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BIOCHEMICAL AGRO-INDUSTRIAL WASTE VALORIZATION IN FAVOR OF ANIMAL FODDER APPLICATION

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Amid rising global food insecurity problem, the need to develop livestock and animal wealth is increasingly pivotal. Compostable agricultural and agro-industrial wastes, consisting primarily of lignocellulosic residues, offer a cheap alternative to conventional fodder or forage, aligning with circular economy and sustainability principles. Additionally, it is considered an environmentally-friendly strategy through evading the pollution hazards ensued from the wastes' indiscriminate disposal. Pre-treatment (physical, chemical, or biological) enhances the inedible waste valorization by improving digestibility, accessibility of nutrients and reducing anti-nutritional factors that confer adverse impact on health and growth. Exogenous enzyme-assisted biochemical treatment standardizes leftover forage composition, enabling commercialization and maximizing its dietary value for both ruminants and monogastric animals. Microorganisms are the best candidates for hydrolytic enzymes production because of the efficient, fast, cost-effective, high yields, and presence of standard protocols for procuring them from heterologous producers via genetic engineering. This prospect requires optimizing scalability, economic feasibility, and food quality traits.

***Keywords**: Agro-industrial waste (AIW), Exogenous enzymes, Sustainability, Circular bioeconomy, Green chemistry*

INTRODUCTION

In 2000, the world leaders signed and committed themselves to the United Nations Millennium Declaration which included combating poverty and hunger among other development goals. However, by the end of 2019, the United Nations announced that one in ten people of the world population (mounting up to approx. 750 million people) suffered a certain level of food insecurity ie: lacking a secure access to nutritious, balanced or even enough food. The results were evident as acute hunger, edge of starvation, malnutrition or undernourishment. The reports in 2019 described stunting and wasting in 47 million children under the age of 5 in addition to the risk of survival and productivity in adults among the severe manifestations of the worldwide food problem, mostly aggravated in low- and middle-income countries on the grounds of political conflicts, climate change and economic recession [1]. Over the past three years following the COVID-19 pandemic and the consequent decline in economic and fiscal activity, reports and statistics have disclosed an increasing gap between food production and consumers' demands which subjected more people to immense limitations and constraints concerning regularly obtaining a sufficient and balanced diet, along with the exacerbated shocking food price inflation[2–4]. Hence, to address this imminent crisis and secure the vulnerable population against food insecurity, governments and influential global organizations are obliged to enact and advocate for serious and sustainable transformations to the food supply processes and agriculture regimens, together with socioeconomic, environmental and technological support

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programs[2, 5]. It is also critical to raise public awareness against food wasting, promote upcycling, and employ efficient food production strategies to better the average global intake of basic food substances e.g.: enhance food yields, nutritive value, food safety, physical and economic accessibility and distribution[5].

Livestock, poultry, broilers and fish farms constitute an imperative pillar in maintaining food security and alleviating caloric and protein hunger. As human beings are naturally omnivorous, regardless of any personal preferences, food from animal origin (meat, egg, milk) is the best dense source of high value proteins and micronutrients that are vital for good physiologic performance, cognitive activity, immune response and general health state. Nevertheless, many reasons have contributed to the bottlenecks hindering high growth rates and increased production thereof. The reasons include, but are not limited to, reduction in grazing land, decreased fodder and forage pasture resources, using grains for bio-energy production, new diseases outbreak, uncontrolled use of pesticides and insecticides and climatic changes, in addition to the poor water quality and stressful alterations in temperature and pH in cases of aquacultures [6, 7]. In this regard, scientists have suggested competent approaches to achieve a higher and more sustainable animal production for better availability and equity e.g.: (i) utilizing local low-cost feed, (ii) enhance feed and water consumption at various agro-climatic circumstances, and (iii) employing affordable, safe and competent disease control strategies[8].

