

Applications of sheep's wool in the fertilization of agricultural crops: A strategy for its valorization

Aplicaciones de la lana de oveja en la fertilización de cultivos agrícolas:
Una estrategia para su valoración

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ABSTRACT

Sheep farming in Mexico, primarily focused on meat production, has lead to an underutilization of sheep wool. However, this material has acquired very low economic value in recent years, making it prone to improper disposal. This review highlights the potential of wool valorization in crop fertilization by exploiting its physical, chemical and biological properties through its transformation into fertilizers, soil amendments, organic composts, and plant biostimulants. Reintegration of this by-product can promotes the development of a circular economy within the sheep farming sector.

KEYWORDS

Organic composts, soil amendments, organic fertilizers, plant biostimulants

RESUMEN

La ganadería ovina en México, enfocada principalmente en la producción de carne, ha llevado a una subutilización de la lana. Sin embargo, este material ha adquirido un valor económico muy bajo en los últimos años, lo que lo hace propenso a una disposición inadecuada. Esta revisión destaca el potencial de la valorización de la lana en cultivos, aprovechando sus propiedades físicas, químicas y biológicas mediante su transformación en fertilizantes, mejoradores del suelo, compostas orgánicas y bioestimulantes vegetales. La reintegración de este subproducto puede promover el desarrollo de una economía circular dentro del sector ovino.

PALABRAS CLAVE

Compostas orgánicas, enmiendas del suelo, fertilizantes orgánicos y bioestimulantes de plantas

INTRODUCTION

Sheep farming in Mexico is an activity of both economic and cultural importance (Calderón-Cabrera et al., 2022). The breeding of sheep for meat production—particularly for the preparation of the traditional dish *barbacoa*— results in the underproduction of sheep's wool (Servicio de Información Agroalimentaria and Pesquera [SIAP], 2024a). The main use of this fibrous material is in the manufacture of yarns (Secretaría de Agricultura y Desarrollo Rural, 2017).

However, not all wool produced meets the quality standards required for use as a textile fiber. Additionally, the market for this fiber has declined considerably in recent years due to strong competition from other natural and/or synthetic textile fibers (Navone et al., 2020).

The growing sheep population has led to an increase in wool production, in 2022, global production grew by 1.5% worldwide (International Wool Textile Organization, 2023). Consequently, with increasing production and a shrinking market, the economic value of wool has decreased in recent years, making it a material prone to improper disposal.

Integrating this fiber into municipal waste streams possess an environmental risk, as wool decomposes rapidly in anaerobic landfills, leading to methane emissions (Russell, 2009). Although wool is not flammable, its incineration releases carbon dioxide and produces an unpleasant odor.

Due to its high protein content, the valorization of wool has shown significant potential in various biotechnological applications, including biomedicine (Su et al., 2020), tissue engineering (Ranjit et al., 2022), development of bioelectric platforms (Zhu et al., 2023), and the food industry (Giteru et al., 2023), as well as in the production of livestock feed and organic fertilizers (Chen et al., 2022). Using this material to support plant nutrition processes represents a smart strategy within a circular economy approach, aimed at valorizing a readily available material. In this review, we address the applications of sheep's wool in crop fertilization, grouped into two main categories: 1) as a substrate for the generation of composts and/or soil amendments, and 2) as value-added products with through its transformation into fertilizers and plant biostimulants.

Economic value and wool production in Mexico

In 2024, SIAP reported a national sheep population of 8,805,206 head. This number represents a 1.1% increase over the past five years. Consequently, 3,785.741 t of sheep wool were produced with an average nationwide price of 0.1255 US\$/kg of wool. It was observed that the state of Hidalgo was the main producer, with a production of 1,575,789 t, representing 41.6% of the total production (Figure 1).

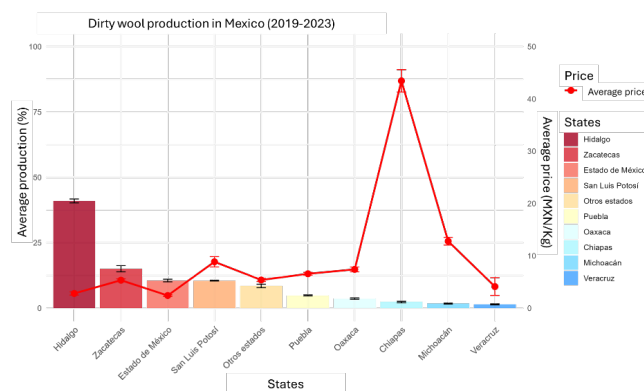


Figure 1. Contribution to national wool production (%), and price (US\$/Kg) obtained by state in Mexico (SIAP, 2024a).

