Ann. Anim. Sci., Vol. 25, No. 2 (2025) 529–545 *DOI: 10.2478/aoas-2024-0081*

ENHANCING THE FEED EFFICIENCY OF CROP RESIDUES IN RUMINANTS – A COMPREHENSIVE REVIEW

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Abstract

Worldwide, the production of agricultural residues exceeds five billion metric tons per year. Regardless of their many applications and substantial potential to increase crop and animal productivity, many crop residues, particularly in Asian, African, and Arabian nations, are burned. This detrimental practice limits the recycling of soil nutrients while increasing air pollution and wellness risks. Enhancing feed efficiency while simultaneously lowering production costs and increasing animal protein is a key objective of nutritional supplements in livestock feeding. Antibiotics have been utilized in farm animals at sub-therapeutic levels to increase feed use effectiveness and digestion, as well as animal welfare and performance. However, the present ban on antibiotics as nutritional supplements has boosted the search for substitutes, with natural feed additives considered cutting-edge options. On the other hand, feed that has undergone biological treatment improves animal productivity, feed intake, and digestibility. Nevertheless, the absence of agents and expertise and substrate weight decrease may result in a 40% dry matter loss limits application. In this review, we look at the importance of detrimental residue administration and the advancement and adoption of technologies to handle surplus residue.

Key words: crop residue, feed efficiency, improvement methods, ruminant feed

The livestock industry, crucial for smallholder farmers and meat production, faces challenges like insufficient feed, diseases, low-quality breeding stock, and inadequate policies affecting performance globally (Kidanemariam and Fesseha, 2020; Banda and Tanganyika, 2021). According to Martens et al. (2022), ruminants' lack of roughage because of the drought that hit parts of Europe in 2018 and 2019 has sparked a renewed hunt for sources of fiber besides "traditional" forages like grass. In Europe, cereal hay is easily obtainable throughout the year. A few variables that affect forage quality are type, variety, maturity, height, climate, mass production, and storage technique. Animal health is affected by variations in dry matter consumption, feeding expenses, and forage quality (Boga and Ayasan, 2022).

Globally, the food processing and agricultural sectors produce billions of by-products, including animal and plant-derived by-products (Abdelnour et al., 2019; Bandara and Chalamaiah, 2019; Alagawany et al., 2020; Abd El-Hakim et al. 2021; Ayyat et al., 2021). These by-products are accessible and inexpensive but must be used to prevent pollution. Investigating techniques to enhance agricultural by-products' value is crucial, as crop residue is a significant livelihood source (Duncan et al., 2016; Schrobback et al., 2023). Crop residues play a bigger role in cattle diets due to arable land scarcity and reduced feeding resources. However, small-scale farmers in developing countries comprise an important part of the feed used for ruminants during the dry season (Lukuyu et al., 2012; Ugwoke et al., 2023).

For many poor farmers worldwide, combined crop farms serve as their primary source of income. Additionally, much of the world's food comes from them; according to current projections, mixed systems contribute about 50% of global food production (Herrero et al., 2010). Due to the incorporated structure of combined crop farming with livestock, crops and livestock provide complementary inputs to one another, most notably crop residues (straws and stoves) that support livestock. Animals give essential inputs for cultivable production, such as feces and traction (Powell et al., 2004; Pédèches et al., 2023).

The amount of meat produced per head of animals is typically poor due to various issues, given the high demand for animals and agricultural goods in developing nations (Thornton, 2010; Ederer et al., 2023). Insufficient nourishment is the primary global cause of low animal productivity. Feeding accounts for approximately 60% to 70% of livestock and poultry production expenses. An essential factor is optimal feed utilization (Seré et al., 2008; Mohamed et al., 2024). Organic feed additives have recently replaced synthetic growth boosters and antibiotics to optimize growth performance and improve carcass features in birds and farm animals. Researchers use these additives to boost immunity and efficiency (Abd El-Hack et al., 2023; Kamal et al., 2023 a, b; El-Ratel et al., 2024). Crop leftovers, like high-fiber straws, are crucial for tropical regions' nutrition but unsuitable for animal feed due to low digestion (Elghandour et al., 2014). Alsersy et al. (2015) have developed techniques to break down carbohydrate-lignin complexes, improve straw nutrient content, and enhance health benefits.

To improve cellulosic division and digestion, scientists are looking into how microbes, especially basidiomycetes fungi, can break down lignin-carbohydrate structures and bypass lignin-mediated physical protection barriers (Suryadi et al., 2022). This enhances the use of the plant materials in the rumen by making more fermentable energy available to ruminal microbes (Tadesse, 2014). Biological substances like fungi are an effective remedy to boost the digestibility of poor-quality forages and eliminate lignin (Sharma and Arora, 2015). Basidiomycetes, representing 32% of the species, including white-rot fungi, can break down lignin in cell walls, transforming easily digested carbohydrates into complex sugars (Khattab et al., 2013). Fungus metabolism includes taking in sugar and secondary metabolism, which improves the nutritional value and environmental safety of agricultural waste, even though it has low nutritional quality and high production (Kholif et al., 2014). Table 1 is an inventory of technologies utilized to improve crop residues' quality, improve forage varieties, utilize by-products and processed concentrates, and promote private sector participation in feed production and marketing.

Therefore, this review aims to clarify the importance of detrimental residue administration and the advancement and adoption of technologies to handle surplus residue.

Importance of crop residues

Bogale et al. (2008) examined the nutritional composition of primary agricultural byproducts in the Sinana and Dinsho sub-districts, identifying differences in their accessibility. The harvest season had no significant impact on crude protein levels, neutral detergent fiber, or *in vitro* dry matter digestibility (IVDMD). Compared to barley and emmer wheat, wheat straw exhibited a lower IVDMD. Conversely, cereal residues displayed a higher hemicellulose content. Crop residue, as defined by Schiere (2010), is the biomass from fibrous crops (such as leaves, stem cuts, and seed pods) that remains following more worthwhile sections, like grain, that are harvested. This biomass is frequently viewed as the noneconomic portion of crop production. Shinde et al. (2022) estimated that utilizing a grain-residue transformation aspect, the global output of crop residue was 5 billion metric tons in 2020–2021, more than a third bigger than the production levels from 1960–1961.

In agricultural cost-benefit analyses and technology assessments, crop residue's many applications and financial advantages are not fully considered. Forecasts of the quantity of crop residues produced and utilized in various cropping systems and nations are also scarce. The yield of crops and area harvested figures are roughly converted to the amount of residue production using common conversion coefficients (Faostat, 2021). Because of a lack of data and hazy emissions converting factors, predictions of the contribution of burning crop residues to greenhouse gas (GHG) emissions have the highest level of uncertainty among all the emission categories reported by the Intergovernmental Panel on Climate Change (IPCC) (Solazzo et al., 2021). A significant portion of crop residue is burned each year, with detrimental effects on agriculture, the environment, and the general population, despite its many uses, government subsidies, and public efforts for responsible utilization (Chen et al., 2019; Shyamsundar et al., 2019).

