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ABSTRACT

Background: Worldwide demand for meat, milk is projected to increase by 57 % and 48%, respectively, between 2005 and 2050. More than 70% of the livestock farming cost is allocated for feed. However, climate change requires a systemic approach to feed research. A paradigm shift has to occur within a wider food system context with an agroecological approach to optimise the interactions between plants, animals, humans and the environment for a sustainable and equitable food system. Thus, farmers are faced with the challenge of feeding livestock with low-cost feed of good nutritional and sanitary quality and with a low environmental footprint.

Approach: This review makes an inventory and critical analysis of technologies to conserve and/or improve the quality of feed available on mixed crop-livestock farms in a frugal economy approach. We focused on biomass available on farm especially co-products, unsold crop and crop residues. Agroecological impacts technologies were discussed so as to determine great strategies to feed livestock.

Conclusions: Agro-industrial technologies can be used, to preserve feed, to improve feed value of ingredients for livestock from various by-products and so enhance animal performance and feed preservation. However, lack of knowledge, labour and investment limit the adoption of these strategies. Frugal technologies are suitable on farm for their appropriation by smallholders. Consequently, participatory approaches are required to provide and promote adoption of these innovations on-farm.

Keywords*:* Crop residues, Agro-industrial technologies, Feeding strategies, Livestock, Smallholders, Agroecology.

Abbreviations: SCP, Single Cell Protein; SSF, Solid State Fermentation; DM, dry matter; Mt, million ton; ANFs, antinutritional factors.

1. Introduction

The world's population will increase from 7 billion in 2020 to 9.8 billion in 2050. Global demand for meat and milk is projected to increase by 57% and 48%, respectively, between 2005 and 2050 (FAO, 2012). If demand for cereals for human consumption also continues to increase over the next few years (Godfray et al., 2010), the feed industry will have to cope with shortages of cereals, one third of whose total production is used as feed (Mottet et al., 2017). Feed production and processing are responsible for deforestation due to land-use change and generate about 45% of GHG emissions (Gerber et al., 2013). There is a pressing necessity to reduce the environmental footprint of the livestock sector as it continues to expand in order to ensure food security and feed a growing world population. It is therefore necessary to find alternative solutions to the use of cereals in feed. Moreover, the surface area of grassland and arable land devoted to livestock should not increase, hence the requirement to consider the use of biomass co-products of food crops.

The feed costs represent over 70% of the breeding expenditures (Alqaisi et al., 2019). One of the dilemmas in livestock productions is to feed livestock with low-cost, good nutritional quality, and readily available feed in a suitable manner without altering their productivity and compromising their well-being. The strategy of searching for alternative feed to those consumed by humans differs between herbivores and monogastric, the latter occupying feed niches close to that of humans. The originality of digestion with herbivore like ruminants is due to the activity of a multitude of microorganisms, bacteria, protozoa and fungi, living in symbiosis with the animal (Archimède et al., 2008). Compared to monogastric none herbivore, ruminants have the advantage of being able to extract and use the energy contained in a plant biomass that cannot be used directly by humans because it is too rich in lignocellulose. Moreover, the microorganism of the digestive tract produces a part of the protein requirement. Monogastric, for which the potential for digestion and microbial synthesis is digest fibre very poorly. Their main sources of energy are starch and sugars.

Today, the multi-performance of agriculture is not only related to the ability to produce food, feed and raw materials for industry, but also in the maintenance of environment and rurality. While agricultural intensification has significantly increased the amount of food available in recent decades, it has at the same time led to significant negative environmental impacts. Feed production and processing are linked to land-use changes and account for approximately 45% of GHG emissions from livestock sector (Salami et al., 2019). Today, public policies, farmers and even consumers want to limit the negative impacts of crop and livestock farming on the environment by reducing GHG emissions and looking for innovative technologies allowing on-farm improved feed production.

According to the Food and Agriculture Organization (FAO), agroecology is based on applying ecological concepts and principles to optimize interactions between plants, animals, humans and the environment while taking into consideration the social aspects that require to be addressed for a sustainable and fair food system. The production of feed from agro-residues represents one of the highest cash returns due to the fact that the demand for feed is always stable and huge. Therefore, using crop residues in order to feed livestock seems to be a great strategy to help meet the nutritional requirements of farm animals in quantity and quality. Processes involved in order to produce feed are not too sophisticated to be handled in small-scale industries or on-farm also, close to livestock. The production of feed is stuck between different areas under stress. Today, almost half of animal feedstuffs are the traditional grasses and pastures consuming increasingly scarce agricultural land, a third comes from a wide diversity from farm and agro-industrial by-products sector, and 1/8 are agricultural products that can be consumed by humans (Mottet et al., 2017).

However, the utilisation of plant by-products in livestock feeding is limited because of variation in their nutrient composition. Often, small farmers do not have the skills and equipment to process raw materials and preserve the processed products which is capital for product stabilization and permanent availability. Moreover, preservation techniques such as thermal processing may impose high cost and reduce the environmental sustainability of feed plant by-products (Bremer et al., 2011).

