

*Review*

## Challenges for Plant Breeders from the View of Animal Nutrition

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Academic Editor: Wayne L. Bryden

*Received: 14 May 2015 / Accepted: 3 December 2015 / Published: 12 December 2015*

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**Abstract:** The question of how to feed the growing world population is very old, but because of the increase of population and possible climate change, currently it has an explosive impact. Plant breeding can be considered as the starting point for the whole human food chain. Therefore, high, stable and highly digestible yields of phytogetic biomass with low external inputs of non-renewable resources, such as water, fuel, arable land, fertilizers, *etc.*; low emissions of gases with greenhouse potential during cultivation; and high resistance against biotic and abiotic stressors, including adaptation to potential climate change, and a low concentration of undesirable substances in the plants are real challenges for plant breeders in the future. Virtually unlimited resources such as sunlight, nitrogen and carbon dioxide from the air as well as the genetic pool of microbes, plants and animals can be used to breed/develop optimal plants/crops. Biofortification of plants may also be an objective of plants breeders, but it is more important for human nutrition to avoid micronutrient deficiencies. A lower concentration of undesirable substances in the plants can be considered as more important than higher concentrations of micronutrients in plants/feeds. Animal nutritionists have various possibilities for feed additive supplementation to meet animal nutrient requirements. Examples to reduce undesirable substances in feed plants are discussed and shown in the paper. In summary, plant breeding has a large and strategic potential for global feed and food security. All breeding technologies may contribute to solving important global challenges, such as sustainable use of limited global resources, improved use of unlimited resources, adaptation to climate change and lowering global greenhouse gas emission. More publically supported research seems to be necessary

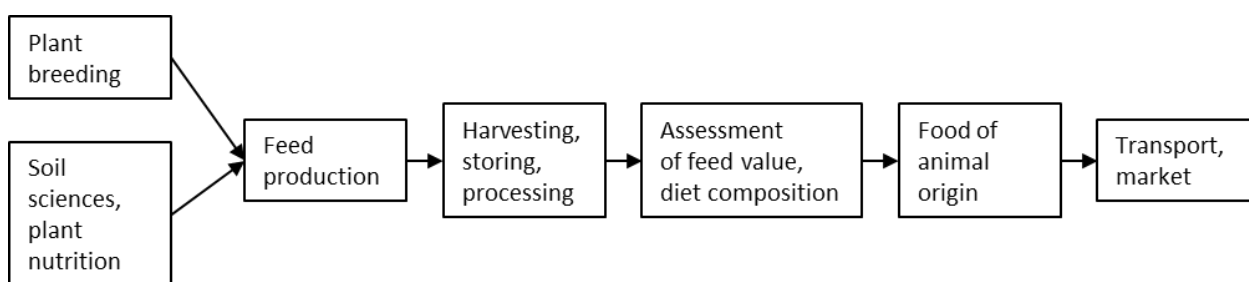
in this field. All methods of plant breeding that contribute to a more resource-efficient production of high and stable yields of available biomass should be used/combined.

**Keywords:** plant breeding; animal protein; feeds; co-products; feed additives; biofortification; anti-nutritional factors

## 1. Introduction

Feed accounts for 50% to 70% of the cost of production of animal protein (*i.e.*, meat, milk and eggs). Feeds can be defined as edible material(s) that are consumed by animals and deliver energy and/or nutrients such as protein/amino acids, fatty acids, minerals, vitamins, *etc.* to the animals' diet. On the other hand, feed plants may also contain undesirable substances, such as glucosinolates, mycotoxins, phytates, phytoestrogens, lignin, *etc.* Furthermore, feed production consumes high amounts of limited natural resources such as water, land area, fuel, fertilizers, *etc.* Therefore, feed efficiency or feed conversion (amount of feed per product of animal origin such as milk, eggs, meat or fish) is a potential parameter to assess feed utilization in animal nutrition [1,2].

Plant breeding can be considered as the starting point of the food chain all over the world [3–8], as shown in the simple food chain model in Figure 1. Traditional breeding, as well as “green” biotechnology or green chemistry [9], may result in changing of composition and nutritive value of feed plants.



**Figure 1.** Plant breeding, feed production and feed science as key elements of the production of food of animal origin in the human food chain.

The present situation will continue with a steadily growing population, severe land and water constraints, an increase in demands for food and biofuel as well as with progressing climate change [10–12]. The objective of the present paper is to analyze challenges for plant breeding under special consideration of high and stable yields, efficient use of limited resources and reduction of the content of undesirable ingredients in feed plants.

## 2. Global Food Situation and Challenges

According to the FAO (Food and Agriculture Organization of the United Nations) [13,14], the human population will increase globally from currently about seven billion to more than nine billion

people in 2050, but the increase in the output of food of animal origin is estimated to be about 70% above the current production [15,16].