The economic value of this material comes mainly from its use as a textile fiber. For example, in the state of Chiapas, the value of wool (2.119 US\$/kg) comes from its use in the manufacture of traditional clothing by the “Tzotzil” indigenous community in the Los Altos region of Chiapas (Perezgrovas, 2018). In Mexico, sheep farming focuses primarily on meat production (SIAP, 2024b); therefore, wool is not a trait of interest in sheep breeding. In addition, the low control of cross-breeding between existing breeds in the country has favored a high genetic diversity in the herds and an undefined multiracial composition (Ulloa-Arvizu et al., 2009). This generates heterogeneous wool phenotypes, limiting its use in textiles.

The demand for sheep wool in the textile industry is highly related to the presence of quality characteristics. For example, fiber diameter is the feature that determines its value and potential uses; Merino wool of 19 μm or less is considered high-quality (International Wool Textile Organization, 2023). In Mexico, there is no information on the amount of wool marketed; however, in 2024, there was a reported demand for products such as wool and fine or ordinary hair, horsehair yarns, and fabrics, which were

purchased mainly from China, representing an expense of US\$21.1M (Secretaría de Economía, 2024). Therefore, as there is a higher supply of high-quality wool from other countries with wool-production-oriented sheep breeding systems, wool fiber produced in Mexico that does not meet quality standards is vulnerable to disposal in municipal waste and/or incineration, generating a risk of environmental contamination (Russell, 2009).

Sheep wool, a natural biopolymer

Wool fiber is a material that exhibits multiple levels of structural organization due to biochemical interactions between its components. Generally, 95-98% weight/weight (w/w) of wool is protein, with keratins (fibrous proteins with high cysteine content) being the most abundant group (up to 82% w/w). The remainder is composed of proteins rich in glycine and tyrosine (~17%), and a very small fraction (~1%) of non-protein compounds, such as serous lipids and polysaccharides (Giteru et al., 2023; Lewis y Rippon, 2013; Ranjit et al., 2022).

The high keratin content provides wool with high stability and specific mechanical properties due to disulfide bonds (S-S) formed by cysteine amino acids (Su et al., 2020). This property allows the formation of defined polymer arrays of keratin-rich materials, ranging from the nanoscale to the centimeter scale (Mattiello et al., 2023). The smallest unit at the nanoscale of wool fiber is a group of keratins called α -keratins, which adopt an α -helix secondary structure (Lazarus et al., 2021). Depending on sulfur content, these structures are classified as low sulfur (<3% w/w) or high sulfur >3% w/w (Ranjit et al., 2022). In

wool fiber, low-sulfur keratins assemble into intermediate filaments (IFs), which are then embedded in an interfibrillar matrix containing keratin-associated proteins (KAPs) (Gong et al., 2016).

IFs are formed by the union of two keratin molecules in α -helical conformation via disulfide bonds, which cluster tail-to-tail forming protofilaments (2 nm in diameter) (Figure 2). Two protofilaments associate laterally to form a protofibril, and four protofibrils form an intermediate filament (Wang et al., 2016). IFs, or microfibrils, are embedded in an amorphous matrix of high-sulfur proteins, that is, proteins rich in cysteine, proline, serine, and threonine, as well as proteins rich in serine, glycine, and tyrosine (Huson, 2018). Acting as the basic structure for macrofibrils (~400-500 nm in diameter), this structure enables each keratinous system to diverge to fulfill its specific function (Lazarus et al., 2021). Sheep wool has a high IF content (up to 95% of keratins), making it a natural reservoir of IFs, which could have numerous biotechnological applications (Cardamone et al., 2009).

Applications of wool in the fertilization crops

Sheep wool is a biological material susceptible to slow biodegradation (Shavandi et al., 2017). For agricultural crops, keratin hydrolyzed from sheep wool can be used as a natural and sustainable fertilizer because it contains essential amino acids and micronutrients that promote plant growth and improve soil health. The generation of composts, soil amendments, organic fertilizers, and plant biostimulants allows the reintegration of this waste, taking advantage of its physical and chemical properties to directly and/or