Food, agricultural and agro-industrial waste residues as a rich mine for substances with nutritional prospective

Domestic and commercial farms, as well as agricultural food processing and agriculture-based industries (e.g.: beverages, bakery, confectionary, oils, chips, etc.) produce tons of inedible recyclable waste in all steps of the production and supply chain, mounting up to one third of the total food produced. The caloric loss has been estimated at 30-60% of carbohydrate content, 5-10% proteins and 10-40% fats [9, 10]. The food wastage is regarded as problematic burden both environmentally (ie: water and surface pollution with substances of high biological oxygen demand BOD and chemical oxygen demand COD, endangering aquatic life, compromising soil fertility, almost 7% of the greenhouse gas GHG emissions estimated at ca. 3.3 billion tons of carbon dioxide yearly) and economically (ie: costs of transportation, proper disposal, rodent control, health risks) [10–14]. Agricultural and agro-industrial waste (AIW) terms describe materials that cannot be consumed for human benefit and exit the food chain in the form of indigestible, unpalatable or undesirable biomass (IUUB)[15–17]. It has indeed long been used in rural areas by farmers for feeding cattle, domestic fuel or as animal bedding. Yet, more recently, the wastes' use as fodder has decreased in modern farming facilities to standardize the feed for precise yields and rule out the risk of pathogens' transmission, in conjunction with its unreliability because of the seasonality and hence, inadequate capacity to supply the market demands[14, 17].

The expanding progress in food industry and urban consumption patterns, however, has culminated enormous amounts of agrarian residues that constitute an economic burden, disadvantageous effect on soil via landfilling and threat to water sources via eutrophication. The current understanding of the impact of environmental hazards and the food insufficiency in the light of climate change, sustainability and circularity, have made recycling of the food and agriculture residues an actual critical matter. Favorably, the richness and complexity of the composition of those discards encouraged their portrayal as raw material for other vital industries rather than mere leftovers. Waste has been investigated for yielding a plethora of essential and valuable commodities e.g.: fertilizers, pesticides, bioplastics, pigments, cosmetics, biosorbents, etc. AIW contains a wide heterologous array of nutritional content (e.g.: carbon, nitrogen, minerals) and bioactive compounds (e.g.: terpenes, alkaloids, flavonoids, etc.), that vary depending on plant-specific factors as well as harvesting and post-harvest handling criteria [3, 18]. By exploiting AIW for supporting the growth of microbial cells biofactories, it has been reported to maintain the growth and production of several secondary metabolites which represent substantial high value products [10, 12] e.g.: biopigments, biofuel, prebiotics, vitamins, antibiotics, antioxidants, etc. Yet, due to the pressing food shortage threats, scientists are pursuing strategies to re-introduce the compostable food “garbage” into the food cycle as feed for livestock, poultry and fish, which is herein discussed.

In relation to the sustainable production of animal products, circular economy depicts plant-based industries’ compostable by-products as a potential candidate for animal and poultry feed **(Fig. 1)**. They can also be valuable for providing animals with bioactive compounds, micro- and macro-minerals while avoiding the competition with humans for food resources (cf. crops and grains). Besides, it can have a major impact on preserving the redox balance, in addition to the overall reduced cost for animals’ production (esp. in monogastric animals) and reducing the corresponding environmental footprint [6, 7, 17, 19].

Agricultural waste, fruit residues and agroforestry (e.g.: pomaces, bagasse, seeds, husks, stems, stalks, etc.) mainly consist of cell wall polysaccharides, hemicellulose, cellulose and lignin; the amount of each depends on the geographical territory, kind and maturity of plant at harvest **(Table 1)**[18, 20]. On the industrial scale, waste pre-treatment and supplementation are important for the uniformity of the feed from different sources, improving protein and carbohydrate availability for *in vivo* digestion, controlling the moisture level that affects the spoilage tendency, deactivating anti-nutritional factors (ANF), preventing animals’ diseases (e.g.: foot and mouth disease, salmonellosis, tuberculosis), etc. [6, 16, 17]. In this context, it is important to note that both the food waste and the processing techniques and machinery define the resulting dietary benefits, safety, digestibility and palatability. The different livestock or poultry possess different capabilities of digesting the available feed and benefiting from the nutrients or getting exposed to pathogens. For example: geese are more able to chop up and acidify crop residues and food waste than pig, chicken or cow [16]. Furthermore, plant-derived fodder usually contains ANFs that bestow a disadvantageous health response that can range from obstructing the dietary benefits or compromising digestibility up to growth hindering, decreased milk yields, adverse immunity system responses or tumor development [11], e.g.: antigenic components, phytates, oxalates, tannins, saponins, dietary fibres, etc. Hence, and despite the counter effect on the intended cost-effectiveness, it is important to detail and standardize the composition of the potential local food waste as much as possible for efficacious outcome and to avoid any discrepancies.