More people and a higher need for feed and food are associated with a growing demand for limited natural resources such as water, fuel, minerals, arable land, *etc.*, and elevated emissions with greenhouse gas (GHG) potential such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O) and other substances (e.g., N, P, trace elements, *etc.*). These changes characterize the situation all over the world [2,5,9,13,14,17–24]. Malnutrition in all its forms (undernutrition, micronutrient deficiencies (e.g., iron, iodine, vitamin A) and overnutrition—the so-called “triple burden” of malnutrition) is still recognized as a serious and intractable problem for human beings [25,26]. The latest FAO estimates [27] indicate that about 805 million people are still chronically undernourished (11.3% of global population). Food of animal nutrition, also called animal source food [28], may contribute to overcoming micronutrient deficiencies [26].

### 2.1. Food of Animal Origin

The energy and protein conversion efficiency from feed into food of animal origin is low and may vary between 3% (energy–beef) up to 40% (energy–dairy; protein–chicken) for fattening [29,30]. In some countries (e.g., USA), between 67% (energy) and 80% (protein) of the crops are used as animal feed [29].

These developments and complex connections present the following question: “Is there any need for food of animal origin?” As vegans demonstrate, there is no essential need for food of animal origin, if the human diets are supplemented with all essential nutrients. However, on the other hand, the consumption of meat, fish, milk and eggs may contribute significantly to meeting the human requirements for amino acids [26,31–35] and some important trace nutrients (such as Ca, P, Zn, Fe, I, Se, and Vitamins A, D, E, and B12), especially for children and juveniles, as well as for pregnant and lactating women [36]. Human nutritionists [37,38] have recommended that about one-third of the daily protein requirements (0.66–1 g per kg body weight) [34,37,39–42] of adults should originate from protein of animal origin. Consequently, about 20 g of the daily intake of about 60 g protein should be of animal origin, which is lower than the present average consumption throughout the world. Presently, there is an average consumption of protein of animal origin (without fish) of about 24 g per capita per day, ranging between 1.7 (Burundi) and 69.0 g (USA; Table 1). It is a challenge for the future to overcome this imbalance [33]. Meat, milk and eggs provide around 13% of the energy and 28% of protein consumed globally, respectively, with the higher share in the so-called developed countries (around 20% and 40%, respectively [14]). It is difficult to assess the protein intake from fish and other animal protein sources (e.g., insects). Avadi and Freon [43] estimate that half of the world’s population consumed at least 15% of their animal protein from aquaculture. Protein from insects may contribute to improving the protein intake of human and animals in many developing countries [44].

Other reasons for consumption of food of animal origin are the high bioavailability of most nutrients and their considerable “enjoyment value”. Such food is also presently considered as an indicator for the standard of living in many regions of the world. Eating food of animal origin, especially meat, is not only a reflection of nutritional needs, but it is also determined by organoleptic, as well as by geographical area, culture, ethics and wealth. Further reasons for the higher demand of food of animal origin in some countries are the increased income of the population [25,45–47] and the imitation of the

so-called “Western lifestyle” concerning nutritional habits. Many developing countries continue to consume more animal products than they produce. Therefore, they will continue to drive the world demand for all agricultural products, including food of animal origin [48]. Higher food amounts of animal origin require higher plant yields and/or more area for feed production [49–51] and more animals and/or higher animal yields as well an increase in agricultural trade. Therefore, some authors propose a redefinition of agricultural yield and agriculture in general: “from tons to people nourished per hectare” [29,45] and ask for more sustainable animal agriculture [52–54].

**Table 1.** Intake of milk, meat and eggs as well as protein of animal origin per capita per year and portion (%) of total protein intake (global minimum-values; maximum-values and averages as well as German values for comparison; kg per capita per year: data base 2005; [14].

Food	Minimum	Average	Maximum	Germany
Milk (kg per year)	1.3 (Congo)	82.1	367.7 (Sweden)	248.7
Meat <sup>1</sup> (kg per year)	3.1 (Bangladesh)	41.2	142.5 (Luxembourg)	83.3
Eggs (kg per year)	0.1 (Congo)	9.0	20.2 (China)	11.8
Edible protein of animal origin (g per capita and day)	1.7 (Burundi)	23.9	69.0 (USA)	52.8
Portion of animal protein in % of total protein intake per capita	4.0 (Burundi)	27.9	59.5 (USA)	53.7

<sup>1</sup> Probably empty body weight (meat plus bones).

On the other hand, changing the eating patterns [55] and eating less or no livestock products, especially meat, are often seen as possible solutions to reduce the environmental impact of animal agriculture [56–58] and to reduce the per capita land requirements [59,60]. In this context, it should be mentioned that the use of permanent pastures, which represent a significant proportion of the agricultural area for the production of food, is only possible with food-producing animals.