This review aims to highlight the potential of crop residues and sorting residues from the agro-industrial chain to produce quality feedstuffs that meet the livestock requirements. We focused on innovative on-farm strategies to produce and preserve cheap feed, applying an agroecological approach to limit environmental impacts while addressing economic and feed requirements.

2. Plant resources used in feed

Globally, grass and leaves constitute the main livestock feed dry matter intake, *i.e.* 46% DM. Moreover, livestock convert millions of tons of agro-industrial co-products that are non-edible for humans, these are 19% of crop by-products, 8% of fodder crops, 5% of oilseed cake as well as 5% of by-products. So, about 14% of the feed dry matter ingested by livestock is edible for humans, of which 93% are grains (Adesogan et al., 2020; Mottet et al., 2017).

Table 1 lists many cultivated plants that are used to feed farm animals. Numerous diet ingredients (roots and tubers, starchy fruits, sugar cane plant, molasse) used in the tropics as alternatives to conventional feeds. However, these ingredients have very low protein/energy ratios, relative to the nutritional requirements of livestock and compared to conventional ingredients (grass, legumes, cereals, soya bean, pulses). With regard to fibrous crop residues, a major constraint to their use as feed is their high concentration in indigestible cellulosic contents and consequently their low feed value. Generally these crop residues support low performance relatively to livestock potential (Beigh et al., 2017). However, as illustrated in Table 2, such plants have a lot of interests to feed farm animals.

Also, there are harvest residues after sales and deliveries. For several years, studies have been carried out to assess potentials of crop residues as feed for livestock and also aquatic animals (Guil-Guerrero et al., 2016; Njie and Reed, 1995; Ventura et al., 2009). Plant co-products are interesting to process as feed mainly within mixed crop-livestock farm systems, which are very common in the tropics. Straw and other fibrous co-products can represent up to 5 tons DM/ha of crops. The growth of the human population in Southern and developing countries will lead to a decrease in the availability of land for fodder production and may increase the dependence of livestock on crop co-products (Archimède, Bastianelli, Boval, Tran, & Sauvant, 2011). There is a real requirement to redirect co-products from human food production in a manner to produce balance feeds and thus reduce waste accumulation.

Fodder is characterized by a high cellulose and lignin content but a low feed value. Oilseed by-products are characterized by their high nitrogen and energy values and are milled and then used in the formulation of feed rations as pellets or feed blocks. Co-products from the food industry include pulps, peels and molasses, which have a high energy potential can be used directly to feed the animal or as a supplement to balance the ration. However, these by-products are often low in nitrogen, so it is interesting to enrich them through microbial growing technologies. Finally, co-products that do not meet the requirements of the animal, because of their feed value, are intended for energy production (methanation) or soil maintenance (fertilizers, composts).

Table 1

Global production of crops suitable for use as feed, their protein and fibre content, in 2019

Resources	[a] Global production (Mt)	[b] Protein content (%DM)	[c] Crude fibre (%DM)
Cereals			
Maize	1,148.5	7.2 – 12.4	1.6 – 3.8
Paddy rice	755.5	5.9 – 11.8	8.6 – 14.8
Wheat	765.8	8.9 – 19.2	16 – 4.1
Barley	159	8.5 – 16.1	3.1 – 8.2
Sorghum	57.9	8.1 – 14.3	1.7 – 4.6
Oats	23.1	8.0 – 14.7	9.3 – 19.3
Rye	12.8		
Pulses			
Soy	333.7	35.3 - 43.8	3.1 – 10.0
Fresh peas	21.8	20.8 – 26.8	3.7 – 14.5
Bean	27	22.2 – 27.4	4.3 – 7.9
Lupin	1.1	26.5 – 44.5	10.9 – 22.2
Vetch	0.8	12.5 – 35.9	21.3 – 35.1
Fruits and seeds			
Banana	116.8	3.3 – 7.4	2.2 – 7.2
Rapeseed	70.5		
Sunflower	56.1	14.1 – 20.0	14.5 – 20.8
Linen	3.7		
Carob	0.05	16.7 – 18.5	8.0 – 11.5
Roots and tubers			
Potato	370.4	10.8	2.5
Cassava	303.6	1.4 - 4.6	2.0 – 5.7
Sweet potato	91.8	5.5	3.8
Yam	74.3	5.9	2.4
Taro	10.5	5.4	2.5
Cabbage	70.2		
Sugar plants			
Beet	278.5	6.2 – 9.9	5.6 – 14.7
Sugarcane	1,949.3	1.4 – 2.4	35.8 – 50.3

[a] (FAOSTAT, 2021)

[b, c] (Feedipedia, 2015)

