1.5	0.2
Eggs	0.21	3.5	0.8
Milk	0.14	3.8	0.6
Total	**1.74**	**37.4**	**9.2**

[a]Consumption from aquaculture only, estimated as two-thirds of the total consumption of fish, shrimp, and other aquatic products (1.03 Mt proteins · year^{-1})[17].

Animal protein consumption in Indonesia (excluding fodder/grazing)

On the basis of the production data from 97 feed mills in Indonesia, the commercial animal feed consumption in 2018 was estimated to be 20 Mt,[10] roughly corresponding to 4.9 Mt of feed proteins. We estimated the animal proteins consumed by humans (Fig. 1) and calculated the amount of proteins required to feed animals. The consumption of animal proteins (from meat, eggs, dairy, fish, shrimp, and other aquatic products) was calculated to be 2.1 Mt proteins · year^{-1} (Fig. 1). On the basis of the consumption patterns, we also calculated total animal feed consumption of 37 Mt feed · year^{-1}, corresponding to 9.2 Mt feed proteins · year^{-1} (Table 3). Our estimated total feed consumption is considerably higher than the commercial feed consumption (20 Mt feed · year^{-1}). The main reason for this difference is that not all farmers use commercial animal feed from dedicated mills. For example, 20% of chicken production is done traditionally by smallholder farmers and individual households. In these cases, chickens are fed with any available feed, including rice bran, grains, grass, insects, earthworms, and food waste.[36,37] Meanwhile, foraging is a common practice for ruminant production. In Java, this is often integrated with the cropping system: forage is cut and carried from roadsides or field margins.[38] In Eastern Indonesia, where more land is available, grazing is also common, especially during the wet season.[36,39]

Current protein production in Indonesia

Production of food proteins

Relevant food crops are listed in Table 4 together with their protein and essential amino acid content, plantation area, and estimated annual production level. The annual protein

Table 4. Food protein production in Indonesia in 2018.

Crop	Protein content[12] (% of DM)	Essential amino acids (% of proteins)[a]	Plantation area[b] (million ha)	Productivity[b] ($t \cdot ha^{-1} \cdot year^{-1}$)		Production[b] ($Mt \cdot year^{-1}$)	
				Dry matter	Protein	Dry matter	Protein
Rice	8.5	35	16.0	3.1	0.26	49.8	4.22
Corn	8.3	39	1.9[c]	3.2	0.26	6.1	0.50
Peanuts	25.3	30	0.4	0.8	0.20	0.3	0.07
Soybean	40.4	37	0.7	0.8	0.32	0.6	0.23
Tubers (bulk)	1.2	NA	0.9	12.7	0.15	11.8	0.14
Vegetables (bulk)	10.2	NA	1.1	2.0	0.21	2.3	0.23
Fruits (bulk)	2.9	NA	0.8	5.0	0.15	4.1	0.12
Total production							**5.52**

[a]Essential amino acids: isoleucine, leucine, valine, phenylalanine, tryptophan, methionine, histidine, lysine, and threonine. The amino acid compositions were obtained from Orr and Watt.[40]
[b]Data on the plantation area, annual production, and productivity are from FAOSTAT.[8] The dry matter content of fresh products was assumed to be 60% for rice, corn, cassava, sweet potato, peanuts, and soybean, and 20% for vegetables and fruits.
[c]One-third of the corn production was used for food and two-thirds for feed.[10] The corn plantation area for food production was estimated from a total of 5.7 million ha for both food and feed production.

production was estimated to be 5.5 Mt. Rice is currently by far the main protein source in Indonesia, and about 77% of the annual plant protein production in the country is derived from it.

Other sources of plant protein are corn, legumes, cassava, and sweet potato. Soybean curd (tofu) and fermented soybean (tempeh) consumption account for 8% of the average protein consumption.[12] In Indonesia, soybean is mostly grown as a secondary crop: its productivity is only 1.3 $t \cdot ha^{-1}$ (0.8 $t\ DM \cdot ha^{-1}$) for an annual nationwide dry-matter production of 0.6 Mt.[8,18] However, this country annually imports 2.7 Mt of soybean for the production of food (i.e., soybean curd, fermented soybean, and soy milk).[18]

There are discrepancies between the food protein production (Table 4) and consumption (Fig. 1) of proteins from main food crops, most notably for rice. For instance, the human consumption of proteins from rice was estimated to be 1.8 Mt proteins $\cdot\ year^{-1}$ against a total production of 4.2 Mt proteins $\cdot\ year^{-1}$. Taking into account that 30% of the total protein production (1.3 Mt proteins $\cdot\ year^{-1}$) is for storage,[41] there is still a difference of around 1.2 Mt proteins $\cdot\ year^{-1}$ between those values. One of the reasons for this difference is the use of different methods by different agencies involved in the data collection and production–consumption calculations.[42] Dry matter and protein content vary considerably among regions, plant varieties, and seasons, further complicating the calculations.