As aforementioned, pre-treatment of the residual waste material is commonly employed to ease and improve the substrates’ bio-accessibility and availability for consumption, in comparison to its raw state [15]. The non-discriminatory waste pre-treatment comprises a preliminary physico-chemical pelleting step while the following processing may be physical or mechanical encompassing several steps (e.g.: milling and sieving to produce uniform particle size, dehydration via heating/pyrolysis or freeze-drying, shearing and mixing for homogeneity, ultrasonic or microwave exposure) or chemical (e.g.: acidic, alkaline or enzymatic hydrolysis). Biological agents (microbes or enzymes) mediated treatment is more specific in action and mainly aims to digest the plant cell wall and liberate the associated locked-up health-beneficial compounds (e.g.: carbohydrates, proteins, β-glucans, terpenoids. coumarins, etc.) [3, 13].

It is obvious, therefore, to infer that market engagement and commercialization of the treated AIW, especially fermented ones, is hindered by the difficulty to efficiently bring the final products’ characteristics into line. On the one hand, the waste nutritional properties and bioactive compounds content depend on the nature of AIW, geographical territory, cultivation and harvesting conditions as well as the post-harvest handling, and on the other hand, strict nutritional analyses annihilate the economic sense of waste incorporation. Furthermore, the biological agent usually requires defined conditions (temperature, pH, oxygenation) to get reproducible results [3]. Unfortunately, these drawbacks are accountable for discouraging farmers and food products’ investors and stakeholders from endorsing the waste for feeding fearing consumers’ disapproval, along with the need for proper storage to protect against spoilage [14]. However, this can be partially mitigated by primary optimization studies, and adopting meticulous measures to assess the growth performance and quality parameters of the animal-source food (meat, egg, milk). This can be later followed by building a high caliber repetitive process following good practices and quality guidelines, especially that the safety is quasi-unquestionable.

It is noteworthy to point out that the food waste valorization for animal feed application is also attempted at poultry, insects, fish and seafood waste. Examples include; chitin and chitosan retrieval from shrimps, keratinolytic treatment of chicken feathers from slaughterhouse waste, ensilage products from aquaculture's or fisheries' bycatches, discards, sludge or offal.

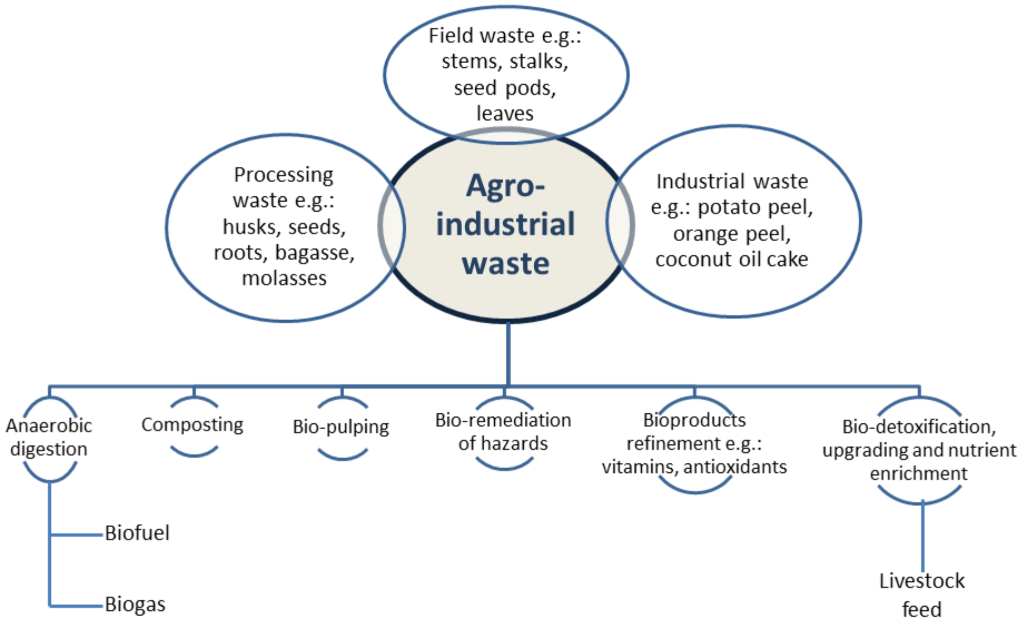

Fig. 1: Schematic illustration for some of the key processes for exploiting agro-industrial waste.