Feeding animals that ruminate with crop residues is the most common and traditional use of them. Conventional animal feeds like husks, straws, stovers, bagasse, and other fibrous lignocellulosic materials can be digested more easily with the help of biological treatments (Mahesh and Mohini, 2013). The research conducted in Morocco demonstrates that crop residue constitutes around 25% of cereal production in a typical year with sufficient rainfall and 75% in a drought, vital for small-scale farmers who engage in crop cultivation and animal rearing. The economic significance of crop leftovers and the potential loss of opportunities from other land uses discourage farmers from transitioning to high-value cash crops or utilizing crop residue for soil conservation (Magnan et al., 2012). Nonetheless, considerable heterogeneity due to variations in farmers' perceptions of the perceived quality regarding using a particular crop residue as feed is present, as does an extensive range in the dietary value of residues from various crops regarding consumption and organic matter digestion (López et al., 2005; Lamega et al., 2024). These variables determine the market value of crop residue as feed, as well as automated farming, the use of contemporary variety in farming, and the number of ruminant animals in the area (Erenstein and Thorpe, 2011).

Table 1. Effective feed enhancement technologies for livestock farming systems and their identified effects

Type	Technology	Description	Identified effects	References
1	2	3	4	5
Increasing the productivity of feed	Enhanced plants for livestock feed	Introducing legumes and other forage species with higher yields and better quality.	Enhance the availability and nutritional value of fodder and lessen seasonal fluctuations.	(Alemayehu et al., 2017)
	Forage development grounded in conservation	Introduction of forage plants, which provide food while promoting soil and water conservation, in natural resource conservation structures.	Preserve land degradation and soil loss while increasing feed availability.	(Alemayehu et al., 2017)
	Integration of food-feed crops	Enhance the availability and nutritional value of fodder and lessen seasonal fluctuations in supply.	Increased feed availability, decreased pest load on food crops, and enhanced soil fertility.	(Lenné et al., 2003)
	Safe grazing	Using intercropping or alley farming to maximize the benefits of pest control, soil and water conservation, and increased forage availability.	Increased forage biomass, enhanced the quality of the feed produced, and reduced the degradation of the grazing land.	(Yayneshet et al., 2009)
	Protected agriculture	Producing fodder under protected circumstances in regions where traditional methods are impractical.	Permit soilless agriculture or the production of fodder on small plots of land. Increased accessibility to green feed.	(Masud and Bhowmik, 2018)
	Utilizing locally underutilized feed resources	The utilization of underutilized locally accessible feed resources, such as crop residues and native fodder species.	Increased farm profitability, decreased reliance on commercial concentrates, and increased feed availability.	(Balehegn et al., 2014)
Improving feed quality	Chemical treatment of crop residues	It involves applying urea to crop residues and soaking or spraying them with diluted alkaline and acid solutions, among other treatments.	Enhanced consumption and crop residues' ability to be digested; increased crude protein content (after urea treatment).	(Sarnklong et al., 2010)
	Biological treatment of crop residues	Using enzymes, bacterial inoculants, or fungi that cause brown or white rot to agricultural residues.	Enhanced crop residue intake and digestion.	(Li et al., 2010; Asmare, 2020)
	Lowering the crop residues' particle size	Grinding and chopping crop residues.	Enhances animal intake and decreases bulk.	(Hamed and Elimam, 2009)
	Crop fertilization	Adding fertilizers to crop residues to increase their nutrient content crude protein.	Fertilization enhances the quality of crop residues used as livestock feed, leading to up to 40% greater milk production.	(Haileslassie et al., 2013)
	Breeding forage crops	Specific breeding of forages to produce better-quality and higher-yielding forage accessions.	Increased feed quality and biomass productivity, which in turn increased livestock productivity	(Sijtsma, 2013)
Preserving feed quality	Appropriate time to harvest forage	Harvesting forages at their peak nutritional content or their peak biomass yield or nutritional value.	Increased productivity, intake, and digestibility of cattle.	(Makkar, 2016)
	Making silage	Keeping fresh fodder in anaerobic storage to maintain its quality.	Preserved feed that has not lost much energy or nutrients or spoiled.	(Titterton and Bareeba, 2000)
	Producing hay	Minimizing nutrient loss from green fodder through drying.	Preserved feed with low energy, nutrient, and spoilage.	(Collins et al., 2017)
	Utilizing preservatives	Utilizing microorganisms or substances that prevent spoilage organisms and maintain the freshness of feed.	Reduced energy and nutrient loss and spoiling in preserved feed.	(Wang et al., 2018)

Table 1 – contd.

1	2	3	4	5
Enhance animals' nutritional condition	Phased or balanced rationing	Feeding a balanced ration tailored to meet an animal's nutrient needs or focusing on specific performance levels.	Milk yield increased by 2–14%, net daily income increased by 10–15%, and greenhouse gas emissions decreased by 15–20%.	(Garg et al., 2013)
	Addition of concentrates	Adding nutrient-rich concentrates to animals' poor-quality basic diets.	Increased body weight gain, milk yield, digestibility, and intake.	(Selemani et al., 2016)
	Supplementation utilizing blocks of multiple nutrients	Giving animals multi-nutrient blocks that supply necessary supplemental nutrients in place of low-quality basal diets.	The study improved cattle reproductive performance by increasing milk yield by 1–1.5 per day by reducing green fodder and protein supplement intake.	(Makkar et al., 2007)
	Feed additive	Supplements such as yeast, probiotics, and enzymes that are added to feeds to help animals better absorb and process nutrition.	Enhanced performance, digestion, and intake of feed.	(Arsène et al., 2021)
Technologies for analysis and operation	Near infrared reflectance spectroscopy (NIRS)	Without reagents, NIRS technology is used to assess the nutritional quality of different feed kinds quickly and affordably.	Increased feed analysis efficacy and cost efficiency could be leveraged to improve feed marketing.	(Modroño et al., 2017)
	Techniques for easy ratio formulation	Farmers can create efficient rations based on local feed resources using simple ration formulation tools such as Excel or mobile applications.	Simplify the formulation of rations and encourage their implementation.	(Sebastian et al., 2008)
	Application for livestock and feed administration	Applications for mobile phones that are easy to use to track, monitor, and analyze feed that is produced, wasted, and consumed.	Increase the profitability of livestock farms.	(Hwang et al., 2011)

Disrupting the presence of agricultural residues impacts the circulation of water and nutrients. Ignoring this can result in unanticipated impacts on other aspects of crop productivity. Johnson (2019) examined how addressing a single problem might lead to unforeseen consequences. An excessive crop residue harvest primarily leads to heightened erosion, causing soil surface crusting, diminished water infiltration, and heightened water stress. Overall, these effects can decrease the effectiveness of nutrients and intensify pest problems (Hansen et al., 2013). The residual harvest significantly impacts crop development, productivity, and excellence. According to a study by Satiro et al. (2019), removing straw from sugarcane in Brazil leads to a drop in soil carbon but does not affect crop output.