Production of feed proteins

Table 5 shows the production data of the main protein sources of commercial feed in Indonesia. These include corn, fish meal, rice bran, copra meal, and palm kernel meal. Apart from commercial feeds, it is important to consider that livestock owners (especially smallholders) often create their own feed formulations or use locally available fodder.[36,37]

Current gap between production and consumption of proteins in Indonesia

Food proteins

The actual consumption of proteins by humans in Indonesia is 6.0 Mt proteins $\cdot\ year^{-1}$, of which 4.0 Mt proteins $\cdot\ year^{-1}$ is derived from plants (Fig. 1). The current food protein production from plants in Indonesia was estimated to be 5.5 Mt proteins $\cdot\ year^{-1}$ (Table 4). On this basis, we can conclude that the production of food proteins from plants is sufficient to meet the current demand.

Feed proteins

The actual animal food protein consumption by humans was estimated to be 2.1 Mt proteins $\cdot\ year^{-1}$ (Fig. 1), of which 0.3 Mt proteins $\cdot\ year^{-1}$ would be derived from captured fish. The remaining 1.7 Mt proteins $\cdot\ year^{-1}$ would come instead from livestock and aquaculture, requiring the use of 9.2 Mt feed proteins $\cdot\ year^{-1}$ (Table 3). In total, the combined amount of feed proteins imported and produced in Indonesia would be of 6.5 Mt feed proteins $\cdot\ year^{-1}$ (Table 5). This gap between feed protein consumption and production (including import) is likely due to inaccuracies in the data used for the calculations.

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Table 5. Current production and import of feed proteins.

Feed ingredient	Crude protein content[43] (% of DM)	Protein production in Indonesia[a] (Mt · year^{-1})		Imported feed proteins[b] (Mt · year^{-1})	
		Dry matter	Protein	Dry matter	Protein
Corn	9–11	12.0	1.20	1.0	0.10
Fish meal	57–70	0.1	0.07	1.3	0.85
Rice bran	14	3.6	0.51	-	-
Copra meal	22	0.5	0.11	-	-
Palm kernel meal	17–22	0.6	0.12	-	-
Soybean meal	44–48	-	-	4.4	2.05
Corn gluten meal	60–67	0.1[c]	0.02[c]	1.9	1.19
Wheat pollard	15–18	-	-	0.7	0.11
Distiller's dried grain with solubles (DDGS)	37	-	-	0.6	0.21
Total			**2.03**		**4.52**

[a]Data on corn, copra meal, and palm kernel meal production were obtained from the USDA.[10,18] Fish meal and rice bran production were estimated from the feed composition.[10]
[b]Data on imported corn and soybean meal were obtained from the USDA.[10,18] Data on imported fish meal, corn gluten meal, wheat pollard, and DDGS data were instead estimated from feed composition[10].
[c]Actual data on local corn gluten meal were not available. Its amount was therefore estimated from corn oil production.[8] The estimated value was obtained by combining the amounts of corn gluten meal (60% protein content) and corn gluten feed (21% protein content)[44].

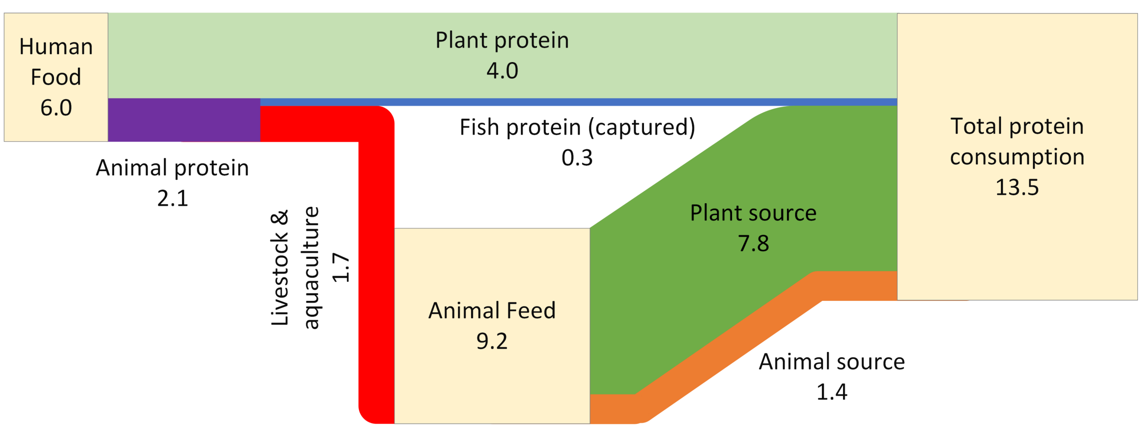

Figure 2. Actual protein consumption for human food and animal feed in Indonesia in 2019. All values are expressed in Mt proteins · year^{-1}.