Table 2
Diversity of the main processed plant and/or their parts used as feed

Plant classification	Plant part	Form	Animal	References
Cereals				
Rice	Straw	Ground/pelleted	Goats	(Romero et al., 2020)
Wheat	Wheat straw	Silage	Lambs	(Scerra et al., 2001)
Barley	Grain	Ground/pelleted	Goats	(Romero et al., 2020)
Corn	Whole plant	Silage	Cows	(Acharya and Casper, 2020; Nennich et al., 2003)
Sorghum	Stover	Feed block	Buffaloes	(Anandan et al., 2010)
Pulses				
Pigeon pea	Grain	Meal	Pigs	(Whiteman and Norton, 1981)
Cow pea	Grain	Meal	Broilers	(Luis et al., 1993)
	Leaf	Meal	Shrimps	(Eusebio and Coloso, 1998)
Mucuna	Grain	Roasted/ cracked/soaked	Pigs	(Eteka et al., 1999)
	Grain	Grinded	Goats	(Mendoza-Castillo et al., 2003)
	Grain	Cooked, toasted	Guinea fowl	(Dahouda et al., 2009)
	Grain	Boiled/toasted	Broilers	(Emenalom and Udedibie, 1998)
Mungbean	Grain	Raw	Pigs	(Ravi et al., 1999)
	Grain	Sprouted	Broilers	(Singh et al., 2013)
Rice bean	Grain	Roasted, meal	Chickens	(Gupta et al., 1992)
Centro	Forage	Pellet	Rabbits	(Aderinola et al., 2011; Asuquo, 1997)
Perennial peanut	Leaf	Meal	Broilers	(Teguia et al., 1997)
Forage peanut	Forage	Dried	Pigs	(Posada et al., 2006)
Leucaena	Leaf	Sun dried/ground/ Pelleted	Buffaloes Goats	(Hung et al., 2013) (Marie-Magdeleine et al., 2020)

Table 2 (continued)

Plant classification	Plant part	Form	Animal	References
Sugar crops				
Sugarcane	Bagasse	Chopped	Cows	(Molavian et al., 2020)
	Stalk	Dried	Steers	(Ortiz-Rubio et al., 2007)
	Whole plant	Chopped	Rams	(Archimède et al., 2014)
Sugar beet	Pulp	Dried/Pelleted	Beef cattle	(Boucque et al., 1976)
Fruits and vegetables				
Mango	Pulp	Dried	Pigs	(Grant et al., 2019)
	Seed	Cooked	Broilers	(Joseph and Abolaji, 1997)
	Leaf	Fresh	Goats	(Akbar and Alam, 1991)
Lemon	Leaf	Ground/pelleted	Goats	(Romero et al., 2020)
Orange	Leaf	Pelleted	Goats	(Fernández et al., 2018)
	Pulp	Silage	Lambs	(Scerra et al., 2001)
	Pulp	Dried	Ewes	(Fegeros et al., 1995)
Mulberry	Leaf	Pelleted/sun dried	Beef cattle	(Huyen et al., 2012)
Root and tuber crops				
Cassava	Leaf	Fresh	Pigs	(Ty et al., 2011)
Sweet potato	Leaf	Dried	Broilers	(Teguia et al., 1997)
Oilseed crops				
Palm	Kernel	Cake	Goats	(Abubakr et al., 2015)
Rapeseed	Seed	Fermented meal	Broilers	(Chiang et al., 2010)
Cotton	Seed	Fermented meal	Broilers	(Sun et al., 2013)
Forage, herbs, shrubs and trees				
Dwarf koa	Leaf	Meal	Pigs	(Ly and Samkol, 2001)
Moringa	Leaf	Dried/ground/mixed	Goats	(Sarwatt et al., 2002)
Stylo	Forage	Fresh	Pigs	(Phengsavanh and Stür, 2006)
	Leaf	Meal	Pigs	(Keoboualapheth and Mikled, 2003)
Nacedero	Leaf	Meal	Pigs	(Sarria et al., 1991)
Water spinach	Leaf	Silage	Pigs	(Giang and Preston, 2011)

3. Technologies for the processing of quality feeds and ingredients

The requirement to increase food production to meet the demands of the human population has also led to a necessity to increase the production of animal feed. This has favoured the introduction of a set of technological solutions that offer the possibility of improving the quality and quantity of feed available, using resources that are not always permanently available. Different agro-industrial processes can be used to process plant resources into feed but our perspective is to resort to processes with a low environmental impact and at a lower cost, appropriable within small-scale mixed crop-livestock farms.

3.1. Global historical milestones in feed processing

As early as the beginning of the 19th century, industrial technology appeared in the field of feed so as to transform plant resources. The industrial revolution had already ignited growth in grain milling, meat packing, and milk processing. Indeed, the first feeding by heavy grain to feed beef cattle started in 1800, in Ohio. Forty years later, corn sheller and hammer mill were invented in order to processing grain to feed livestock. But it's the end of the 19th century that marked a culmination of events that put the industrialisation of feed into force. So, in 1885, commercial feed manufacturing industry began in Chicago.