Table 1: Composition of some agro-industrial waste (AIW) materials and their use as animal feed, as summarized in.[9, 20]

Agro-industrial waste	Chemical composition (% w/w)				Animals
	Cellulose	Hemi-cellulose	Lignin	Ash	
Barley straw	33.8	21.9	13.8	11	cows, fish
Corn stalks	61.2	19.3	6.9	10.8	cows, fish, poultry
Orange peel	9.21	10.5	0.84	3.5	cattle
Potato peel	2.2	-	-	7.7	pigs and goats
Rice straw	39.2	23.5	36.1	12.4	cows, horses, buffaloes
Sugar beet waste	26.3	18.5	2.5	4.8	cows and buffaloes
Wheat straw	32.9	24	8.9	6.7	cows, fish, pigs and goats

Microbial additives for valorization of food waste

Whilst mechanical and chemical processing can be multi-step, expensive and laborious, biological treatment affords a cheaper and environmentally-friendly green alternative, meanwhile the fermented biomass is sometimes referred to as silage. Of note, biological agents or microorganisms have been utilized to support the food industry since pre-historic times for producing cheese, yoghurt, beer, bread, etc. More contemporarily, microbial fermentation is one of the employed methods for the treatment of hemi-cellulosic waste biomass and crude fiber digestion, **(Fig. 2)** and includes fungal, actinomycetes and *Lactobacilli* fermentations, being referred to as zootechnical additives, e.g.: Basidiomycetes and *Pleurotus* for lignin degradation, *Coprinus* to increase the protein content, *Sporotrichum* and *Trichoderma* for lignin, cellulose and hemicellulose degradation, *Bacilli* and *Lactobacilli* to increase chitin and chitosan load [3, 13, 15]. The utilized microorganisms, however, have to be designated as GRAS (generally regarded as safe) in order to be fit for food consumption. Other employed genera involve (i) filamentous fungi *Aspergillus*, *Penicillium*, *Fusarium*, *Rhizopus*, *Mucor* and *Trichoderma*, (ii) yeasts *Candida* and *Saccharomyces*, and (iii) bacteria *Bacillus* and *Lactobacillus* [11]. Along with enhancing AIW properties as animal feed by digesting fibrous content and increasing digestible matter, microbially-fermented silage was also found to bestow other advantages cost-effectively [3, 9] such as (i) help generating food material with extra value (ie: functional food for boosting the immune defenses or preventing certain diseases in animals e.g.: displaced abomasa and rumen acidosis, or foodborne diseases e.g.: salmonellosis and botulism), (ii) convert bioactive compounds to a more active form, (iii) ameliorate the gut health in the corresponding animals, as evidenced by increased microbiota diversity and better morphology of intestinal mucosa protecting the gastrointestinal tract against pathogens' invasion, and (iv) augment the conventional feeding in arid seasons and inadequate pasture. Solid-state fermentation (SSF) or ensiling is the method of choice for this purpose as it resembles the original habitat of microorganisms in nature and valorizes the waste in scanty water conditions, which is another advantage in the wake of the current worldwide water resources scarcity. For this, fungi are mostly encountered due to the superior robustness of their spores and their ability to thrive, colonize, assimilate the available nutrients and grow under SSF approach. Fungi are usually applied as *mono-cultures*, as a single solitary strain, *co-cultures*, when two types are supplemented together, or *sequential-cultures*, when two or more strains are introduced consecutively [11, 21, 22].