Conclusions regarding the current protein production and consumption in Indonesia

An overview of the protein consumption in Indonesia is given in Fig. 2. In general, the data clearly suggest that protein consumption (particularly that for animal feed) exceeds protein production in Indonesia, creating a necessity for imports.

Interestingly, there are differences among the main protein sources of locally produced and imported feed proteins (Table 5). The main locally produced feed protein source is corn,[10] which is high in energy but, owing to its low protein content and digestibility, is not a good protein source. Imported feed protein sources are mainly represented by soybean and fish meals, which have favorable amino acid compositions compared to others. Thus, Indonesia should focus on producing high-quality proteins to reduce its dependency on imports.

Projections of future protein demands in Indonesia

We estimated the protein demands in Indonesia in 2035 under two scenarios: Scenario 1, in which the protein composition (animal based versus plant based) remains the same, and Scenario 2, in which there is a higher demand for animal-based proteins compared to nowadays (Fig. 3). The data shown in Fig. 3(a) were obtained by considering Scenario 1, assuming that the increase in protein demand would come solely from an increase in population from 267 million (in 2019) to 304 million (in 2035). The consumption of proteins by humans in Indonesia in 2035 was estimated to be 6.9 Mt proteins · year^{-1}, of which 4.5 Mt proteins · year^{-1} would be of plant origin. The remaining 2.4 Mt proteins · year^{-1} would be of animal origin: 0.4 Mt proteins · year^{-1} from captured fish and 2.0 Mt proteins · year^{-1} from livestock and aquaculture. Obtaining this amount of animal food proteins would require the use of 10.5 Mt feed proteins · year^{-1}, both from plant (8.9 Mt feed proteins · year^{-1}) and animal (1.6 Mt feed proteins · year^{-1}) sources. The projected total protein demand under this scenario would be 15.4 Mt proteins · year^{-1} (14% increase from 2019 to 2035).

The results for Scenario 2 are shown in Fig. 3(b), and these results were obtained by assuming that the total food protein consumption would increase by 31% and the consumption of animal-based proteins would increase by 41% (based on Tilman *et al.*[7] and Vranken *et al.*;[15] the corresponding calculations are described in the supplementary information). Under this scenario, the consumption of proteins by humans in Indonesia would be 9.1 Mt proteins · year^{-1}, of which 5.7 proteins Mt · year^{-1} would be of plant origin. The projected animal food protein consumption by humans was estimated to be 3.4 Mt proteins · year^{-1}: 0.6 Mt proteins · year^{-1} from captured fish and 2.8 Mt proteins · year^{-1} from livestock and aquaculture. Obtaining this amount of animal food proteins would require the use of 14.8 Mt feed proteins · year^{-1} both from plant (12.6 Mt feed proteins · year^{-1}) and animal (2.2 Mt feed proteins · year^{-1}) sources. The projected total protein demand under this scenario would be 21.1 Mt proteins · year^{-1} (56% increase from 2019 to 2035).