Improvement methods for crop residues

Based on a grain-to-straw percentage of 1:0.8, the continent produced 213 million tons of wheat straw in 2019, nearly 35% of the world's total production (Faostat, 2019). However, the primary barrier to the widespread use of straw in animal nutrition is its high lignin content, resulting in low digestibility (Adesogan et al., 2019). The cell wall structure of plants is extremely intricate. There are connections between lignin, hemicellulose, and cellulose (Lee et al., 2014). Certain processes can break these bonds, increasing the palatability of both hemicellulose and cellulose for the rumen microbiota (Weimer, 2022).

Increasing feed intake, digestibility, or both are the aim of chemical, biological, and physical procedures, separately or in combination, particularly for ruminants (Kulkarni et al., 2022). Supplemental feeding has been employed to enhance the diet's nutritional content by providing additional nitrogen, calories, and minerals. Additionally, we have utilized chemical and physical treatment procedures for the same purpose. The compounds included are sodium hydroxide (NaOH), calcium hydroxide ($Ca(OH)_2$), ammonium hydroxide (NH_4OH), calcium oxide (CaO), urea, ozone (O_3), and sulfur dioxide (SO_2). The available information indicates that NaOH treatment is currently cost-prohibitive. It is recommended to prioritize ammonification and consider using urea as a more viable option, particularly for developing nations (Elseed, 2005; Gabriel et al., 2018). Unlike the current efforts (Yoswathana et al., 2010) to produce bioethanol from straw, this does not involve converting cellulose to sugar before the rumen.

There were numerous attempts at physical and chemical treatments to boost digestion or enhance palatability and feed quality. But each of these therapies has drawbacks, and some are not good for the environment (Silverstein et al., 2007). Due to concerns and warnings regarding the use of chemicals and the limited effectiveness and unsuitability of physical methods for producing large quantities and higher-quality improved crop residues for animal feed, there has been a significant shift away from chemical and physical methods. Breeders now employ biological methods instead to produce superior crop residues (Bocquier and González-García, 2010; Soares et al., 2023). Investigators are currently very interested in the biological processing of crop residues to enhance the availability of cellulosic parts, thereby enhancing their digestion and nutritional value (Zhang et al., 2007; Yu et al., 2009). Feed residue additives employ microorganisms such as bacteria or fungi to decompose lignin, provide sugars that may be easily digested, and enhance the synthesis of microbial proteins (Asmare, 2020). Lignin's physical defense against enzymes hinders lignocellulose transformation. Basidiomycetes fungi can partially break down the lignin-carbohydrate complex, enhancing plant material utilization in the rumen by providing fermentable energy for microbes (Keller et al., 2003). The methods for treating crop residue are depicted in Figure 1.

Physical treatment

Chopping

The most popular physical treatment for crop residues that smallholder farmers employ is chopping. It is particularly significant for crop residues such as pearl millet, sorghum, and maize that have thick stems. Chopping roughages reduces its size and increases the surface area to mass ratio. This makes it more accessible to rumen bacteria. Nevertheless, an excessive amount of grinding can result in accelerated transit, causing a decrease in retention time and limiting the chances for effective digestion. The decrease in particles facilitates animal ingestion by making it easier to grab and chew and improving palatability (Assefa et al., 2022). Excessive meal ingestion leads to increased pressure and decreased retention time in the intestines. It diminishes the digestibility of paddy straw. The processes of chopping, grinding, and pelleting have advantageous effects on disintegrating the cellular components of rice straw (Aquino et al., 2020) and enhancing its palatability. However, exercising caution and avoiding excessive food consumption is important. Animals can better digest the food and conserve energy by chaffing fodder and straws into smaller pieces before feeding them (El Ghobashy et al., 2023).

Grinding

Grinding is the process of crushing and sieving residues into tiny sizes of 0.6 to 0.8 mm using grinding machines. The residue can then be made into pellets or mixed directly with animal-derived fuels. Assefa et al. (2022) state that animals consume more than 25% more crop residue when chopped and ground. Additionally, these methods have been shown to increase feed transit rate and feed effectiveness in general. To increase intake and quality, farmers combine chopped or sifted straws or stover alongside their haulms of legumes.