In 1939, Huffman, a Michigan state university researcher, introduced the rumen fistula to study the ruminal digestion and have helped to understand best forms for feed efficiency of various resources.

The 1940s in Mexico were characterised by the Green Revolution, which refers to the development of innovative agricultural practices. Thus, between the 1950s and 1960s, the technologies of the Green Revolution spread throughout the world in order to produce more food for a growing world population. Indeed, mechanisation, land irrigation, the use of mineral fertilisers and plant protection products, as well as varietal selection, have made it possible to increase productivity and thus higher crop yields. In tandem, genetic improvement, better veterinary medicine and increased use of artificial feeding have raised animal production to feed humans.

Furthermore, in 1959, the European Feed Manufacturer's Federation (FEFAC) has been established by Belgium, France, Germany, Italy, and the Netherlands as an umbrella organisation for the European feed industry.

The history of the livestock feed industry, faced with the prospects of global demographic increase and with spaces under severe constraints to produce feed and food in quantity and quality, must therefore take into consideration new resources and innovative means to produce more and better, in an agroecological manner.

3.2. Processing feed: Technological operations list

Some attempts have been made to upgrade the nutritive quality of crop residues by chemical, biological and physical treatments, but few of these interventions have been widely adopted.

Table 3 identifies agro-industrial technologies that could be used for on-farm feed production as well as their environmental and socio-economic issues.

Robinson and Nigam (2003) led a study on the design of bioreactors for protein enrichment. They concluded that "the benefits of SSF (Solid State Fermentation) for protein enrichment maybe better realised *in situ*, on farms in developing countries, which can avail of this relatively low-tech fermentation system". As an agroecological approach, microbial fermentation and sun drying are both environmental-friendly and suitable on the farm, especially for small farms due to the fact that no sophisticated equipment and control means are required. After fermentation in liquid media had been the subject of numerous studies and developments, from 1940 onwards, it was out until 1975 that a few studies were undertaken on fermentation in solid media. According to a review of work undertaken at the French IRD (Institute of Research for Development), the enrichment of solid substrates (such as cassava) with protein by this fermentation method was the subject of two thesis and a patent. However, there are no applications in the field. The application of microbiological fermentation as a process for protein enrichment of plant products appears to be an innovative approach. Size reduction (chopping, grinding) and hulling are often prerequisite to transform raw materials into feed. Formulation, in addition to being inexpensive, is essential for a balanced ration. Then, using and processing raw materials located on the farm should reduce the environmental impact and costs associated with the transport of imported raw materials.

Table 3

Processes used to produce feed

Processes	Purpose	Environmental impact	Socio-economic impact
Delivery and transport (fly, boat, truck, railways)	Route imported raw material and feed	High Greenhouse Gas emissions	Fuel cost Requirement and cost of labour
Microbial fermentation *Silage* *Lactic acid fermentation* *Protein enrichment*	Enhance nutritive quality Preserve feed for duration	Environmental-friendly Low power consumption Maximise the use of local resources	Less expensive Maximise the use of local resources On-farm adaptable
Formulation *Weighing* *Dosing*	Balance the rations	Low power consumption	Inexpensive Essential on the farm
Germination *Grains*	Reduce Antinutritional Factors (ANFs)	Water consumption	Can be difficult to manage Process management is required
Granulation	Avoid untangling Improve nutritionally	High power consumption	High investment in equipment (press, cooler, crumbler) Power expenditure
Heat treatment *Dewatering* *Drying* *Roasting*	Reduce the volume Stabilize the end-product Reduce (ANFs) Increase total dry matter intake	High power consumption	Investment for equipment
Sun drying		Environmental-friendly Reduction of the ecological footprint and protection against farming pollution	Very low cost On-farm adaptable with greenhouse
Hulling/husking	Remove ANFs	Power consumption	Low cost Small-scale adaptable

Table 3 (continued)

Processes	Purpose	Environmental impact	Socio-economic impact
Pelleting	Increase palatability and digestibility	Power consumption	Investment for machine Labour intensive Process management
Size reduction	Improve digestibility		
Crushing	Increase palatability	Power consumption	High energy cost
Grinding/milling	Reduce the volume of feed for storage Increase nutrient availability	Power consumption	Investment for machine Power cost
Chopping			Labour intensive
with hand		Environmental-friendly	
with machine		Power consumption	Investment for machine Power cost
Soaking	Reduce ANFs Improve feeding value	Water consumption	Water expenditure
Use of enzymes	Reduce ANFs Increase the efficiency of digestion	Can be produced by microorganisms Replaces synthetic chemicals Reduction of waste from these processes, thanks to biodegradability and lower energy consumption	Cost of enzymes if it is not produced by microorganisms Unsuitable for smallholder Reducing costs related to the use of artificial chemical inputs

4. Purpose of raw materials processing

Poor feed quality is known to reduce animal performance. The processing of raw materials to produce feedstuffs results in a better nutritional quality and therefore improves the performance of the animals. All this should be achieved without decreasing the nutritive value and increase the cost of the feed.