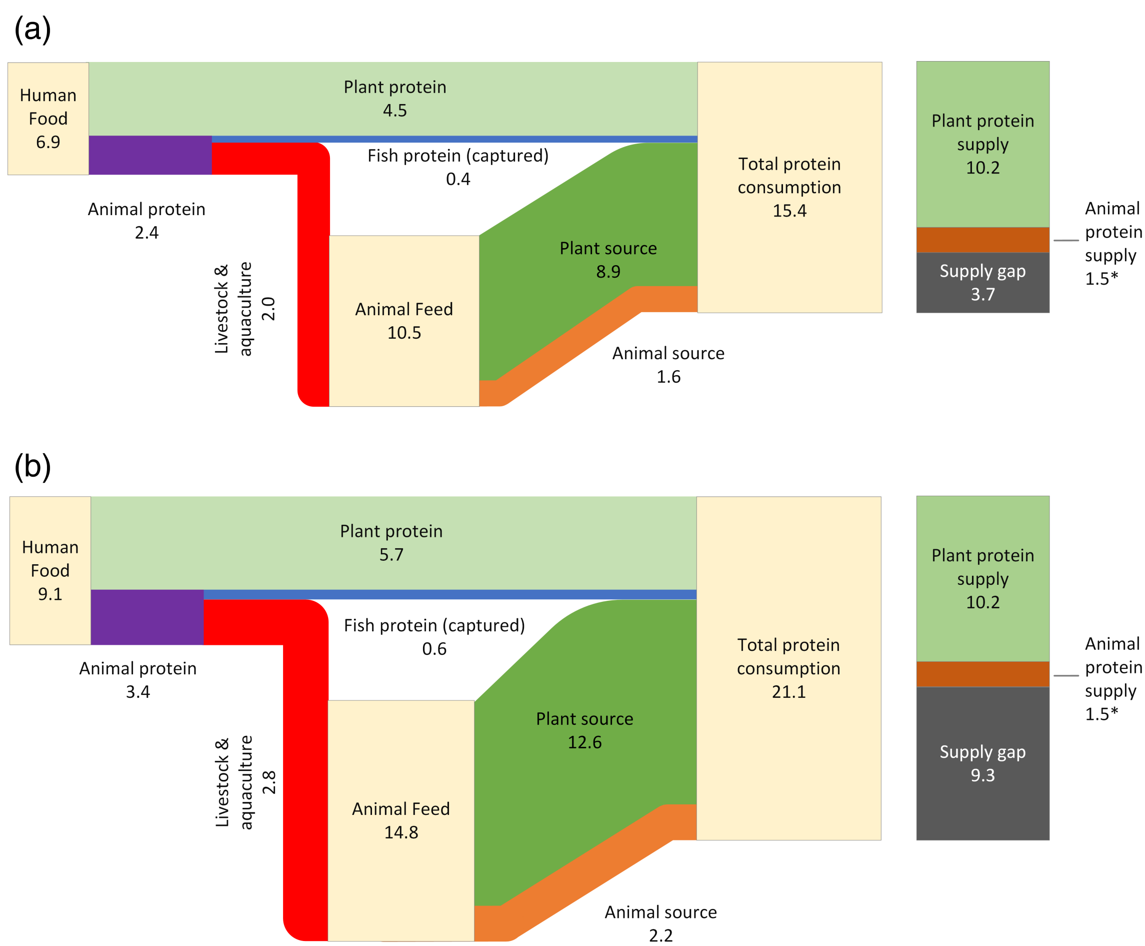

Figure 3. Projections of the protein demand in 2035 obtained by considering the following: (a) no changes in the consumption pattern and (b) an increased protein consumption. All values are expressed in Mt proteins · year^{-1}. *The animal protein supply was estimated to be 15% of the plant protein supply.

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Possible solutions to match future demand and production in Indonesia

In the following subsections, we will propose possible solutions to cope with the increase in the demand for proteins projected for the next 15 years. These include an analysis of the possibility of increasing the protein production by traditional means (i.e., by increasing the harvested area and crop productivity), identification of novel protein sources, and application of the 'biorefinery' concept. We will also demonstrate that, by combining these measures, the Indonesian protein production will have the potential to fulfill the local protein supply and reduce the country's import dependency.

Projections of protein production by traditional means

Figure 4 shows the changes in harvested area, production, and productivity for three food crops in Indonesia (i.e., rice, corn, and soybean) between 2009 and 2018. Rice production increased on average by about 1.3 Mt DM · year^{-1}. This growth can be attributed to an increase in both the harvested area (0.3 million ha · year^{-1}) and productivity (0.02 t DM · ha^{-1} · year^{-1}). The harvested area for corn increased by 0.2 million ha · year^{-1}, and the productivity increased by 0.07 t DM · ha^{-1} · year^{-1}. On the other hand, the harvested area for soybean remained approximately constant, and its productivity increased by 0.01 t DM · ha^{-1} · year^{-1}. On the basis of these data, we projected the protein production in 2035 for the three products mentioned above, as well as for other food crops (Table 6).

In 2035, the total protein production from food crops was estimated to be 10.2 Mt proteins · year^{-1}. Notably, the main protein sources are still rice and corn (Table 6). This amount of protein production is lower than the demand of plant proteins for food and feed under Scenario 1 (13.4 Mt proteins · year^{-1}) (Fig. 3(a)). Under Scenario 2 (Fig. 3(b)), the situation would be even more unbalanced: we estimated a shortage of around 8.1 Mt proteins · year^{-1} in plant proteins, particularly for animal feed. On the basis of the projections done for the two scenarios, we can conclude that the current agricultural system in Indonesia will not be able to solve the protein challenge.

Identification of novel protein sources

A second option to cope with the increase in the demand for proteins involves the identification of novel protein sources in Indonesia. A wealth of alternative protein resources can be envisaged, although not all of them may be suitable because, for example, of a low protein content, the presence of components that reduce their digestibility, or the presence of toxic components. Some types of unsuitable protein resources are green leaves from trees and other plants, including grasses and crop residues that stay on the field or are burned after the harvesting of the food crop. Moreover, residues from industrial processes (e.g., starch and biodiesel production) contain proteins that might be used as protein sources.