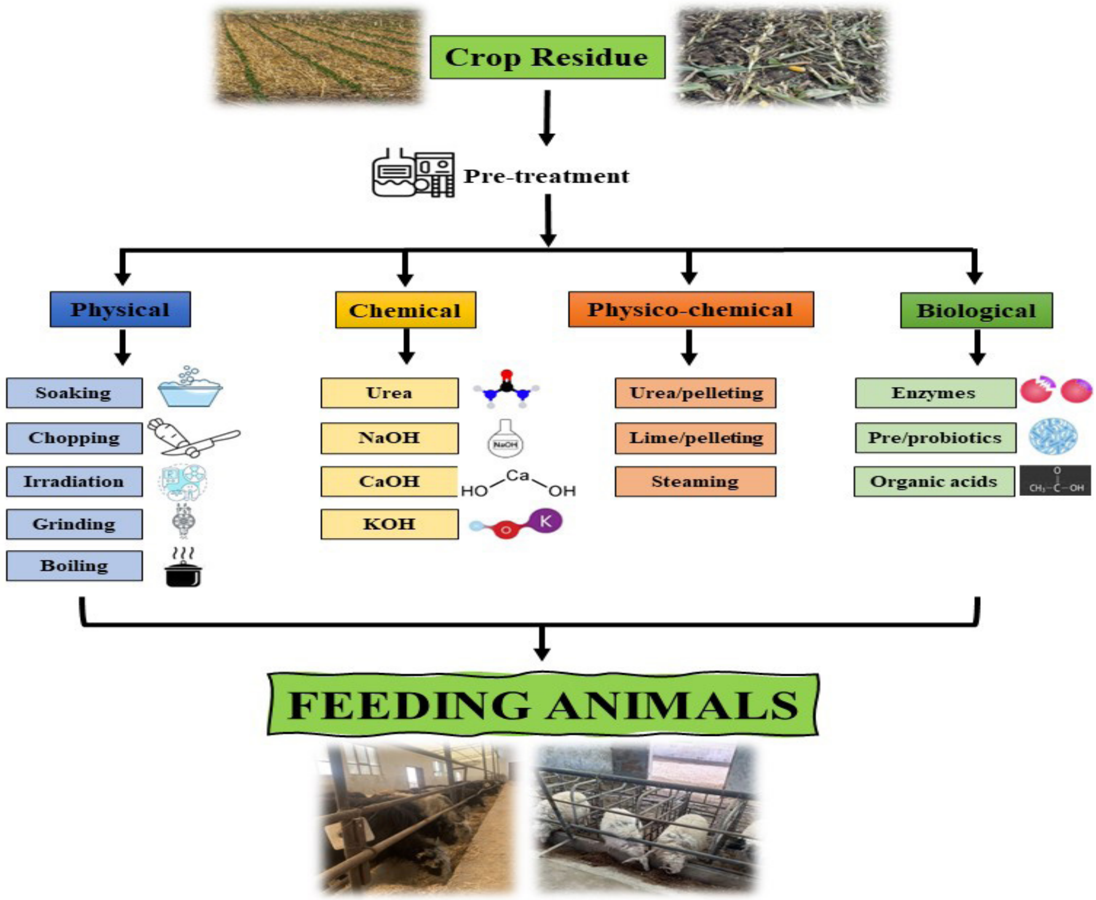

Figure 1. Techniques treating crop residue

According to Izadbakhsh et al. (2024), utilizing small fiber sources as pasture alternatives, they found that the size of the particles does not correlate with rumen pH or mastication time. The size of particles has a favorable effect on the way animals eat and digest NDF, resulting in longer chewing times, a higher rumen pH, and an increased acetate-to-propionate ratio (Zhang et al., 2024). Reducing the size of particles enhances the ability of microorganisms to access and efficiently ferment them, which may lead to a decrease in methane generation (Salami et al., 2019). The size of fibrous substrate particles impacts rumen microbial fermentation, but it does not alter the fermentation rate. The efficiency of digestion has a direct impact on animals' feeding habits. There is no substantial difference in methane generation between the feed and straw presentations. The degree of fermentation impacts methane production (Ortolani et al., 2020).

Chemical treatment

Urea treatment of crop residues

Various chemical treatments were established to enhance the cereal crop residues' feeding values. One such treatment is urea therapy, which has been used for a long time in many nations to improve the metabolism of grain crop residues and the amount of nitrogen CP (Sharma and Arora, 2015). Because urea treatment is so simple to utilize and obtain, it is appropriate in numerous developing countries contexts. The ease of use of the urea treatment processes is the primary advantage for smallholder farmers. Many places have easy access to urea, and using it has no detrimental impacts on the health of humans or animals (Mudzengi et al., 2014).

According to Suharyono et al. (2014), the facilities and inputs required for the processing of crop residues include chopped grains, straw and stover, or poor-quality hay, disposable plates for mixing, fertilizer-grade urea, molasses (optional), clean water, various types of silos, or other containers like bags made of plastic, material containers, and sealing materials like airtight plastic sheets, watering cans, and weighing balance devices.

According to Reshi et al. (2022), farmers in India frequently feed their livestock with fibrous feeds and agro-industrial by-products, which causes malnutrition. Livestock requires fortification and supplemental feeding to reach their full genetic potential. Urea molasses mineral blocks, also known as multi-nutrient blocks, are useful for strengthening lower-quality roughages. These blocks offer an inexpensive and abundant supply of nutrients for maximum growth, development, reproduction, and health. They contain mineral combinations, oil cakes, urea, molasses, and bran. They are the go-to option for feeding livestock in the summer and winter. Besides, adding urea molasses mineral blocks boosts dietary intake, digestion, weight gain, and blood indicators of growing Mithun calves. Therefore, adding to the urea-molasses multi-nutrient block (UMMB) might be advised to improve Mithun's growth and overall health, according to SungChinTial et al. (2023).

NaOH treatment of crop residues

Germany conducted extensive research on the chemical processing of straw in the 1980s (Flachowsky, 1987). Global reports on research and implementation exist (Owen et al., 2012; Adesogan et al., 2019). While some of these methods were promising, they are impractical due to EU environmental regulations and how NH_3 or NaOH were previously used. For instance, the straw was primarily cleaned with NaOH, which led to the by-product of tainted residual water. Gas emissions were caused by the frequent application of ammonia in a gaseous state. NaOH is prescribed as a regulator of acidity for dogs, cats, and decorative fish (Code 1j524) in the European Union Register of Feed Additives (EC, 2021). On the other hand, it can be described as a processing aid in this particular use (EC, 2003). Conversely, feed-grade urea can be used on ruminants (EC, 2012).

According to Martens et al. (2022), urea and NaOH treatments were significantly less effective at 400 g/kg^{-1} moisture content. Nevertheless, digestibility was not improved by doubling the NaOH concentration. They also stated that higher temperatures and longer storage times resulted in higher gas production. Wheat straw digestibility *in vitro* after urea or NaOH treatment was increased; however, storage at 25°C is necessary.

Physicochemical treatment

Climate change is causing a rise in drought, high temperatures, and heavy precipitation in areas with substantial agricultural output, like Central Europe and Central North America (Lorenz et al., 2019; Zhao et al., 2020). Due to crop and pasture shortages, this will significantly reduce the production of food and feed (Hänsel et al., 2019). The forage shortages Europe experienced in 2018–2020, combined with these forecasts, have prompted a renewed effort to find alternative forage sources. Because of their symbiotic relationship with rumen microbial populations, ruminants are adept at using high-fiber feeds. For this reason, by-products from food production, grassland, forests, and agricultural land can all be utilized with some degree of achievement (Koike and Kobayashi, 2009). This is another reason that considering continuing climate change, ruminants will be crucial to the success of global land use and agricultural processes in the future (Schader et al., 2015). Cereal straws are still widely available year-round despite the scarcity of forage.

An estimated 321 million tons of straw waste were produced globally in 2020 from the following crops: 60% of barley, 60% of oats, 86% of rye, 34% of wheat, and 94% of triticale (Gauder et al., 2011; FAO, 2022). However, because straws contain up to 17% of their dry matter (DM) in the form of lignin, they are not well absorbed by the body (Buranov et al., 2008; Adesogan et al., 2019). Lignin, a key cell wall component, provides rigidity, water and nutrient transport, and protection. Its polymer, composed of phenylpropane units, forms linkages to form structures with other polymers, such as cellulose and hemicellulose (Buranov et al., 2008).