4.1. Increase nutritive quality

Local raw materials for livestock feed in arid areas are typically of lower digestibility and crude protein concentration, and with slower fibre and nitrogen degradation rates than in humid or temperate regions. These lower energy densities led to lower intake and animal productivity, and result in lower feed-use efficiencies (Herrero et al., 2013). Many studies respectively shown that microbial fermentation, germination, size reduction and chopping are able to improve protein content of resources (Boonnop et al., 2009), reduced ANFs (Sharma et al., 1996), increased dry matter intake by animals (Lancheros et al., 2020) and decreased bulkiness (Hamed and Elimam, 2009).

4.2. Improve animal performance

Livestock, specially ruminants, convert human-inedible, human-unpalatable sources of energy and protein into high-quality protein food for human consumption, despite a large variation in the conversion ratio among different species (Tedeschi et al., 2017). The effects of pelleting (Du et al., 2019), crumbling (Millet et al., 2012) and grinding (Ulens et al., 2015) on animal performance was evaluated. For instance, Garg et al., (2013) observed that feeding with nutritionally balanced rations improved milk yield by 2-14% and net daily incomes by 10-15% and also reduced greenhouse gas emissions by 15-20%.

4.3. Extend shelf life

Even with a very fine planning of the agricultural productions for the scale of a territory, there will always be an excess of food which it is advisable to manage. Indeed, fresh crops are often perishable (*i.e.* fruit and vegetable, forages, hay) unless these are tubers, grains. Function of some agro-processing is to make agricultural raw materials, raw feed resources, available in space and time, in forms with food and nutritional qualities appropriate to their final consumers. After manufacturing, feed can be distributed immediately, which is one of the main advantages of on-farm feed processing, or can be stored in bulk or in bags, after solar drying under greenhouse. This availability of feed determines livestock production. López-Gómez et al, (2016) shown that *Rhizopus oryzae* is able to inhibit the growth of undesirable microorganisms on wheat for at least 20 days compared to 2 days for uninoculated samples and 7 days for samples treated with a commercial preservative. Other studies revealed the interesting effects on feed shelf life by processing (Hillion et al., 2018; Le Dividich et al., 1976).

5. Microbial fermentation as a biotechnological method to produce feed

Biotechnology in agricultural applications refers to a range of biological tools that use living processes, organisms or systems to make or modify products or technology, improve plants or animals or develop microorganisms for agricultural use (USDA, 2017). The fact that this kind of process is particularly well adapted to the metabolism of fungi and bacteria is an important feature. Indeed, the characteristics of these microorganisms (apical growth, enzymatic activities, high growth rate) are propitious to their growth in a fermentative medium (Durand, 2003). Digestibility of nutrients in general can be improved and the amino acid profile adapted closer to ideal patterns (Nkhata et al., 2018).

Solid state fermentation is defined as any fermentation process carried out on a solid material in the absence of free-flowing liquid (Pandey, 2003). Many papers have appeared on the use of solid state fermentation, with studies on the potential for producing different metabolites (Aggelopoulos et al., 2014; Castillo-Castillo et al., 2016; Jiang et al., 2019; Novelli et al., 2017). SSF can improve the nutritive value of agro-resources and its products represent a potential solution for better animal feeding (Robinson and Nigam, 2003).

5.1. Silage

Silage is a preservation technique by wet process, using anaerobiosis and acidifying fermentation with a predominantly lactic acid content so as to minimise the loss of dry matter and feed value and to prevent the development of harmful micro-organisms. A stabilized product is obtained by an acidic pH and packed in various silos (mole silo, bunker silo, bundle silo or wrapped bales). Corn silage production in the United States was estimated at 133 million tons for 2019, up 9 percent from the revised 2018 estimate (USDA, 2020). Bolsen et al. (1996) established that the criteria for a resource to be suitable for silage are: 1) dry matter (DM) content (30% for grasses and 35% for legumes); 2) sugar content (12% of fermentable sugars/DM); and 3) buffering capacity. To avoid loss of nutrients such as sugars or proteins, the herbs are cut and placed in silos for fermentation. The fermentation is ensured by the microorganisms present on the grass. Furthermore, grasses are more adequate for silage than legumes due to their content of water-soluble carbohydrates and their buffering capacity. However, legume silages seemed to be better accepted by the animal than grass silages, with a tendency to higher animal performance (Steinshamn, 2010). Several studies demonstrated the potential of silage (Grant and Ferraretto, 2018; Weinberg and Muck, 1996). Silage is an unsophisticated process, documented and practised by farmers. This process is a model of what should be achieved in the development of innovative routes on-farm for protein-enrichment of plant biomass. The low content of certain resources, including grasses, can be a limiting factor for silage technology. The use of more or less sophisticated and questionable additives (sugar, acids, micro-organisms, etc.) in an agro-ecological approach can be proposed for successful ensiling.