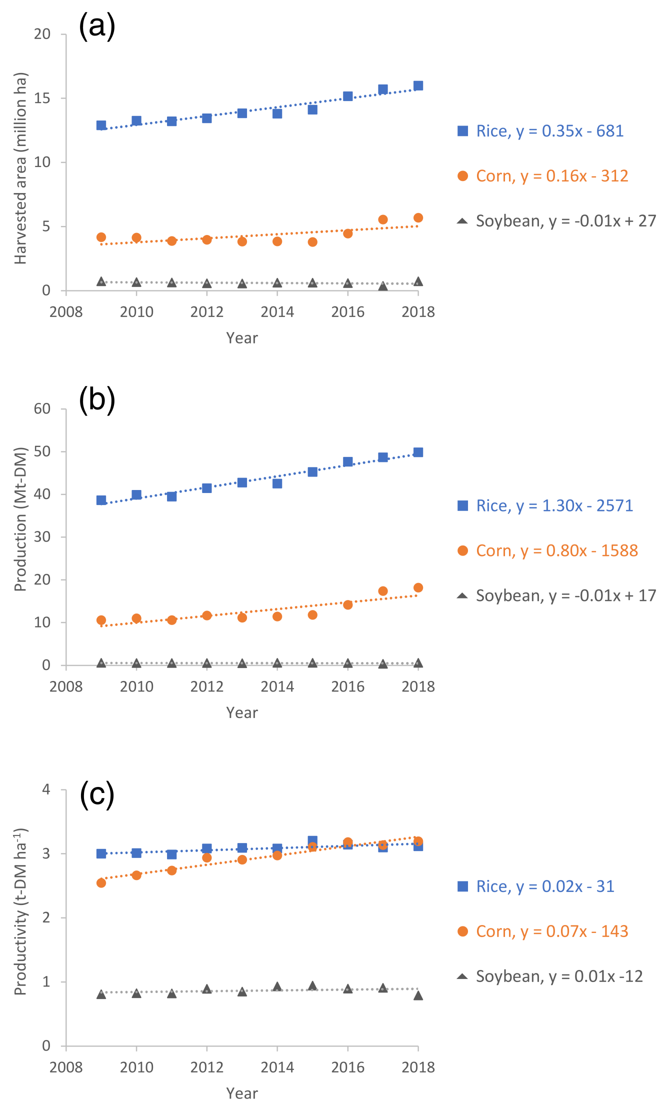


Figure 4. Changes in harvested area (a), production (b), and productivity (c) for rice, corn, and soybean between 2009 and 2018 (based on data obtained from FAOSTAT).[8]

Food-processing residues

Table 7 shows some potential protein resources from agricultural residues. A list of them, including more than 40 items, is provided in the supplementary information.

Table 6. Projected protein production from the main food crops in Indonesia in 2035.[8]

Crop	Harvested area (million ha)		Productivity (t DM · ha^{-1} · year^{-1})		Production(Mt · year^{-1})	
	Estimated annual growth	Area in 2035	Estimated annual growth	Productivity in 2035	Dry matter	Protein
Rice	0.35	21.6	0.02	3.4	74.3	6.3
Corn	0.16	7.7[b]	0.07	4.5	34.6	2.9
Peanuts	0[a]	0.4	0[c]	0.8	0.3	0.1
Soybean	0[a]	0.7	0.01	1.0	0.7	0.3
Tubers	0[a]	0.9	0.31	18.7	17.3	0.2
Vegetables	0.01	1.3	0.03	2.5	3.3	0.3
Fruits	0[a]	0.8	0.08	6.5	5.3	0.2
Total						**10.2**

[a]For crops with negative growth, the harvested area was assumed to be similar to that in 2018[8].
[b]The area includes that for both food and feed production.
[c]For crops with negative growth, productivity was assumed to be similar to that in 2018[8].

Table 7. Selected overview of potential protein resources from agricultural residues.

Biomass	Distribution	Plantation area (million ha)	Current use	Crude protein content (% of DM)	Essential amino acids (% of proteins)	Productivity		Potential protein production (Mt proteins · year^{-1})
						t DM · ha^{-1} · year^{-1}	t proteins · ha^{-1} · year^{-1}	
Cassava[8,45,46]:	All islands	0.7						
• Leaves			Food	15–40	44–58	2–5	0.2–1.9	0.2–1.3
Corn[8,40,44]:	All islands	6						
• Corn gluten meal			NA	60	11–22	1.5[b]	0.9[b]	0.01
• Corn gluten feed			NA	21	11–22	6.2[b]	1.3[b]	0.01
Grass[47–52]:	All islands							
• *Brachiaria*		8[a]	Animal feed, not collected	8–11	NA	7–20	0.7–1.9	5.4–15.1
• *Imperata* (Alang-Alang)		9	Animal feed, not collected	4–18	NA	4	0.1–0.7	1.2–6.3
• Napier (king/ elephant)		6[a]	Animal feed, not collected	6–13	NA	27–58	2.6–5.5	15.4–33.1
Oil palm[8,18,27,53–55]:	Java, Sumatera, Kalimantan	15						
• Palm kernel meal			Animal feed, exported	14–15	24–40	0.4–0.6	0.1	0.7–1.3
• Frond (leaflet)			Left on the field as fertilizer	7 (11)	40 (43)	10 (6)	0.7 (0.4)	9.8 (5.6)
Rice[8,56,57]:	All islands	16						
• Leaves			Left on the field as fertilizer	19–24	31	4	0.8–1.0	12.0–15.4
Rubber[8,58]:	Sumatera, Kalimantan	4						
• Leaves			Left on the field as fertilizer	18	NA	2	0.4	1.4
Available protein from plant residues								**41.9–83.6**