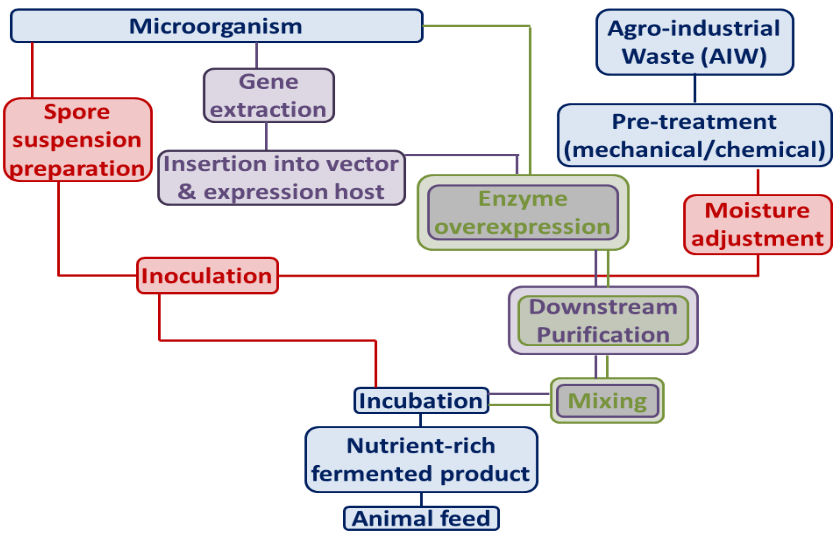

Fig. 2: Simplified schematic flowchart for production of animal feed from agro-industrial waste (AIW) via microbial treatment (red line), endogenous enzymatic treatment (green line) or heterologous enzyme treatment (purple line).

The outcome of feeding cattle with fermented AIW is a factor of the animals' kind, physiological state, type of silage and whether it was used solely or in combination with pasture forage. In this regard, white and brown rot fungi basidiomycetes (e.g.: *Pluorotus ostreatus*, *Phanerochaete sordida* and *Pycnoporus cinnabarinus*) are famous for being the best lignolytics on account of the action of carbohydrate-digesting hydrolases and the oxidative lignin-degrading system that compromises laccases, lignin peroxidases and manganese peroxidases (Singh and Singh, 2022). *Aspergillus oryzae*-fermented soybean meal resulted in better dry matter and crude protein digestibility and consequent higher weight gain (~8.5%) and lower feed/gain ratio in piglets than the unfermented counterparts. This was attributed to breaking down of large antigenic globulins and removal of trypsin inhibitors ANFs[23]. In another study, and despite 13% decline in growth rate upon replacing 50% of pigs' feed with silage, the pork quality was impressively equivalent to that from regularly-fed ones in virtue of juiciness, color, palatability and marbling[9]. *Aureobasidium pullulans*, known to be rich in xylanase, cellulase and protease, lignocellulose-degrading *Neurospora crassa* rich in β-glucosidase and cellulolytic *Trichoderma reesei* were tested alone and in multiple combinations and showed an increasing protein content in fermented canola meal, accompanied with a reduction in the ANFs crude, acid- and neutral-detergent fibers (ADF and NDF) while only *T. reesei* increased the total carbohydrates due to the high cellulase levels **(Fig. 3)**[22]. Similarly, *Lactobacillus salivarius* degraded the ANFs glucosinolate and crude fibers content in canola meal [24], while ferulic acid from esterase-producing lactic acid bacteria (LAB) increased the organic dry matter and decreased ADF and NDF content upon corn stover ensilage [25]. Fermented corn cobs increased cattle's weight gain and body condition scoring compared to the unfermented feed [26]. Fermented rice straw resulted in the same goats' weight gain, crude protein and fiber content, and consequent digestibility and palatability, like commercial feed formulations and fresh forage, which nominates the cheaper straw residues for use[27]. Fermented residues of different kinds of herbal tea increased crude protein and short chain fatty acids, along with decreased ADF and NDF, enhanced cattle growth, immunity indexes and stress response [28]. Fish waste and lemon peel were elucidated as good candidates for aquaculture feed after fermentation by *Lactobacillus reuteri* and *Saccharomyces cerevisiae* as the protein and lipids levels, fatty-acids composition were satisfactory with decreased polyunsaturated congeners and minimal ash content [29].