5.2. *Protein enrichment*

With the growth of the world's population, the demand for protein foodstuff increases is a serious issue. Proteins and amino acids are essential for consumer health and cannot be substituted by other food components. So far, soybean and fish in the form of fish meal have been important sources of protein for feed. In turn, the animals and their main products (milk, eggs) have served as protein sources in human nutrition. However, with the diminishing fish reserves in the oceans, it will be a challenge to sustain the protein demand of an increasing population. Technological advancements must provide new ways to produce proteins in a cost efficient manner (Olsen et al., 2010). Microbial protein enrichment by SSF is a process in which a solid substrate is used as the substrate or the support of microbial cell growing. Single cell protein (SCP), which is the protein extracted from cultivated microbial biomass, can be used as supplement in foods or feeds to face with this issue. Algae, fungi and bacteria are the main sources of microbial protein, which contain about 30%, 45% and 80% of protein of the DM, respectively, whereas soybean contain about 35% of protein. These microorganisms are rarely pathogenic or toxic, they are known as GRAS (Generally Recognized As Safe). In addition, SCP enable the recovery of agro-residues or co-products and thus contribute to reducing environmental harmful impacts by limiting waste-disposal problem. As compared to traditional agricultural protein sources, they are independent of the climate and seasons and are less demanding in terms of surface area.

Table 4 shows, according to different authors, the levels of protein content achieved by SCP culture. These are mostly aerated SSF, with more or less sophisticated culture conditions. All these data correspond to experimental results and that these results have so far not led to any implementations.

Table 4
Protein enrichment of tropical substrates with different microorganisms

Substrate	Microorganism used	Protein content (%DM)		Reference
		Initial	Final	
Banana meal	*Aspergillus niger*	6.0	18.0	(Baldensperger et al., 1985)
Cactus pear	*Saccharomyces cerevisiae*	7.9	25.5	(De Fátima Araújo et al., 2005)
Cassava flour	*Saccharomyces cerevisiae*	9.5	18.4	(Sengxayalth and Preston, 2017)
Cassava peels	*S. cerevisiae, Lactobacillus spp*	8.2	14.0	(Oboh and Akindahunsi, 2003)
Cassava pulp	*Saccharomyces cerevisiae*	2.9	18.9	(Boonnop et al., 2009)
Sugarcane bagasse	*Aspergillus terreus*	3.4	11.3	(González-Blanco et al., 1990)
Sweet potato	*Aspergillus oryzae, Bacillus subtilis*	14.8	21.9	(Zuo et al., 2018)

6. Feed safety regulation

The food industry generates co-products of primary or secondary processing that can be used in feed provided that they comply with marketing regulations, general principles of food safety and limits on contaminants or residues. As soon as it is intended for feed, a co-product of primary or secondary processing becomes a raw material for feed and must comply with the safety regulations.

Indeed, all companies that place on the market raw materials intended for the feed industry or for a breeder are considered as operators in the feed sector. Therefore, they must comply with Regulation (EC) No 183/2005 laying down rules on feed hygiene. They must ensure that such feed is sound, fair, fit for purpose and of merchantable quality and is labelled, packaged and presented in accordance with the provisions applicable to it.

In addition, any operator who produces raw materials for feed must be registered under Regulation (EC) No 183/2005 and feed manufacturers and breeders must obtain their supplies from a registered operator. Regulation (EC) No 767/2009 on the placing on the market and use of feeding stuffs lays down the rules for labelling feed materials by listing mandatory label statements such as the words "Feed materials" or the contents of analytical constituents.

The regulations concerning contaminants and residues are very demanding. Indeed, the field of regulated contaminants is quite broad but we can mention: metallic trace elements (lead, mercury...) and certain phytopharmaceutical products. In addition, the directive 2002/32/EC taken up by the modified decree of January 12, 2001 specifies the maximum doses of undesirable substances to which raw materials intended for feed are subjected. And maximum residue limits (MRLs) for plant protection products are defined in Regulation (EC) No. 396/2005. In addition, a set of French decrees pursuant to Regulation (EC) No. 2160/2003 provides a framework for microbiology in feed.

All in all, the use of these products in feed is governed by regulations. Compliance with regulatory health requirements ensures the safety of animal feedstuffs, *i.e.* animal foodstuffs destined for human's consumption at the end of the chain. On-farm feed production routes must incorporate the objectives of the above regulatory provisions.

7. Strategies and prospects

Some agro-industrial technologies could be innovative strategies for farmers to produce feed themselves, following an agroecological approach. However, adoption of these innovations is not sufficiently accepted.

7.1. Reducing environmental impacts

While improving animal nutrition, the technologies should help maintain soil fertility by fixing nitrogen, increase carbon sequestration to mitigate climate change and reduce pressure on natural pastures (Rao et al., 2015).