NA, data not available.
[a]Estimated data.[8]
[b]All values are in t · t oil^{-1}.

Rice is the most important food commodity in Indonesia, with a harvesting area of 16 million ha and an annual production of 83 Mt (50 Mt DM).[8] To obtain white rice endosperm, rice grain is exposed to two steps of dry milling. The first milling removes the hard, protective hull (or husk). Once this is removed, the rice grain is called 'brown rice'. The second step involves gentle milling aimed at removing the germ and bran from the grain, thus exposing the white, starchy rice endosperm. Hulls, brans, broken grains, and straw are all by-products derived from rice processing and are commonly used as ingredients in horticultural, livestock, industrial, household, building, and food products.[59]

Corn gluten meal is a by-product derived from corn wet milling during the production of corn oil. The production of this oil is still at a low level in Indonesia, being estimated at 8400 t in 2018, with a growth of 317 t · year^{-1}.[8] A quantity of 1.5 t · t oil^{-1} of corn gluten meal with a protein content of 60% can be produced. The wet milling process also produces corn gluten feed at a higher volume (6.2 t · t oil^{-1}) but with a lower protein content (21%).[44]

Other residues have the advantage of already being collected during food processing. Their processing can therefore be integrated within existing industries. Coffee drink production generates spent coffee residue at 0.9 t · t coffee^{-1}, with a protein content of 11%–15%.[60] Tofu (soybean curd) production generates solid residue (2 t · t soybean^{-1} at 35% protein) and whey (5 m^3 whey · t soybean^{-1} at 1.6 g proteins · L^{-1}).[61,62] The solid residue from tofu production is currently used as animal feed at a price of USD 0.10–0.40 per kg wet-weight (moisture = 60%–90%).[63]

Other residues may be considered as potential protein sources based on their abundance or protein content. Pods and peels are abundantly available from agricultural production and processing. These have a high lignocellulosic content and, usually, a protein content lower than 5%. For instance, cassava peels have a protein content of only 5% but their production is also abundant (1.5 t DM · ha^{-1} · year^{-1}) and can be easily obtained from the tapioca or bioethanol industries. Meanwhile, cocoa bean shells have a protein content of 22%, but their production is relatively scarce (lower than 0.1 t · ha^{-1} · year^{-1}),[64] making them a less attractive protein source.

Animal protein and processing by-products

The Indonesian livestock production is growing by 5%–8% each year. This sector is dominated by chicken meat production, which is higher than the production of all other meats combined.[17] Animal slaughterhouse wastes are abundant and may lead to environmental problems when not treated or used. The amount of waste from cattle production, which includes a mixture of blood, internal organs, bones, hair, and leftover feed, has been estimated to be 19 kg · head^{-1} (in fresh weight).[65] Cattle blood, which is produced at 2–3 kg proteins · head^{-1}, is a good source of protein and is currently used as animal feed, mainly for fish and poultry. Chicken feather can be obtained from chicken production at 40–60 kg DM · 1000 heads^{-1} and has instead a protein content of up to 90%. Chicken feather protein consists mainly of low-digestible keratin, but after processing of the meal, it can be used as animal feed.[66]

Aquaculture and seafood processing generate waste in the form of inedible parts (e.g., heads, scales, and internal organs). This waste has a high good-quality protein content (14%–67%). Fish meal, for instance, has a protein content of 67% and essential amino acid content of 29% (particularly lysine, with 5% of crude protein).[67]

Many types of animal waste proteins have high potential because of their high PDCAAS content. However, there is an important issue involved in protein extraction from animal waste: different types of proteins are present in various tissues, making the extraction challenging and more complicated.[68] Furthermore, as a general consideration, pathogenic agents might be present in this type of waste, requiring special attention. Table 8 shows that the total amount of animal waste

Table 8. Properties of potential protein resources from animal residues.