## 2.2. Limited Resources and Low Emissions

In the future, there will be strong competition for arable land and further non-renewable resources such as fossil carbon-sources, water [61–64], some minerals (such as phosphorus; [65,66]), as well as between feed, food, fuel, fiber, flowers and fun (6 F-concept) [67] and areas for settlements and natural protected areas.

In this regard, more attention should be paid to the need of limited natural resources per amount of animal product, expressed as footprints per product such as “Water Footprints”, [68,69] “Mineral (especially phosphorus; P) Footprints”, “Land (arable or total land) Footprints” [59,70–72]. These Footprints are given in kg; L or tons per unit of product and characterize the efficiency of various production processes.

On the other hand, special attention has also been paid to the outputs from agriculture [19,23] including livestock keeping especially so-called GHG relevant emissions such as CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O and further gases. All the climate relevant emissions are summarized to so-called Carbon Footprints (CF). They have also been modified or called Ecological Footprint (EF), Eco-Balances (EB), Life Cycle Assessments (LCA) or Life Cycle Impact Assessment (LCIA). In all cases the term means a summarized parameter for all gaseous emissions with greenhouse gas potential to sensitize producers

and consumers [73,74] to an efficient use of fossil carbon sources and to reduce GHG emissions per product [75]. CF or LCA are used as a tool for estimating environmental effects caused by products or processes. Furthermore, CF may also contribute to assessing the resource and feed efficiency between various regions and production systems [49].

### 2.3. Social Aspects

In addition to these limited natural conditions, there is also a social side to the present situation. Based on developments mentioned above, social and natural scientists of various disciplines have increasingly studied and analyzed these global developments. The balance between the Planet (global resources and emissions), People (social aspects of population all over the world) and Profit (economic aspects, money-making) in the so-called 3P-concept [76,77] is an important prerequisite for a sustainable life and development on the Earth. Some authors are afraid that the balance between the 3Ps being increasingly disturbed and that an ethical dimension should be introduced as a fourth dimension [1,77,78].

Profit should not and cannot be the single objective of production. We need to find a balance between a careful and sustainable use of limited resources (see section 2.2) on the one hand [79–81] and low emissions with local and global consequences for later generations [82] on the other hand. Progress in plant breeding to more efficient plants in using natural resources and plants with high and stable yields which contribute to stabilizing human nutrition with food of plant and animal origin can be a starting to overcome imbalances in the 3P-concept.

### 2.4. Challenges for Plant Breeders

A rising demand for animal feed due to increasing consumption of food of animal origin is expected to drive the market for many feed crops such as maize, soybean, rapeseed, sugarcane, sugar beet and forages. Further alternatives to stabilize and improve human and animal nutrition, such as insects [1,83–87], microbial biomasses [88,89], food imitates, *etc.*, are under discussion.

More studies and analyses seem to be necessary to improve the data basis for a more efficient use of limited resources and lower emissions per product. Therefore, in addition to a previous review [90] the objective of the present contribution is to analyze the challenges for plant breeders to meet the expectations of animal nutritionists to feed food-producing animals adequate to their requirements and under consideration of future human demand. The term “plant breeding” is used for all methods to improve the potential of plants, independent of traditional methods or green biotechnologies.

## 3. Feeds and Animal Requirements

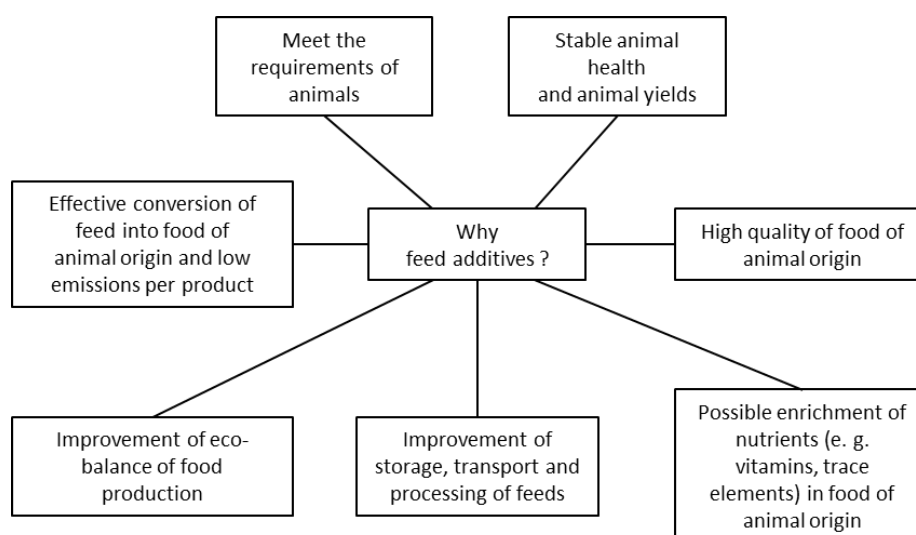
### 3.1. Feeds

Feeds are characterized according to their composition as summarized in Table 2. Water for drinking is not considered as an own group of feeds, but it is an essential prerequisite for animal health and welfare. The most important feed groups are roughages, concentrates and co-products from agriculture, food and biofuel industry [91]. Feeds from these groups contain various amounts of crude nutrients, but also traces of further essential and non-essential substances.