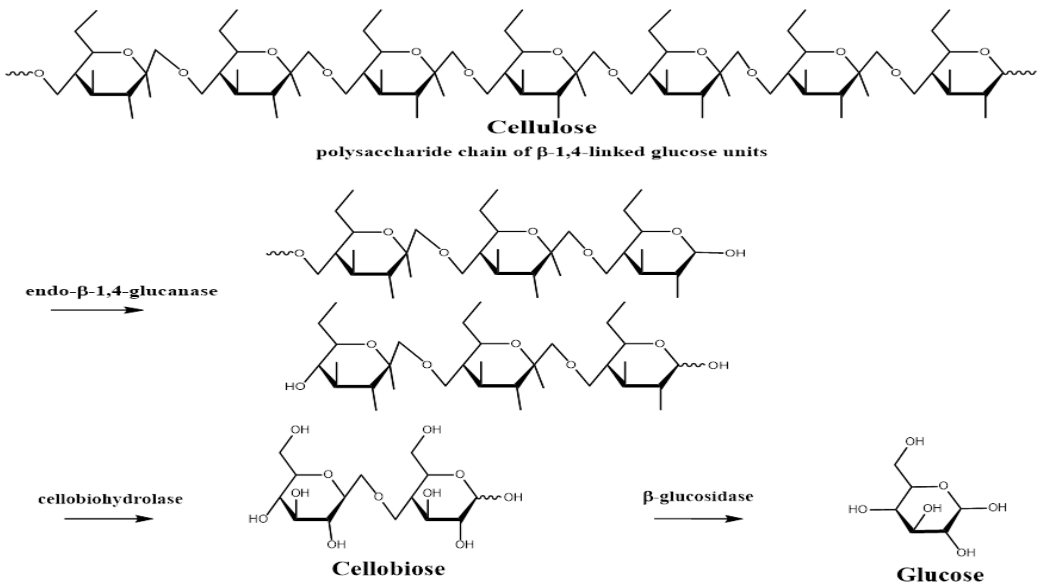

Fig. 3: Sequential enzymatic cellulolytic digestion to produce water soluble glucose by the aid of cellulases (β-1,4-endoglucanase, cellobiohydrolase, and β-glucosidase.

Enzymes application for waste processing

Using exogenous enzyme(s) instead of the whole organism inoculation has evolved over the past few years and is now acceptable due to their specificity of action affording fine control to guarantee the end products' properties (targeted digestion), and avoiding off-target by-products while keeping the process environmentally-friendly under mild reaction conditions as they decrease the reactions' activation energy **(Fig. 2)**. Hydrolytic enzymes (e.g.: carbohydrases, phytases, proteases, ligninases, etc.) are the major enzyme classes that can be useful in harnessing the full fodder value of the waste[3,30,31]. Enzymes can be obtained from various origins; plants, animals, microorganisms or even ruminal fluid from slaughterhouses. Microbial enzymes (bacteria, yeast, fungi) are preferred because of the easier, faster, more consistent and cheaper production, in addition to the great diversities in their qualities depending on the strain, and their high stability. Based on productivity yields, fungi are superior especially with their ubiquity and general recognition as a rich and abundant supply of bioactive secondary metabolites of significant biotechnological value. According to metagenomic screening, terrestrial fungi are characterized by a special pool of genes with interesting applications. They also possess a useful trait, that is the extracellular enzymes' secretion which facilitates the downstreaming and retrieval in a pure form, and decreasing the whole production cost[32]. Downstream processes include, but are not limited to, fractionation and precipitation using neutral salt or organic solvent, and chromatographic processes such as size exclusion and ion-exchange chromatography[33]. This nominated soil fungi to cover up to 50% of the market share of enzymes for different applications, ie: industrial, medical and environmental uses[30, 32].

The application of pure enzymes has been long hurdled by the difficulty and high cost of procuring them from their endogenous producers in a stable and catalytically-efficient form. Yet, recent advances in microbiology, biotechnology and up-scale fermentations have facilitated producing them, in large quantities, both homologously from the native strain and heterologously from an expression host, while preserving the original traits. Further, enzymes' encapsulation, immobilization within a solid matrix, or lyophilization has become feasible with reasonable costs and under standard clear operating protocols, which increases their stability and extends their catalytic life. It is imperative that the enzymes should endure the waste treatment processes and the conditions down the animals' gastrointestinal tract e.g.: temperature, mechanical stress, pH, ionic strength, autochthonic proteases, etc. Thermozymes, or thermostable enzymes derived from thermophilic or hyperthermophilic organisms, have been applied due to their high stability under harsh conditions since pelleting steps were found to deactivate enzymes, while high temperatures allow for better mass transfer and better substrate solubility and hence, increasing the catalytic yields [34]. Similarly, some processes employ enzyme immobilization for protection against the adverse operational conditions and in the meantime, allowing retrieval and recycling of the enzymes.