Chemicals can be used besides physical and biological techniques to break the interpolymer bonds in straw cell walls, releasing carbohydrates (including hemicelluloses) that rumen microorganisms do easily ferment (Weimer, 2022). The paddy straw undergoes treatment with 1.5% NaOH for 18–20 hours, followed by rinsing with tap water. This treatment reduces proteolysis and speeds up delignification by breaking down phenol-cellulosic bonds (Harun and Geok, 2016). Urea treatment is a chemical method employed to enhance the protein content of paddy straw during fermentation. It involves dissolving urea in water, promoting rumen microbes' growth, and releasing ammonia. Consequently, the straw becomes softer and more easily digestible. The recommended ratio is 4 kg of urea per 100 kg of straw (Ma et al., 2020). Utilization of alkalis, such as NaOH, KOH, $Ca(OH)_2$, or urea, is primarily linked to improved digestibility (Adesogan et al., 2019) and might enhance the value of poor-quality feeds. Treatments with NaOH and urea have been extensively investigated and their effects are well-established (Adesogan et al., 2019).

According to Bachmann et al. (2022), cereal straws supplement the diet of ruminants by offering an extra source of fiber and possibly energy. Straw fiber can be fermented in the rumen more successfully when treated with NaOH or feed-grade urea on farms. This releases fermentable components of the cell walls. When straw has been treated with NaOH, the quantity used in a total mixed ration (TMR) cannot reduce feed intake or digestibility. Crude ash content rises after NaOH treatment, lowering energy density. When straw was exposed to NaOH, the fiber digestion increased by 10%, whereas urea treatment reduced metabolizable and digestible energy concentrations. Phytochemical metabolites may exacerbate metabolic energy losses from treated phenolics.

Biological methods

Roughages have been treated in various ways, but societal and ecological issues have limited their practical application. Biological treatment, like utilizing ligninolytic fungi and the enzymes they produce, may offer a workable and sustainable way to increase the nutritional content of roughages. However, for the best feeding quality, choosing the right white-rot species and ensuring the ideal incubation environment are essential. In tropical regions, integrating these procedures with pre-treatments may increase the productivity of animals and crop residues (Asmare, 2020). Biological substances like fungi are a viable treatment option to remove lignin and increase the dietary value of poor-quality forages (Sharma and Arora, 2015). Fungi are effective treatments that eliminate lignin and make low-quality forages easier to digest (Lankiewicz et al., 2023). Basidiomycetes fungus can break down lignin in the cell walls (Cardoso et al., 2022). White rot fungi can break down and convert plant cell components into simpler sugars. This process occurs when the fungi colonize a suitable substrate and convert easily digested carbohydrates (Latif et al., 2023). This is referred to as the fungus' main metabolism. The fungus completely consumes these sugars, and then secondary metabolism begins. This process uses extracellular enzymes such as laccase, manganese peroxidase, and peroxidase to break down structural polysaccharides and lignin from substrates (Silva et al., 2021).

The fungi known as basidiomycetes can break down the lignin found in cell walls (Khattab et al., 2013). Some of these include white rot fungi, which can break down and mineralize the different parts of plant cells as they convert effortlessly; more straightforward sugars are produced from digestible carbs (Kholif et al., 2014). Despite the poor quality of nutrition and the large production of agricultural residues, fungal primary metabolism breaks down lignin. It utilizes these sugars, encouraging secondary metabolism by decomposing outcomes and structural carbohydrates by extracellular enzymes (Khattab et al., 2013). Additionally, El-Bordeny et al. (2015) found that while rice straw that has been biologically handled marginally ($P \geq 0.05$) reduced growth performance, it did not produce adverse impacts on nutrient digestion, nitrogen balance, or physiological response when fed to ewe lambs. Furthermore, the use of biologically handled crop residues in feeding animals has been linked to positive responses in terms of body weight gain, balance of nitrogen, and use of nutrients (Omer et al., 2012; Shrivastava et al., 2012).

A wealth of information on research on the successful biological treatment of crop residues with white rot fungi was given (Asmare, 2020). The biological treatment could release cellulose from the lignocellulose structure, enhance nutrition value, increase nutrition and digestion, and boost animal output. According to earlier research, applying white rot treatment to various crop residues caused notable alterations in the amounts of lignin, ADF, and NDF, with values ranging from less than 10% to more than 70% (Adesogan et al., 2019; Asmare, 2020). Crop residue can produce microbial protein, as shown in Figure 2.

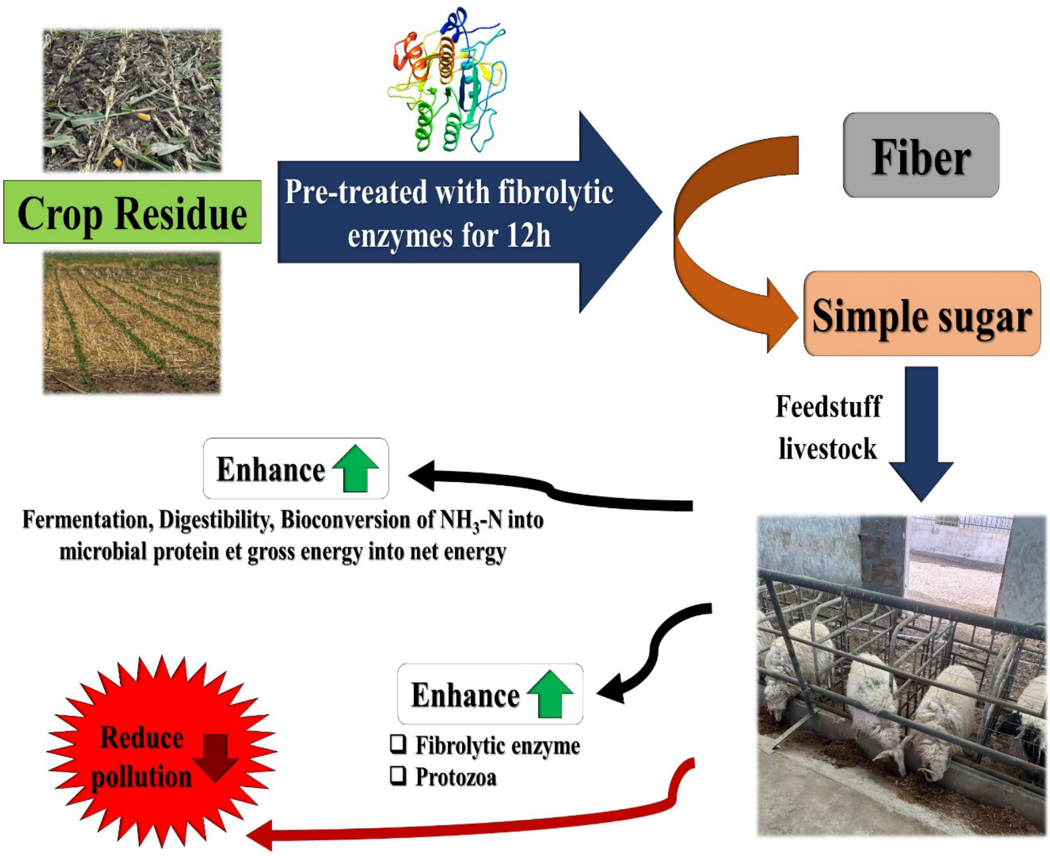

Figure 2. The various phases involved in utilizing crop residues until microbial protein is obtained