More details on feeds, feed evaluation and feed value tables may be found in various textbooks and publications such as Becker and Nehring [92], Menke and Huss [93], Kling and Woehlbier [94], Jeroch *et al.* [95], Jeroch *et al.* [96], Jeroch *et al.* [97], Theodorou and France [98]; Ewing [99], Ewing [100], and Kamphues *et al.* [101].

In some countries (e.g., in Germany), so-called “Positiv list’s” for straight feeding stuffs exist [102] where parameters of using as feedstuffs are summarized. This “Positive list” is not a legal document, but it should be considered as a voluntary commitment of the feed industry to produce high quality mixed feed.

Feed additives are used to supplement feed (mixed or complete feed) with essential and/or non-essential substances (see Figure 2). Further details on the effects of various feed additives in animals, food of animal origin and on the environment are described in some reviews [103–105], in many publications, in opinions papers of the European Food Safety Authority (EFSA), and other national and international scientific bodies.



**Figure 2.** Reasons for the use of feed additives in animal nutrition.

**Table 2.** Systematic of feed groups.

Feed Group	Characterization
Water for drinking	Essential in adequate amounts (2–5 L per kg feed dry matter (DM); average: about 3 L/kg DM) for animal health, efficient feed conversion and quality of food of animal origin
Roughage	Vegetative plant parts (leaves, stalks) of grasses and legumes fed in fresh (forages), conserved (silages) or dried form (hay, straw). Roughages contain $\beta$ -glycosidic bound carbohydrates mainly as cellulose and hemicelluloses associated with lignin. Cell wall fractions are dominating in roughages.
Concentrate	Generative plant parts (seeds) of cereals, legumes and oilseeds, roots, tubers and other feeds rich in $\alpha$ -glycosidic bound carbohydrates (starch, <i>etc.</i> ). Concentrates are also rich in cell content-containing proteins and fats.
By-/Co-products	Co-products are residues of agriculture (e.g., straw), food (e.g., bran, beat pulp, bagasse) and biofuel industry (such as distillers grain solubles, oil cake or extracted oil meal, glycerine, <i>etc.</i> )
Feed additives	Essential (such as amino acids, minerals, vitamins) and non-essential substances (e.g., enzymes, microorganisms) which are added to feed in small amounts

*3.2. Animal Requirements*

Requirements for energy and essential nutrients of food producing animals and laboratory animals are given in feeding standards. For example, in the United States, Latin America and many other regions of the world, the recommendations of the National Research Council (NRC; since 1945) of the National Academy of Sciences provide the basis for the formulation of the diets in livestock feeding. In the UK and many Commonwealth countries, recommendations were given by the Agricultural Research Council (ARC), since 1983 called the Agricultural and Food Research Council (ARFC). Since 1994, the Biotechnology and Biological Science Research Council (BBSRC), as the successor organization to the ARFC, has stopped publishing the energy and nutrient requirements for farm animals. In France the INRA (Institute National de la Recherche Agronomique) and in Australia the CSIRO (Commonwealth Scientific and Industrial Research Organisation), as Australia’s national science agency, issue appropriate recommendations. In Germany, recommendations for the supply of energy and nutrients to different farm animals are given by the Society of Nutrition Physiology (Gesellschaft für Ernährungsphysiologie; GfE).

Because of rapidly expanding knowledge in feed science and animal nutrition, nutritional standards are under continuous review and modification. New scientific results are used in the revision of adequate standards. During the last few years, recommendations of the NRC dominated and data by other organizations, except the GfE, were more or less neglected, or other organizations stopped their activities in the field of animal nutrition. Irrespective of the guidelines and recommendations from scientific societies, the legislation on animal feed of different countries includes provisions concerning the quality of feedstuffs.

**4. Challenges for Plant Breeding**

*4.1. General Challenges*

As already mentioned, plant breeding and cultivation will be the key elements and starting points for feed and food chain (see Figure 1) and for feed and food security in the future as well [4,5,7,12,20,106,107].

Such crops should have high and stable yields, they should grow with the least possible use of globally limited resources such as arable land, water, fuel, and some minerals and they should ensure the best use of the unlimited resources such as plant nutrients in the atmosphere, sun energy and the available genetic pool (Table 3).