As previously stated, and like exploiting whole organisms, the key goal of waste treatment is to increase nutrients' bio-accessibility (e.g.: starch, minerals, proteins, etc.) and digestibility level over 75% as well as eliminating anti-nutrient elements in order for effectual feeding to take place[15, 30]. Hence, biological catalysts, or enzymes, should carry out the following functions; (i) hydrolyzing the bonds of complex polymers that are not processed by the animals' physiological enzymes, (ii) cell wall hydrolysis, (iii) eliminating or bio-detoxifying ANFs with opposing influence, (iv) decrease the forage viscosity, and (v) adding to the animals' inherent digestive enzymes pool [15, 35]. As enzymes are known for their specificity in action, also known as substrate promiscuity, they can be added in combination cocktails, for multi-step reactions, each for an individual role. Thus, the incorporation of enzyme(s), with or without the relevant microorganism or even a different organism, with the lignocellulosic biomass serves to increase the digestion capacity e.g.: cellulase and fibrinolytic enzymes, respectively, provided glucose for LAB **(Fig. 3)** and degraded ADF and NDF in ensiled rice and oil palm residues. The LAB growth, in turn, decreased the pH promptly which protected the silage against plant enzymes, harmful bacterial and fungal growth. Cellulase-assisted treatment also decreased volatile fatty acids, and increased dry and organic matter denoting successful fermentation and high nutrients digestibility [36]. Lately, commercial formulations have been available for the purpose of releasing nutrients and/or removing ANFs e.g.: avizyme® (xylanase, protease and amylase) that specializes in grain treatment for poultry feed, and the cellulolytic viscozyme®L preparation.

Yet, there are drawbacks for using pure enzymes and relinquishing whole organisms, beside the cost factor, e.g.: (i) forfeiting a cheap source of co-factors like nicotinamide adenine dinucleotide phosphate (NADPH) and adenosine triphosphate (ATP), (ii) losing the nutritional or health-related added values from fermented organisms' metabolites e.g.: enzymes' assortment, functional compounds like antioxidants, vitamins and prebiotics, (iii) pure enzymes might undergo non-competitive inhibition by polyphenolics in the waste materials e.g.: pomace or tannic acid vs. pectinase, and potato polyphenolics vs. α-amylase, α-glucosidase and aldose reductase [3]. The limitations of enzymes' utilization open room for investigations to overcome them as seeking new enzymes with different features from unusual habitats, or *de novo* synthesis of new catalytic entities by employing rational design through protein engineering of existing biocatalysts via single or multiple site-directed mutagenesis, directed evolution, synthetic biology to achieve the desired properties such as increasing temperature and pH resistance or catalytic potential e.g.: optimal pH range for phytase from *Aspergillus fumigatus* increased by a single amino acid mutation (lysine to alanine; K68A) [37], and thermal stability of xylanase from *Trichoderma reesei* was enhanced when two threonine molecules were replaced with cysteine (T2C, T28C) [30]. Other limitations stem from the safety criteria of the products and their fit for use. The specs for producing enzymes for food-related usage should be undeniably strict and complicated to exclude the risk of allergies, toxicity and residual microbial products [12]. It is crucial that they get validated for their safety to qualify for food-grade, as specified by regulatory bodies like FAO and WHO, so as to ensure the end consumers' health. Some parameters are being free from mycotoxins, and having acceptable levels of nucleic acids which can be responsible for gout and kidney stones, and biogenic amines that may have repercussions as severe as tumor induction and anaphylaxis. In addition to ensuring the safety, another limitation facing the waste valorization as fodder is maintaining the consumers' acceptance for the final sensory qualities in comparison to the natural forage.

Coupled with the biochemistry-derived optimization studies, other development opportunities could present themselves by considering the environmental impact of all the production steps, especially that one of the motivations of such approach was the environmental burden of landfilling and the climate change hazards. This can take place by studying the life cycle assessment (LCA) of the complete procedure or the different encompassed steps. The LCA studies allow evaluating the environmental impact of the different stages (referred to as; cradle to grave, cradle to gate, gate to gate and gate to grave) and comparing them to alternatives to help decision-makers or stakeholders make an informed decision in the light of GHG emissions[38, 39].