Table 2. Effects of feeding pretreated crop residues to ruminants

The treatment	Impact on crop residues	Impact on animals	References
Chopping	Chopping is common, particularly for thick-stem crop residues like maize, sorghum, and pearl millet.	Chopping roughages such as hay and crop residues reduces feed waste, prevents nutrition loss, and maximizes feed utilization. This increases animal productivity.	(Assefa et al., 2022)
Urea-molasses-treated rice straw	Urea-molasses-treated rice straw significantly enhanced the crude protein content of treated rice straw from 4.7% to 7.9% and the DM digestibility from 47% to 55%.	Urea-molasses-treated rice straw increased the amount of milking/day compared to pure rice straw.	(Aquino et al., 2016)
Urea molasses mineral blocks	A helpful instrument for reinforcing roughages of inferior quality.	With combinations of minerals, oil cakes, urea, molasses, and bran, these blocks offer an economical and nutrient-rich solution for livestock development, growth, pregnancy, and health.	(Reshi et al., 2022; SungChinTial et al., 2023)
Use of alkalis	Increase the value of inadequate feeds.	Urea treatment decreases metabolizable and digestible energy concentrations, NaOH treatment improves crude ash levels, reduces energy density, and raises fiber digestion in straw.	(Adesogan et al., 2019; Bachmann et al., 2022)
Fermented total-mixed rations composed of rice straw	Rice straw supplemented with 50% banana byproducts and 25% water lily significantly increased the digestibility of DM and CP, rising from 50.95% to 60.35% and 62.30–66.33 percent, respectively.	The ADG and milk production of dairy buffaloes were substantially boosted by the fermented total-mixed rations (FTMRs) made from rice straw, banana byproducts, or water hyacinth.	(Aquino et al., 2020)
Rice straw by inoculating with three different microbial combinations using moist, soaked, and pasteurized straws	Microbial treatment and physical pretreatments significantly reduce organic matter, crude fiber, neutral detergent fiber, and acid detergent fiber while increasing crude protein.	Rice straw inoculated with *Saccharomyces cerevisiae* and *Azotobacter chroococcum* increased crude protein while reducing organic matter, crude fiber, neutral detergent fiber, and acid detergent fiber.	(Zayed, 2018)
Rice straw was treated with fungi (*Phanerochaete chrysoporium*)	Higher CP, EE, and ash contents were obtained from the biological treatment of rice straw, whereas lower OM, CF, NFE, NDF, ADF, ADL, hemicellulose, and cellulose contents were observed.	Improved the body weight gain, cost-effectiveness, and nutritional digestibility of the growing calves' diet using a biologically treated straw.	(Abd El-Rahman et al., 2014)
Technologies and biomass processing strategies	Improve the value of poor feeds.	Using biomass processing approaches and crop residue may provide a valuable source of substances such as enzymes, antioxidants, biosurfactants, antibiotics, and bio-alcohols through successful lignocellulosic biorefinery.	(Verardi et al., 2023)
White rot fungi (*P. ostreatus*)	Raising the corn stover's energetic values, CP, volatile fatty acid levels, and microbial mass, *P. ostreatus* improved the food value of the crop.	The microbial mass, CP, energetic values, and volatile fatty acid levels of corn stover are increased by *P. ostreatus*, whereas *Pleurotus* species effectively repurpose agricultural waste for medicinal uses.	(Melanouri et al., 2022; Olagunju et al., 2023)
Enzyme treatment	Enzymes improve feed and roughness by increasing the content of crop residue for raw protein and ease of digestion of the lignin and hemicellulose.	Roughages and forages are improved by enzyme treatment. Digestion requires the breakdown of lignin, which is done by animals using enzymes.	(Salem et al., 2015; Abid et al., 2023; Tang and Tan, 2023)
Organic acids	Boost the worth of insufficient feeds.	They boost microbial protein synthesis, lower methane production, and improve ruminant nutrition.	(Seifdavati et al., 2021; Palangi et al., 2023)

Bacterial additions

Among the main direct-fed microbial (DFM) types are bacterial feeding additives. The DFM strains of bacteria can be categorized as other microorganism species, either generating or using lactic acid. Along with other unique bacterial species like *Megasphaera elsdenii* and *Prevotella bryantii*, common microorganisms employed by ruminants comprise *Bacillus*, *Enterococcus*, *Streptococcus*, *Bifidobacterium*, *Propionibacterium*, and *Lactobacillus* (Liu et al., 2015). Potentially, bacterial DFM improves feed efficiency, weight gain, and rumen conditions. Feeding Baladi goats with commercially available feed additive products containing ZADO® and ZAD® enzymatic compounds (multi-enzyme feed additives) improved the digestibility of nutrients, rumen fermentation parameters, milk structure, and fat content without changing blood chemistry, according to Khattab et al. (2011).

Additionally, Valdes et al. (2015), feeding concentrates and maize silage to Suffolk lambs and adding external enzymes and *Salix babylonica* extract increased the lambs' live weight, the synthesis of microbial proteins, and the digestibility of DM and OM. Millions of agricultural by-products are produced with low nutritional values, according to Abdel-Aziz et al. (2015). As a result, several techniques were created to increase their use in ruminant nutrition. Common methods include biological therapies, direct-fed microbial and exogenous enzymes, and lowering the amount of crude fiber content.

According to Verardi et al. (2023), crop residue may be a useful source of compounds with high added value, such as enzymes, antioxidants, biosurfactants, antibiotics, and bio-alcohols, if they are successfully processed via lignocellulosic biorefinery using a variety of technologies and biomass processing strategies. Additionally, Olagunju et al. (2023) demonstrated that *P. ostreatus* increased the energetic values, CP, corn stover's overall volatile fatty acid levels, and microbial mass, thereby improving its nutritional value. Also, of the edible white rot fungi, the *Pleurotus* species has demonstrated superior efficiency when reusing waste from agriculture and producing bioactive with therapeutic qualities (Nurfitri et al., 2021; Melanouri et al., 2022).