Animal	Annual production of the main product	Crude protein content (% of DM)	Annual productivity		Potential protein production (Mt proteins · year^{-1})
			Dry matter	Protein	
Chicken[17,66]: • Feather	3439 million heads	75–90	0.04–0.06 kg · head^{-1}	0.03–0.05 kg · head^{-1}	0.11–0.17
Cattle[17,69]: • Rumen • Blood	16.4 million heads	12–14 68–79	3.6 kg · head^{-1} 3–4 kg · head^{-1}	0.5 kg · head^{-1} 2–3 kg · head^{-1}	0.01 0.03–0.05
Fish[17,70]: • Solid waste	23 Mt	58	0.04–0.13 t · t fish^{-1}	0.02–0.07 t · t fish^{-1}	0.54–1.72
Available protein from animal residues					**0.69–1.94**

protein nowadays is 0.7–1.9 Mt proteins · year^{-1}. With the anticipated annual growth of meat consumption in Indonesia, this residual stream may increase to 2.7 Mt proteins · year^{-1} in 2035.

Municipal solid waste

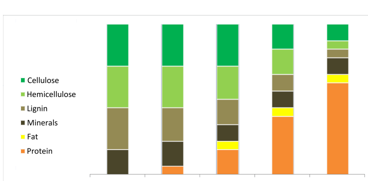
Municipal solid waste (e.g., from households and restaurants) has a protein content of up to 40%, depending on the mixed waste composition.[71] Restaurant waste might be a good candidate for processing because of its ease of collection and relative homogenous composition compared to household waste.

Alternatively, organic fractions of municipal solid waste can be digested by saprophages (e.g., earthworms and larvae of black soldier flies).[72,73] The resulting biomass has a protein content of up to 65% and can be used as animal feed.

The biorefinery concept

The fractionation of alternative biomass resources based on the biorefinery concept may lead to valuable fractions, potentially feasible for animal feed and even human food. The remaining fractions may be used in industrial applications (e.g., to substitute fossil resources). Moreover, biorefining can increase the value of resources that have an extremely high content of fibers, salts, or antinutritional components. Some of these are nowadays used as cattle feed, though they would be more suitable as poultry or fish feed.

Figure 5 gives an overview of the potential of the biorefinery concept for various agricultural residues. Agricultural primary crops and residues were grouped into five categories according to their protein content. Further processing of Group 5 residues (e.g., soybean meal), which have a protein content of around 50%, in biorefineries is not beneficial: soybean meal already has a high value. The biomass resources included in Group 4 residues (e.g., rapeseed meal), which have a protein content of around 35% and whose quality is just sufficient to serve as poultry or pig feed, can instead benefit from biorefining. For instance, when biorefining this residue to a protein product with a protein content of approximately 60%–70% and with no potassium, phosphate, toxic components, or C5 sugars, the value of the product per kg of proteins increases considerably: the latter components are not desirable in poultry and pig feed. Most of these 'adverse' components can be valuably used as fertilizers or as substrates in industrial fermentation processes. Group 3 residues (e.g., grass), which have a protein content of around 15%–20%, are typically used as cattle feed. In this case, the separation of valuable components by biorefining may increase their profitability. Group 2 residues have a low protein content (around 5%–10%), and subsequently, they are often left in the field. Biorefining may increase the value of the components of such residues and at least compensate for the costs involved in the process. For Group 1 residues (which hardly contain any protein), this separation would be costly, and biorefining is hence not considered profitable.



Protein content	0	5 %	15 %	35 %	50 %
Examples	Wheatstraw	Cocoa hulls Corn cobs Sugarcane leaf	Coffee pulp Rape straw Beet leaf	Rape meal	Soybean meal
Cost (€/ton)	50-80	50-110	100-140	150-180	300-350

Figure 5. Classification of agricultural residues based on their protein content and prices in the European market.[74]

Table 7 highlights grass, palm fronds, and rice leaves as the most important agricultural residues. Overall, these might contribute to the production of 42–84 Mt proteins · year^{-1}. A long list, including more than 40 protein sources that might contribute up to 89 Mt proteins · year^{-1}, is provided in the supplementary information. These values, as previously discussed, exceed the predicted demand for 2035 (Fig. 3). The Dutch start-up company Grassa (www.grassa.nl) has developed a (mobile) biorefinery process that may be suitable for grass, palm fronds, and rice leaves. A similar process is under development by Aarhus University in Denmark. The Grassa process involves the splitting of grass into four fractions: (1) a protein/fiber fraction (35% of DM), which is very suitable for cattle feed; (2) a dried protein fraction (45% of DM), which has a protein content comparable with that of soybean meal; (3) a fructo-oligosaccharide fraction that may be used as a prebiotic for small animals like piglets and poultry; and (4) a mineral concentrate that can be used as a fertilizer.

The removal of residues that nowadays stay in agricultural fields would imply the necessity of supplying nitrogen to those same fields. Leguminous plants (e.g., soybean and peanuts) may be used for this purpose because they can fix the required nitrogen from the air.