**Table 3.** Potential to produce phytogetic biomass and its availability per inhabitant under consideration of the increase of the population [108].

<b>Plant Nutrients in the Atmosphere (N<sub>2</sub>, CO<sub>2</sub>)</b>	<b>↑ ↔</b>
Solar energy	↔
Agricultural area	↓
Water	↓
Fossil Energy	↓
Mineral plant nutrients	↓
Variation of genetic pool	↑
(↑ Increase, ↓ Decrease, ↔ no important influence)	

Pennisi [106] characterized the ideal crop or the perfect plant from the perspective of plant breeders with the following parameters:

1. Improve the nutrient content of seeds and edible plant parts
2. Asexual reproduction
3. Optical warning signal or installation of warning lights
4. Higher water efficiency
5. Longer shelf life (enhanced control of ripening and senescence)
6. Improve nitrogen efficiency
7. Better pest resistance
8. Plants for mitigating adverse climatic changes and adverse environmental conditions

Adaptation of plants to the expected climate change is also a real challenge to plant breeders. Presently, special attention is given to the adaptation of plants to expected climate changes [11,109–112] and to improving their yield and the nutritive value for global food security [10]. The expected climate change may be considered as a substantial challenge for plant breeding in general.

Projections of global climate changes expect the concentration of greenhouse gases to increase, temperature fluctuations to occur sharply and frequently, and spatial and temporal distribution of rainfall to be disturbed [110]. All these influencing factors will increase challenges to crops.

In addition to plants with high and stable yields, we need plants that are

- resilient to such adverse environmental conditions,
- able to introduce such changes fast and sustainably, and
- available for all farmers (including smallholders [6]).

More attention should also be spent in further development of local varieties to improve the feed and food security of smallholder farmers. Presently, a small number of food and feed crops are cultivated worldwide (e.g., maize, rice, wheat, soybean, and sugar beet). From the view of sustainability, plants should be further improved by plant breeders.

Furthermore, it might be advantageous to support plant breeding by public institutions to a greater extent and to carry out more scientific work in this area with public research institutions.

## 4.2. Special Challenges from the View of Animal Nutrition

### 4.2.1. Specific Challenges for Feed Plants

Most of the general expectations mentioned before are also important for plants for animal feeding. Under consideration of the present challenges, an ideal feed crop can be characterized by the following goals:

- High and stable yields of highly digestible biomass with low external inputs (low input varieties) of non-renewable external resources such as water, minerals, fossil fuel, plant protection agents, *etc.* (see Table 3).
- Maximal/efficient use of naturally unlimited resources such as solar energy, nitrogen and carbon dioxide in the air (see Table 3).
- Higher resistance against abiotic and biotic stressors.
- Stable plant health and adaptation to potential climate change.



- Low concentrations of anti-nutritive (toxic) substances such as secondary plant ingredients, mycotoxins from toxin-producing fungi, toxins from anthropogenic activities or geogenic origin such as heavy metals.
- Low concentrations of substances that influence the use or bioavailability of nutrients such as lignin, phytate, enzyme inhibitors, tannins, *etc.*
- Higher concentrations of some secondary plant products with “positive” properties for some purposes, such as carotinoids, essential oils, some polyphenols (e.g., flavonoids and anthocyanids) and even alkaloids, if the synthesis in plants is more effective than the industrial production.

A higher concentration of nutritive value-determining components such as amino acids, minerals, vitamins and vitamin precursors, enzymes, pro- and prebiotics, essential oils and other substances is also mentioned as an objective of plant breeding [113]. Of course, the plant breeding goals depend also from the climate conditions of region or continent, the animals kept in the region and the level of productivity of animals.

#### 4.2.2. Increase of Valuable/Desirable Substances

Apart from water and energy, humans and animals require many nutrients to meet their metabolic need (essential nutrients). Table 4 reviews such nutrients known to be essential for sustaining human and animal life.

In some cases, plants enriched with adequate nutrients could be more sustainable for human, but also for animal nutrition. A large number of newly bred plants (crops and vegetables) of the so-called “second generation” (plants with output traits or with substantial changes in composition) with specific benefits for the consumer and animals are being developed or are in development [113]. These plants with increased nutritional content are also called biofortified plants or crops [114–117]. They can have a great impact on improving the already existing food and feed supply [118].