Crop production generates a large amount of residues. Feed processing by valorising co-products, crop residues and unsold, especially those already available on the farm, allows 1) reducing feed waste, 2) increasing on-farm self-sufficiency by reducing importation of feed, 3) decreasing GHG emissions linked to the transport of raw materials, or imported concentrates which also generate additional costs for the farmer, 4) limiting the use of chemical inputs to balance the ration allocated to the animal. As they can feed the livestock with crops available on the farm, mixed smallholders are particularly well placed to benefit from the advantages of feeding crop residues and any technologies that improve their nutritive value.

7.2. Protein enrichment of by-products by microbial fermentation at farm scale

On farm, protein enrichment allows smallholders to produce feed by reducing environmental and socio-economic impacts. The challenge we propose to take up is the promotion of protein enriched feed production containing eventually 12-14% protein in DM, which is a good level for balanced feed according to nutritionists. Protein enrichment is carried out from locally available tropical plant resources (sugarcane stalks, banana sorting differences) by aerated fed-batch fermentation seeded with inexpensive and readily available commercially leaven.

Current knowledge and techniques suggest that in order to multiply a food microorganism on a solid substrate, under material conditions suitable for the farm, a strong constraint is to have an open fermentation container, shaken mechanically, configured in such a way as to ensure aeration of the fermentation medium, allowing a yeast strain to develop an aerobic metabolism, favourable to its rapid multiplication.

Protein-enriched products can be stabilised for shelf life by solar drying under greenhouse available on the farm. As a food industry technologist, we work in collaboration with zootechnicians and nutritionists to build routes for the valorisation of plant resources as feed for farm animals, through protein enrichment by means of yeast culture, in equipment and operating conditions appropriate to the farm. With the engineering of a fermenter, we combine operations that contribute to the production of quality feedstuffs suitable for preservation.

7.3. Technology transfer and adoption

Several technologies are transferable to the farm, especially on small scale farms. The main constraints to the adoption of these technologies are lack of knowledge, labour and funding (Owen et al., 2012). Smallholders require feed with a good nutritional and sanitary quality. Feed must be available in time and space, and at a low-cost. Processing feed is the solution to face to these problems. Due to the fact that the technologies employed are not too sophisticated, these can be handled by smallholders. Figure 1 schematises strategies for feeding animals on a mixed crop-livestock system, reducing environmental impacts and prioritising local plant resources available on farm.

Furthermore, production of feed from crop residues is one of the highest yields in the world due to the constant demand for feed (Ajila et al., 2012). But, many factors must be taken into consideration when developing a feed production route (Table 5). As a result, it's capital to perform participatory approaches to facilitate the transfer innovation on farm and to make the farmers adopt easily these technologies. Agricultural innovations are more likely to solve local issues when they are jointly developed through participatory processes.

On his own, an operator does not have the financial capacity to invest in a recovery infrastructure, nor to collect a sufficient quantity of by-products to make a recovery chain viable (Donner et al., 2020). Moreover, the purchase of machines to process agricultural resources involves an economic burden that many smallholders cannot afford. Agricultural cooperatives provide access to innovative agricultural equipment and technologies, by reducing production costs and building cohesion among members. In an agroecological approach, agricultural cooperatives can provide a strategy to address the socio-economic problems faced by smallholders. However, support by managers for cooperative ideals and principles are evident in order to minimize conflicts particularly with the property rights and benefits of members (Adrian and Green, 2001). Therefore, it is necessary for managers to provide legal advice to farmers on the use of the equipment and to organise training on how to control the equipment.