Biobased applications of amino acids

Some proteins, like those obtained from slaughterhouse or municipal waste, are not suitable for animal feed for hygienic reasons. These proteins can be hydrolyzed to a mixture of single amino acids and subsequently separated.

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Several separation approaches (e.g., amino acid anti-solvent crystallization and separation by density differences) have been published previously.[75]

Amino acids can be used as precursors for the production of nitrogen-containing chemicals. In a conventional petrochemical route, nitrogen is usually added in the form of ammonia. Ammonia is produced via the Haber–Bosch process, which requires high temperature and pressure. In amino acids, the amine functional group is already available. The production of nitrogen-containing bulk chemicals using amino acids therefore presents an advantage compared with the petrochemical route. For instance, *N*-methylpyrrolidone (an important industrial solvent) can be produced from glutamic acid in a two-step reaction under relatively mild conditions and using enzymes.[76] This two-step biobased process is much simpler than the conventional process, which is instead based on the use of natural gas in an eight-step reaction (under temperatures of 80 °C–350 °C) and of ammonia as a nitrogen source.[77] Other processes applied to the production of bulk chemicals from amino acids are the conversion of glutamic acid to succinonitrile and acrylonitrile, aspartic acid to acrylamide, arginine to 1,4 butanediamine, serine to 1,2 ethanediamine, and several amino acids to their nitrile derivatives.[22,78–81]

The use of amino acids for chemical production requires an improvement of the process used to separate amino acids from hydrolysate or fermentation broths. One solution could be the integration of protein hydrolysis and amino acid separation. When hydrolysis is achieved using nonaqueous solvents, enzyme combinations, or (thermo-) chemical treatments, it can influence the liberation of free amino acids from proteins.[82] When using nonaqueous solvents, enzyme combinations, or (thermo-) chemical treatments, it is also possible to convert the amino acids into intermediate product(s) with properties that may be beneficial for their separation.[83]

Conclusions

This paper has provided insights into the Indonesian protein supply and demand projected for 2035. In 2035, the estimated annual production of proteins from traditional cereal-based crops in the country (10.2 Mt proteins · year^{-1}) will not meet the demand for proteins for both food and feed applications (21.1 Mt proteins · year^{-1}). The use of alternative protein resources will hence be required. An inventory of the current agricultural residues shows that, annually, 42–84 Mt proteins · year^{-1} would be potentially available. Among these, agricultural residues with a high protein yield per ha (e.g., grass, rice leaves, and palm fronds) should be given the highest priority.

Next to protein productivity, the ease of collection and transportation of protein resources should also be taken into account. Residues from crop-processing industries and slaughterhouses can hence be considered of high interest. Moreover, the integration of protein processing in established industries can be considered advantageous compared to the creation of new ones. Considering the production scale, availability, and high protein content of several of its residue streams (e.g., palm kernel meal and palm fronds), the palm-oil industry has high potential in this sense. Small-scale processing can also be beneficial – for instance when using residues with a high moisture content (which need to be processed shortly after harvesting to avoid decomposition) or in remote areas (where logistics prevent large-scale processing).

Should the future protein demand for food and feed be fulfilled, excess protein production may be exported or used for other purposes (e.g., as raw materials for the chemical industry to manufacture biobased bulk chemicals). Considering their ease of implementation (e.g., technological readiness level), we propose that the utilization of agricultural residues with a high protein yield per ha (e.g., grass, rice leaves, and palm fronds) for feed production should be given the highest level of attention, both on a large and small scale, to bridge the gap between the protein consumption and production forecast for 2035 in Indonesia.

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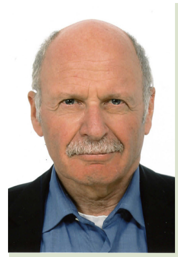
Yessie W Sari

Yessie Widya Sari is an assistant professor in biophysics division of the Department of Physics, Faculty of Mathematics and Natural Sciences, IPB University, Indonesia. She holds a PhD from Wageningen University, the Netherlands. Her research interest includes biomaterial, biomass, and bioenergy.

Widyarani

Widyarani is a researcher at the Research Unit for Clean Technology, Indonesian Institute of Sciences. She completed her PhD at the Biobased Chemistry and Technology Group, Wageningen University. Her current interests include the topics of wastewater treatment and biorefinery, including resource recovery from waste streams.



Johan P. M. Sanders

Professor Johan Sanders studied molecular biology. He worked 25 years in industry, first at a fermentation company and then as the research director in a large potato starch company. He was a professor of biobased economy for 14 years at the Wageningen University, where he developed biorefineries on small and large scale. He now actively contributes to biobased initiatives from his own company.

Hero J. Heeres

H.J. (Erik) Heeres is a full professor in green chemical reaction engineering at the University of Groningen, the Netherlands. His research interests concern the development of efficient catalytic technology for biomass conversions using metal-based catalysts.