**Table 4.** Grouping and essential nutrients for humans and animals.

Groups of Nutrients	Examples of Essential Nutrients
Amino acids	Histidine, Isoleucine, Leucine, <b>Lysine</b> <sup>1</sup> , <b>Methionine</b> , Phenylalanine, <b>Threonine</b> , <b>Tryptophan</b> , Valine (semi-essential: Arginine, Cystine)
Fatty acids	Linoleic acid, Linolenic acid
Major elements	<b>Calcium</b> , <b>Magnesium</b> , <b>Phosphorus</b> , Sodium, Potassium, Sulfur, Chloride
Trace elements	<b>Iron</b> , <b>Zinc</b> , <b>Copper</b> , Manganese, <b>Iodine</b> , <b>Selenium</b> , Cobalt (cobalamin; vitamin B <sub>12</sub> )
Ultra trace elements <sup>2</sup>	Fluorine, Boron, Molybdenum, Nickel, Chromium, Vanadium, Silicon, Arsenic, Cadmium, Lead, Lithium, Tin
Vitamins (fat soluble)	<b>A</b> (retinol, precursor β-carotene), <b>D</b> (D <sub>2</sub> Ergocalciferol, D <sub>3</sub> Cholecalciferol), <b>E (Tocopherol)</b> , <b>K</b> (K <sub>1</sub> Phylloquinone, K <sub>2</sub> Menaquinone, K <sub>3</sub> Menadione)
(water soluble)	<b>B</b> <sub>1</sub> (thiamin), <b>B</b> <sub>2</sub> (riboflavin), <b>B</b> <sub>6</sub> (pyridoxin), <b>B</b> <sub>12</sub> (cobalamin), Pantothenic acid, Niacin, <b>Folate</b> , Biotin, <b>C</b> (ascorbic acid)

<sup>1</sup> Bold letters: first limiting nutrients; <sup>2</sup> Essentiality of some elements is unclear [119]; Occasionally beneficial elements [120].

A similar situation can be observed in smallholder farms. Their farming is characterized by various limitations, such as bad management of natural resources, most home production, limited marketing

and other restrictions [6]. Feed additives to supplement animal diets are mainly not available. Modern plant breeding may be also attractive to smallholders. They could do some changes faster and could cut breeding time. Using new varieties of plants resistant to diseases or pests may prevent the spread of plant diseases within and between fields and thereby could protect and enhance smallholder assets.

Specific advantages are higher content(s) of important nutrients and substances with nutritional values, such as (mentioned with some references): protein and/or amino acids [121–123], fat or specific fatty acids [124–126], starch or special carbohydrates [122], specific minerals [117,127–131], vitamins or vitamin precursors [132–136], and enzymes [137–140]; or lower contents in undesirable substances such as: glucosinolates [141], gluten [142], mycotoxins [143,144], and phytate.

It has also to be considered that not only the quantity of these ingredients has to be provided, but the balance may also be important. This is of particular significance for small holders.

A similar structure is used by Hirschi [115] to characterize biofortified crops for human nutrition. The author distinguished between protein and amino acids, carbohydrates, micronutrients and functional metabolites on the one hand, and on plant components with suggested functionality such as dietary fiber, carotenoids, fatty acids, flavonoids, glucosinolates, phenolics, plant sterols, phytoestrogens, sulfides and tannins on the other hand [145,146].

#### 4.2.3. Biofortification of Feed by Plant Breeding or Feed Additives?

Food from biofortified crops can reach rural populations including smallholder farmers for reducing levels of micronutrient malnutrition as discussed and demonstrated by many authors during the last few years [114,117,147–155].

Many feed additives, such as amino acids, minerals, enzymes, and microorganisms are available for animals [103] and present EU feed law. Inadequate consumption of one of these nutrients will result in metabolic disturbances leading to lower feed intake, weaker performance of animals and lower feed efficiency, but also to sickness, poor health, impaired development of juveniles and higher costs for humans and animals [26,130,152]. Therefore, nutritional supplementation of diets is common for humans and animals to avoid deficit situations.

Such additives are mostly cheaper and their development and production is mostly faster than via plant breeding. In contrast to human nutrition, a higher concentration of the nutritive value determining components such as nutrient precursors, nutrients, enzymes, prebiotics, essential oils, *etc.*, should not be a prior plant breeding objective from the view of animal nutrition (see Table 5).

**Table 5.** Pros and cons of substantial changes in plant composition (Plants of the second generation; plants with output traits or biofortified plants).

Pro	Contra
More advantages for human nutrition (meet requirements, e.g., fatty acids, minerals, vitamins, <i>etc.</i> ) than for animal nutrition (except smallholders or farmers far from transport ways)	Plant breeding needs a long time (longer than the development of food/feed additives)
Lower content of undesirable substances	Many feed additives are available for animal nutrition
Improvement of properties of food/feed	

Plant breeding can also be used to produce plants richer in oils, starch, fiber, protein or other substances useful for food/feed and industrial processes [153]. Generally, such substances are mainly

extracted from the crops and so-called co-products (e.g., soybean meal, rapeseed meal, and cotton seed meal; see [91]) could be available for animal nutrition. Except for the extracted nutrient(s), co-products do not vary strongly from their isogenic counterparts in the composition of main nutrients [156,157], but analyses are necessary for the composition of such co-products.