A DFM bacterial supplement is given to ruminants to enhance feed efficiency and weight gain. Reduced fiber content and biological therapies may be utilized to use agricultural by-products for ruminant nutrition. *P. ostreatus* can enhance nutritional value, and crop residue may constitute a valuable source of medicinal compounds.

External enzymes

As stated by Abdel-Aziz et al. (2015), lignocelluloses must undergo biological treatments for their degradation into cellulose, hemicellulose, and lignin to raise the CP content. An enzyme treatment guarantees the enhancement of roughages and forages of lower quality. To improve the digestibility of lignocellulosic materials, attempts have been made to break down lignin using microbial and enzymatic methods. Since they strip the hay of important nutrients that an animal can process, organisms that break down cellulose and hemicelluloses are useless (Kholif, 2013). Enzymes produced by the animal or by bacteria in the gastrointestinal tract are used by animals to aid in the digestion of feed. As a result, adding enzymes to animal feed to improve digestion efficiency can be considered a continuation of the animal's natural digestive procedure (Alsersy et al., 2015; Salem et al., 2015). Crop residue digestion is increased using enzymes by attacking their lignocellulose structure, as Gado et al. (2013) demonstrated.

Kumar et al. (2023 a) reported that exogenous fibrinolytic enzyme supplements (cellulase 8000 and xylanase 16,000 IU/kg diet DM) improved the weaned Black Bengal children's growth performance and nutrient intake. Enzymes enhance animal performance in milk production, live weight gain, feed efficacy, and immunity. It has a positive relationship with palatable qualities, feed intake, rumen microbial N synthesis, and digestibility (Salem et al., 2015). According to Khattab et al. (2011), enzymatic treatments enhanced milk yield, composition, and nutrient digestibility ($P<0.05$) in Baladi goat diets.

Additionally, Seresinhe et al. (2023) reported that goat diets supplemented with exogenous cellulase and xylanase exhibited advantages due to elevated levels of ADG, DM intake, and NDF digestibility. Also, Tang et al. (2023) indicated that the exogenous cellulase enhanced total VFA production, fiber digestibility from neutral detergents, and forage digestibility. According to Abid et al. (2023), pre-treatment of sesame seed coat with liquid exogenous fibrinolytic enzymes enhanced its dietary value and rumen fermentation traits. This suggests that the eco-friendly bioprocess could transform sesame seed coats into high-energy feeds. Compared to hay and rapeseed meal, Uwineza et al. (2023) discovered that fungal biomass, a form of hay clover silage, has a higher ruminal digestibility. With readily rumen degradable carbohydrates and crude protein, its greater digestion, gas production rate, and volatile fatty acid generation suggest that it has potential as a supplement to ruminant diets. Enzyme treatment enhances CP, aiding feed and crop residue digestion by breaking down lignin in animals and bacteria.

Organic acids

Organic acids, natural by-products of microbial fermentation and plants, have been used as food preservatives for thousands of years, making them a natural choice in the industry and considered acceptable to optimize animal production (Pavlović et al., 2016). Organic acids are substitutes for antibiotics because of their demonstrated ability to eradicate harmful microorganisms from the gastrointestinal tract, increase farm animal yields, and maintain animal health (Gul et al., 2017). According to Palangi and Macit (2021), organic acids have an advantageous impact on ruminant nutrition and can potentially decrease ruminal methane production and avoid feed-waste energy. Palangi et al. (2023) found that adding organic acids to ruminal fermentation can increase lactation values, metabolizable energy, and the digestibility of organic matter without hurting the process. Mixing organic acids can improve microbial protein synthesis by producing more gas. Additional *in vivo* research is required to validate these advantages.

According to Pourbayramian et al. (2021), ideal conditions to produce VFAs and CP content have been achieved utilizing a straightforward fermentation method established to extract value from rumen fluid and potato waste. With a 17.95% CP content and 92 mM/L total VFAs, the process is appropriate for use as an additive in animal feed. Additionally, according to Seifdavati et al. (2021), probiotic-infused pumpkin by-product silage has a higher chance of success as animal feed than organic acids. According to de Oliveira et al. (2017), nutritional supplements are added to try to improve the nutrition profile of silage, prevent preservation harm, reduce the fermentation process loss, and extend the silage bunk's shelf life. Furthermore, according to Ren et al. (2018), acetic acid is the only compound shown to be responsible for enhancing aerobic stability. Because acetic acid inhibits spoilage organisms and effectively lowers the pH of silage, equilibrium improves substantially with acetic acid concentration.

Also, Hou et al. (2023) observed an increase in alcohols and acids and a decrease in main terpenes in their study of the biotransformation of volatile organic compounds in marigold mixed silage. According to Sun et al. (2023), probiotics, organic acids, or plant secondary metabolites can be added as dietary supplements to help reduce CH_4 emissions. Although organic acids present a promising alternative to antibiotics by improving farm animal yields, health, nutrition, and protein synthesis, more *in vivo* research is required. Table 2 presents the results of using different treatments on crop residue and how those treatments affected the ruminants.

Factors affecting the quality and quantity of crop residue

A wide variety of biophysical and economic status limitations are related to the difficulties of enhancing feed quantity and quality. The primary and prevalent concerns in numerous countries pertain to the exhaustion of the feed production resources foundation, which can be caused by excessive grazing and inadequate land management. The inherent substandard quality of prevalent feed resources such as crop residues and natural pasture can also contribute to this issue (Shiferaw, 2011). In low- and middle-income nations, natural grassland and poor-quality crop residues are the main sources of feed; in Ethiopia, for example, they comprise 95% of the feed biomass (Ethiopia, 2018).

The crop's genetic profile, growing circumstances, and procedures for harvesting, shredding, and storing all impact residue quality and yield, according to Kumar et al. (2023 b). Additionally, according to Jørgensen et al. (2022), increasing the digestibility of the portion of the cell walls and the amount of soluble nutrients in the residue (cell content) will be essential for enhancing its quality. As stated by Young et al. (2021), the quantity and quality of crop residues are largely determined by factors other than genetics. Therefore, it is critical to recognize and comprehend the ideal crop management variables that can enhance crop residue quality and yield.

According to Kebede et al. (2016), legume usage in mixed crop-livestock agriculture boosts agricultural productivity by fixing nitrogen, producing high-quality feed, and enhancing soil fertility. Different integration strategies are used depending on the soil type, forage crops, amount of rainfall, and social and economic aspects. The factors influencing the quantity and quality of crop residue are depicted in Figure 3.