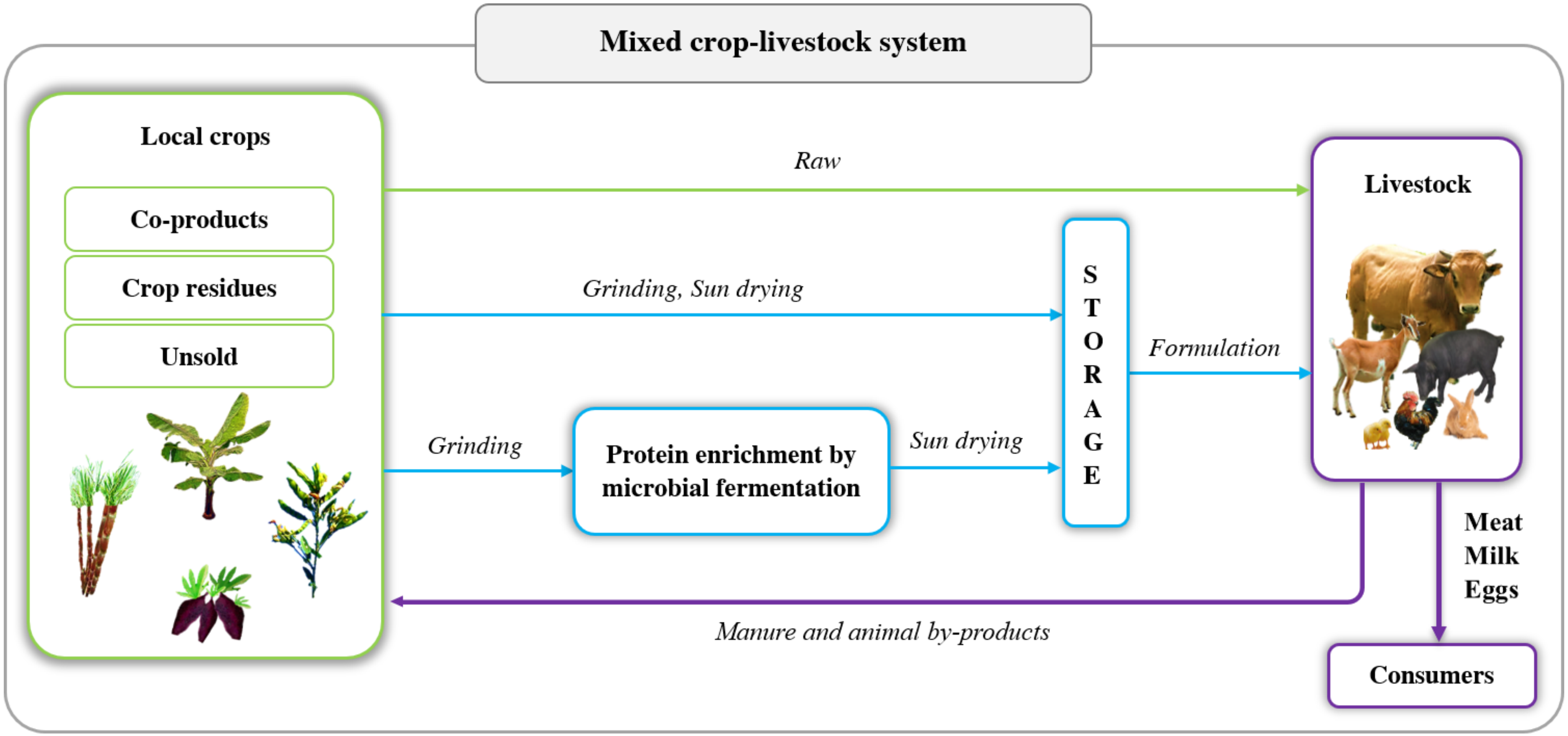

Figure 1. Diagram of agroecological feeding strategies in a mixed crop-livestock system

Table 5

Factors affecting the on-farm feed production project (adapted from Melcion et al., 1986)

Factor	**Details**
Technical	
Animal	Type of breeding
	Species and age of the animal determines the level of accuracy of the feed to be produced
	Livestock number for the amounts of raw materials and feed required
	Feeding mode (presentation and distribution)
Feed	Raw materials used
	Availability and ease of supply of raw materials reduces transport costs
	Quantity to be produced
	Feed appearance (e.g. palatability led to voluntary fed intake)
Equipment	Availability of equipment
	Feed production and storage building
	Electrical installation
	Maintenance and repair
Social	Available labour
	Technical skills of the staff
	Machine control (the technology should make work easy to undertake)
	Technicity of the process (labour)
Economic	Availability of funds for the purchase of equipment and building
	Production costs (labour, energy, amortisation of financial expenditure,)
	Maintenance of equipment

8. Conclusions

Agro-industrial co-products, crop residues and unsold crops from available local plant resources are raw materials for the production of balanced feed, to address the dilemma of having enough food of animal origin for a growing consumer population in a sustainable way. Thus, using crop residues reduces the competition between food and feed. However, some abundant resources have poor nutritional qualities.

If a major multipurpose crop such as maize is relatively well used in feed, as well as some other cereals like wheat, there are important productions from tropical environments, such as sugarcane, cassava and banana, whose different forms of exploitation generate, sorting differences, co-products, crop residues and unsold which constitute large quantities of raw materials that can be the object of innovative treatments, to elaborate quality and stabilized feed for livestock.

Agro-industrial technologies are of great interest for fair feed production. In order to improve the nutritional quality of raw materials and preserve the improved feed so that it is available over time, and increase the performance of livestock. Nevertheless, the use of such technologies must produce a feed that is safe both for the animal and its welfare.

Access to improved and appropriate technologies is a major constraint with small farmers. Among features characterizing small-scale farmers, we adhere, as do some scientists, to the fact that:

- They resist changes to avoid risks and capital to invest.
- They have little or no access to major decision-making processes and of use of new technology.

Improved and appropriate technologies are suitable for the many small-scale mixed farms, but the challenge is for farmers to adopt them. Therefore, participatory approaches are required to assess the time and labour required, the process management and the manpower to be employed. It may be interesting to set up agricultural cooperatives that allow the mutualisation of investments for equipment and charges related to power consumption in order to face the socio-economical constraints.

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