Biofortified plants may contribute to reducing micronutrient under-nutrition in many parts of the world. Presently, nutritionally improved plants have not been fully developed [158] and tested for their potential to improve the micronutrient status of humans and animals. Many biofortified plants are still in the pipeline and must be tested in animal feeding studies in the next years. More *in vitro* studies and animal experiments are necessary to assess the bioavailability of micronutrients in biofortified plants and to demonstrate the effects of further desirable ingredients such as enzymes [113]. Furthermore, there is a need for better communication between plant breeders and human and animal nutritionists about the potentials of plant breeding for future improvements in nutrition and health.

#### 4.2.4. Reduction of Content of Undesired (Anti-Nutritive) Compounds

It is easy to supplement some feed additives to animal diets, but it is difficult and expensive to remove undesired substances from the feed [159]. Therefore, a great challenge for plant breeders is to reduce the content of undesired components in feed plants. The following could be some goals for plant breeders:

- lower concentrations of substances that influence the use or the bioavailability of nutrients, such as phytate, tannin, enzyme inhibitors, lignin, and silicon;
- lower concentrations of toxic substances (secondary plant substances), such as alkaloids, glucosinolates, phenolic compounds, phytoestrogens, and cyanic compounds;
- higher resistance against fungi, such as *Fusarium*, *Aspergillus*, *Penicillium*, ergot, *etc.*; and
- minimal residues resulting from human/agricultural practices or soil composition, such as plant protection substances, soil composition, *etc.*

Brown midrib (bm) hybrids (e.g., corn and sorghum) demonstrate the influence on digestibility [160–163] and rumen fermentation, feed intake and the performance of ruminants [161,164–167] as a result of traditional mutation breeding [168–171]. Lower fiber content and higher digestibility of plants may reduce methane emission from the rumen [172]. On the other hand, Schwarm *et al.* [173] found no effect on methane emissions of German Holstein heifers fed corn silage from a brown midrib mutation compared with control maize. One wish to plant breeders could be to select cereal varieties with low lignin/fiber content in the stalk, but a high standing stability of plants.

Based on these data, plant breeding may also be helpful to increase feed value and feed intake of low quality roughages and co-products. During harvesting of plants, such as cereals, legumes, sugar beets, sugar cane, *etc.*, co-products such as straw, beet leaves and sugar cane are potential feed, especially for ruminants because of the high fiber content [174–177]. The digestibility and, therefore, also the feed value of such co-products, is higher the lower the lignin/fiber content. Therefore, lignin is also considered to be an undesirable constituent of feed. Lignin and fiber fractions (e.g., NDF, ADF,

crude fiber) are very important for the digestibility and the feed value of vegetative parts of plants as well as the performance of ruminants.

In conclusion, from the view of animal nutrition reduction of the content of undesirable substances from feed plants via plant breeding seems to be more important than biofortification. It is extremely difficult and expensive to remove or destroy undesirable substances in feed [159], but large amounts of feed additives are available to supplement feeds/diets with essential and non-essential feed additives [103].

#### 4.2.5. Testing of Results of Plant Breeding in Animal Nutrition

The evaluation of results of plant breeding measures from the perspective of animal nutrition requires a range of measures. Nutritional/physiological evaluation should be included in addition to composition determination. Such studies can take place in the laboratory (*in vitro*) or with laboratory and target animals (*in vivo*). Various types of animal feeding studies, such as measuring digestibility/bioavailability; efficiency studies including the transfer of nutrients from feed into food of animal origin as well as long-term and multi-generational feeding studies with feeds resulting from plant breeding have been described by many organisations [178–183] and were recently summarized by Flachowsky [3] and Van Eenennaam and Young [184].

Studies with target animal species are necessary to evaluate the nutritional value and safety of changes induced in the plant. Animal nutrition can be considered as the connection between plant and animal breeding. The cooperation between plant breeders and animal nutritionists should start in early breeding stages to analyze effects of breeding on the nutritive value of the “new” feed. Such feeding studies are the fundamentals for animal experimentation with new results of plant breeding.

Various types of *in vitro* and animal feeding studies are necessary to demonstrate the effects of results of plant breeding in food producing animals, such as:

- *in vitro* studies,
- studies with animal models to determine the bioavailability,
- efficacy trials with target animals, and
- in addition, safety trials should be considered.

King [151] proposed a three-step process for the nutritional assessment of food from biofortified plants of in human nutrition:

- Test of the bioavailability of newly expressed or nutrient(s) expressed in higher amounts.
- Feeding trial(s) to test the efficacy of the biofortified food for improving the nutrition and health of the target population.
- Final trial for evaluating the nutritional, health, agricultural, societal, environmental and economic aspects of biofortified food in the community.