Finally, along with the previous focus on AIW exploitation, it is necessary to mention that, more than 40% of the agricultural food is wasted in retail and household processing. Also, animal-derived wastes, e.g.: lard, tails, marine shells, are definitely rich with complex carbohydrates, proteins and lipids nominating them as possible sources for nutrition, which better gets re-introduced to the food supply chain under the reduce-reuse-recycle sustainable principles. In this regard, to minimize food loss and encourage upcycling, community-size arrangements are pivotal through; (i) governmental legislations e.g.: strictly-enforced punitive laws against behaviors like landfilling and non-compliance to organic garbage segregation, (ii) logistic facilitations and creating markets for disfigured and misshaped crops, as well as promoting redistribution via donation and creating necessary digital platforms, and (iii) education programs for food producers and consumers, equally, to spread the awareness about topics like waste sorting and irresponsible food hoarding.

Conclusion

As a means of alleviating the global food insecurity crisis and to fill nutritional gaps, seeking ways to decrease the food waste and proposing alternative sources for animal fodder have been among the pressing topics on scientists' and economists' agendas. On this basis, exploiting agro-industrial waste or agroforestry has risen and has been discussed, under circular bioeconomy, to provide dietary requirements for livestock on account of their valuable organic content. By this, many advantages are realized as it avoids the competition with humans (cf. cereals), and makes use of one third of the produced food mass that would be otherwise lost while aggravating the environmental pollution problem. However, to guarantee the maximal use of the nutritional capacity and avoid any probable health hazards, many pre-treatments are required to qualify the waste for use as animal feed for ruminant and monogastric animals, including improving the digestibility and bioavailability of the nutrients. Using biological catalysts or enzymes has been studied for such purposes, and endorsed by the availability of protocols for enzymes' overexpression and the possibility to obtain them under food-grade safe conditions, as recommended by the FAO and WHO. Yet, further investigations and optimizations are crucial to render the valorization process more efficient via (i) specify or characterize the waste from plausible origins (region, climate, soil type, etc.) and hence, standardize the outcome and properties of the fodder, (ii) explore for new enzymes with better catalytic aspects or better tolerance to processing steps, or (iii) apply bioinformatics, molecular biology, protein engineering, directed evolution and synthetic biology tools to develop specific enzymes with the desired biochemical traits. In conclusion, with the increasing awareness about the importance of preserving the ecosystem and implementing sustainable measures to replace the (take-make-dispose) consumption models, valorization of the huge amounts of agro-industrial waste is an excellent chance for decreasing the environmental pollution and consequent health hazards, and increasing the food availability at reduced costs.

Abbreviations

Acid detergent fiber, ADF; Agro-industrial waste, AIW; Anti-nutritional factor, ANF; greenhouse gas, GHG; Lactic acid bacteria, LAB; Life cycle assessment, LCA; Neutral detergent fiber, NDF; Solid-state fermentation, SSF.

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تحويل المخلفات الصناعية الزراعية بيوكيميائيا لاستخدامها في تغذية الحيوانات

هبة يحيى

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في ظل تزايد انعدام الأمن الغذائي على مستوى العالم، أصبح تطوير الثروة الحيوانية والماشية ضرورة حتمية. تقدم المخلفات الزراعية ومخلفات الصناعات الزراعية القابلة للتحلل، التي تتكون بشكل رئيسي من بقايا الليجنوسليلوز، بديلاً اقتصاديًا للأعلاف التقليدية، مما يتماشى مع مبادئ الاقتصاد الدائري والاستدامة، بالإضافة إلى تجنب مخاطر التلوث الناتج عن التخلص العشوائي. تعزز معالجة المخلفات الغير صالحة للأكل (الفيزيائية أو الكيميائية أو البيولوجية) من قيمتها عن طريق تحسين قابلية الهضم وتوفر المغذيات وتقليل العوامل المضادة للتغذية التي تؤثر سلبًا على الصحة والنمو. تساعد المعالجة الكيميائية عن طريق الإنزيمات على توحيد تركيبة العلف، مما يتيح إمكانية التسويق وزيادة القيمة الغذائية التي تتناولها الحيوانات المجترة وغير المجترة. تُعد الكائنات الحية الدقيقة مثالية لإنتاج الإنزيمات التحليلية بفضل كفاءتها وإنتاجيتها العالية ووجود بروتوكولات قياسية للحصول عليها من خلال الكائنات الأولية والمتغيرة عبر الهندسة الوراثية. يتطلب هذا النهج تحسين القابلية للتوسع والجدوى الاقتصادية وصفات الغذاء الناتج.