Reddy et al. (2003) found optimal seed rate and growth conditions for optimal fodder yields and enhanced crop residue quality due to severe drought despite impacting yields. Grzyb et al. (2020) reported that local organic plant-based materials are becoming increasingly accepted globally to restore degraded soils' fertility and production potential. The environment impacts this process, including temperature, amount of water, chemical composition, and the presence of microbiomes.

Treating the problem of feed deficiency in dry areas and its impact on production

Production, efficiency, health, welfare, income, household safety, utilization of land, water pollution, and livestock's greenhouse gas emissions are all greatly impacted by animal feed, which directly or indirectly affects the entire livestock industry (Godde et al., 2021). According to Peñuelas et al. (2017), climate change could reduce the fertilizing impacts of eCO_2, especially in the face of severe droughts, but it may still influence livestock feed. Additionally, plant primary productivity is stimulated by eCO_2 levels (Ainsworth et al., 2020), which raises some species' potential yields. Greater growth stimulation is experienced by plants with a C_3 photosynthetic pathway, which includes wheat, rice, soybeans, and temperate grasses, than by C_4 plants, like maize, sorghum, sugarcane, and tropical grasses. However, the effects of CO_2 fertilization can also lower the quality of animal feed (Augustine et al., 2018; Smith and Myers, 2018).

In grazing systems, increased feed supply volatility poses a significant challenge to managing herd size and grazing intensity (Sloat et al., 2018; Godde et al., 2020). According to Makkar et al. (2018), crop residue is essential for feeding animals, especially in dry areas; however, its high fiber content and poor quality cause malnutrition, lower productivity, and heightened susceptibility to disease. Seasonal feed shortages, inefficient use, inadequate conservation techniques, and ignorance of proper feed and feeding procedures all have an impact on livestock productivity (Gelayenew et al., 2016). Farmers often neglect hay conservation practices during cropping season despite the potential benefits of labor-saving technologies. This could increase fodder conservation and improve livestock production, as seen with cereal straw stacking (Ahamed et al., 2023).

Improved farming techniques, biodiversity preservation, and pasture rehabilitation are a few strategies that can improve feed resources. Inadequate roughage can also benefit from chemical and physical treatments that increase nutrient availability. Comprehensive data on profitable livestock farming in Ethiopia can be found in Makkar et al. (2018). Ethiopia's arid and semi-arid zones rely on naturally available forages for dry seasons, supplemented with crop residues and conserved hay. In contrast, rainy seasons offer high pasture availability and satisfactory livestock productivity (Keba et al., 2013). Therefore, farmers should be aware of the importance of crop residue and trained on roads that increase the biological value of these residues to be well used in animal feeding. According to Bayissa et al. (2022), in both agroecological zones, native fodder trees and shrubs have an increased protein content compared to naturally occurring grass species and crop residues. These trees and shrubs are good additional protein sources, particularly in arid seasons. Nevertheless, the low CP content of crop residues leads to low animal productivity. Increasing forage output and treating it with urea could improve livestock productivity and promote sustainable development. According to Mengistu et al. (2017), one of the biggest obstacles to farming in developing nations is the lack and erratic quality of year-round feed supplies. In developing nations, browse fodders are helpful sources of inexpensive feed for ruminant animals, particularly in the dry seasons when legumes and herbaceous pasture grasses are in short supply (Olafadehan and Okunade, 2018). They are possible sources of protein and energy because of their foliage's capacity to stay green and retain its protein content (Olafadehan, 2013).

Conclusions

In Asian, African, and Arabian countries, the production of agricultural residues – which can boost crop and animal productivity – is primarily burned, creating health hazards and air pollution. Nutritional supplements aim to raise animal protein, lower expenses, and increase feed efficiency. However, the antibiotic prohibition has prompted people to look for substitutes, such as biologically treated feed and natural feed additives. Technological developments are necessary for the efficient management of crop residue. This study will remain a major challenge for both those interested in feeding ruminants to achieve the maximum benefit from crop residue due to climatic changes that affect the productivity of fodder crops as well as those interested in the environment through the optimal exploitation of the remains of crops and the limit of depleting this energy in damage to the environment. Therefore, this topic needs many studies, especially on maximizing the role of biological transactions to benefit crop residues.

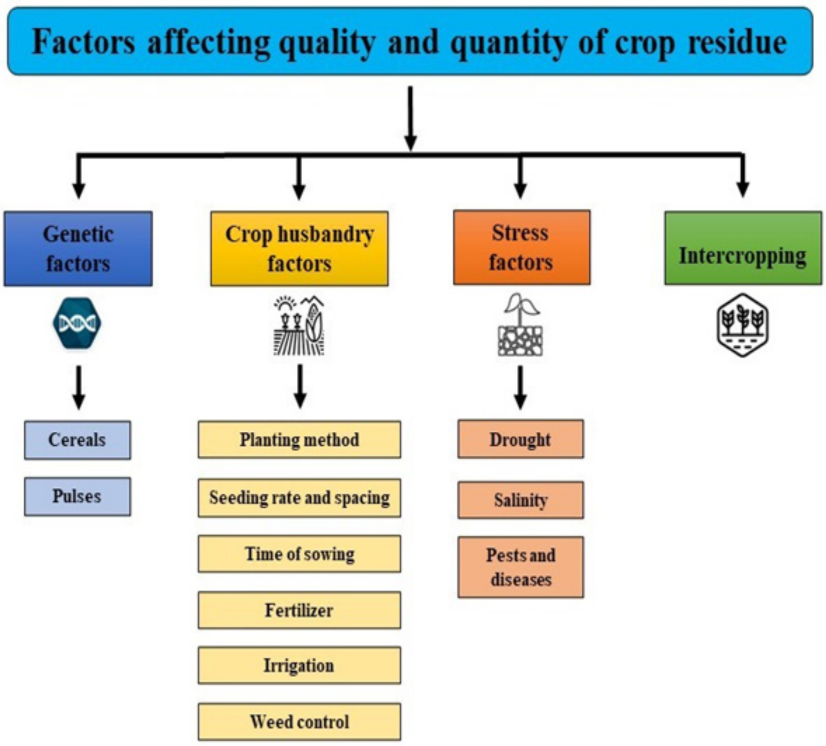

Figure 3. The variables impacting the quantity and quality of crop residu

Funding

Qinghai Provincial Natural Science Fund for Distinguished Young Scholars (2024-ZJ-905), National Key Research and Development Program of China (grant 2021YFD1300302, 2022YFD1302103), Qinghai Key Laboratory of Nutrition and Feed Science (Evaluation Award Project: 2024-1-8) and the National Natural Science Foundation of China (32061143034).

Conflicts of interest

The authors of this manuscript affirm that they have no disputes that could improperly influence it.

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Received: 11 V 2024
Accepted: 17 VII 2024