Similar steps seem to be necessary in animal nutrition. Experimental designs are discussed for such studies and are described in detail by Flachowsky and Böhme [185], Flachowsky *et al.* [186], ILSI [182], EFSA [179], and Llorente *et al.* [187].

Table 6 demonstrates the effects of low phytate maize (reduced content of the undesirable substance phytate) on animal performance, phosphorus excretion and bone stability in a feeding study with pigs.

The “new” low phytate maize showed the same results as maize with more phytate and supplemented with 2 or 1.5 g inorganic phosphorus/kg feed, but a significantly lower P excretion, increased P-efficiency and environmental advantages (Table 6).

**Table 6.** Conventional and low-phytate maize (78.5% of the mixture) in the feed of fattening pigs (from [188,189]).

Groups Parameters	Control		Low-Phytate Maize	
	(0.3 g of available P per kg)		(1.7 g of available P per kg)	
Inorganic P supplement	not added	added	not added	added
P content (g/kg)				
29–73 kg live weight	3.4	5.4 <sup>1</sup>	3.4	5.4 <sup>1</sup>
73–112 kg live weight	3.2	4.7 <sup>2</sup>	3.2	4.7 <sup>2</sup>
Feed intake (kg/day)	2.23 <sup>a</sup>	2.50 <sup>b</sup>	2.53 <sup>b</sup>	2.51 <sup>b</sup>
Live weight gain (g/day)	730	870 <sup>b</sup>	900 <sup>b</sup>	880 <sup>b</sup>
Feed per gain (kg/kg)	3.05 <sup>a</sup>	2.87 <sup>b</sup>	2.81 <sup>b</sup>	2.85 <sup>b</sup>
P excreted (g/kg weight gain)	4.6 <sup>a</sup>	8.9 <sup>c</sup>	3.8 <sup>b</sup>	8.8 <sup>c</sup>
Strength (4th metacarpal bone, kg)	79.3 <sup>a</sup>	138.5 <sup>b,c</sup>	132.2 <sup>b</sup>	153.9 <sup>c</sup>
Ash content (% in 4th metacarpal bone)	53.5 <sup>a</sup>	60.1 <sup>b,c</sup>	59.3 <sup>b</sup>	61.2 <sup>c</sup>

<sup>a,b,c</sup> Different letters in one line indicate significant differences ( $p < 0.05$ ); <sup>1</sup> addition of 2.0 g P/kg; <sup>2</sup> addition of 1.5 g P/kg.

## 5. Conclusions

More people and a higher need for feed and food are associated with a growing demand for limited natural resources such as water, fuel, minerals, arable land, *etc.*, as well as elevated emissions with greenhouse gas potential.

Plant breeding can be considered as the starting point of the food chain. High, stable and highly digestible yields of plants with low external inputs of non-renewable resources, low emissions of gases with greenhouse potential during cultivation, high resistance against biotic and abiotic stressors including adaptation to potential climate change, and a low concentration of undesirable substances in the plants are real challenges for plant breeders in the future and are important for human and animal nutrition.

Additional challenges for plant breeders from the view of animal nutrition are:

- considering of forages and grassland by plant breeders;
- biofortification of plants is not so important for animal nutritionists because of many feed additives available in a large number of countries;
- feed value of co-products should be considered after processing of “new” plants for food and biofuel;
- animal feeding studies with target animal species are recommended to evaluate the nutritional value and safety of the changes induced in the plants; and
- cooperation between plant breeders and animal nutritionists should be an early element of breeding programs.

More attention should be paid to a more efficient use of non-renewable resources and the maximal use of unlimited resources (see Table 3).

Plant breeding with conventional breeding methodologies and/or genetic engineering has the potential, or can at least contribute, to overcome many problems of malnutrition. Furthermore, more education is necessary to inform the masses about the benefits/advantages of modern plant breeding for global food security.

It can be concluded that plant breeding is the starting point for a successful food chain under the title “more (feed and food) for more (people) with less (resources and emissions)”.

More activities are necessary for the sustainable utilization of natural limited resources and for improved use of unlimited resources such as sun energy/light, CO<sub>2</sub> and N<sub>2</sub> from the air, the global gene pool, *etc.* Conventional plant breeding may also contribute to fulfilling some of these objectives, but genetic modification may be faster and more precise [12]. More public supported research in this field seems to be necessary. All methods of plant breeding that contribute to a more resource-efficient production of high and stable yields of available biomass should be used/combined. Public funding of plant and animal research may be considered as an important challenge to meet the future animal protein demand [2].

### Author Contributions

This paper was written by Gerhard Flachowsky and Ulrich Meyer.

### Conflicts of Interest

The authors declare no conflicts of interest.

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