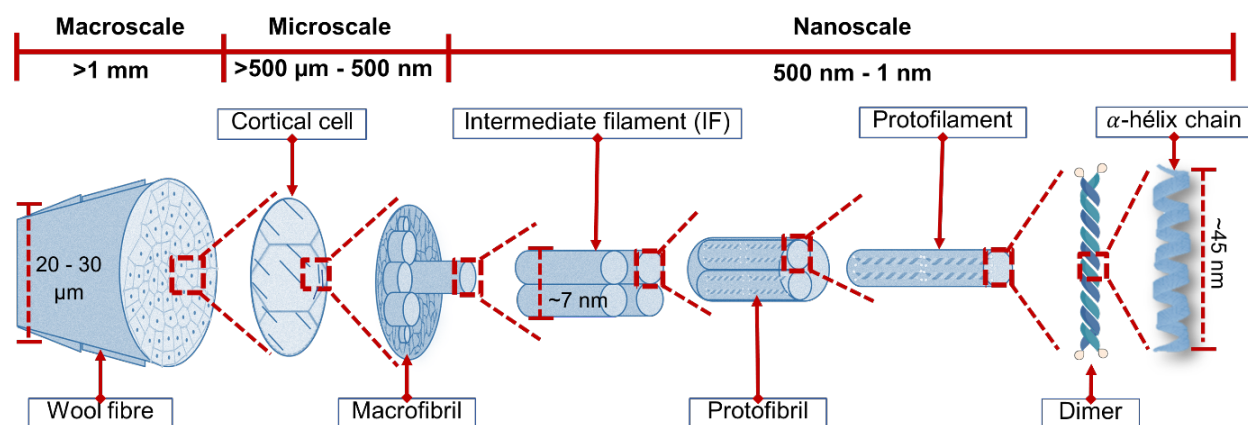


Figure 2. Structural representation of sheep wool fiber from centimeter to nanometer scale [based on Lazarus et al. (2021), Wang et al. (2016)].

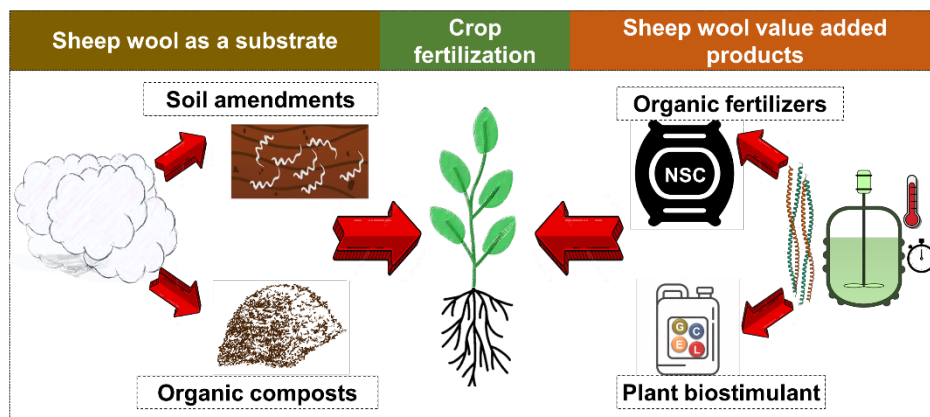


Figure 3. Valorization of sheep wool in the fertilization of agricultural crops.

indirectly enhance agricultural production (Chen et al., 2022; Perța-Crișan et al., 2021) (Figure 3).

Wool as an organic substrate

The use of sheep wool as a substrate has high potential to improve the properties of cultivated soils, positively affecting crop yields (Abdallah et al., 2019; Garbowski et al., 2023). Wool fiber is nitrogen-rich material and decomposes easily in soil (Tiwari et al., 1989). Composting is an aerobic solid-state fermentation process mediated by microorganisms, which transforms into more stable compounds (compost) that contribute to the improvement of the soil's physical, chemical, and microbiological properties (Sánchez et al., 2017). Composting wool together with other biomass, such as plant residues and livestock manure, had produced acceptable levels of organic matter (OM), between 25.2-31.3% dry weight, suitable for horticultural and agricultural use (Hustvedt et al., 2016). This strategy represents an ecological and low-cost practice for managing this waste (Petek y Marinšek, 2021). However, due to the material's nature, wool presents limitations in handling and nitrogen release, which is often lower than desired (1-5%) (Hustvedt et al., 2016). Therefore, this process can be enhanced by supplementation with nutrients and/or microorganisms (Petek y Marinšek, 2021). Bioaugmentation with microorganisms equipped to utilize wool as a source of carbon and nitrogen can favor the release of compounds that benefit plant nutrition (Delgado-González, 2022) (Table 1).

In recent years, the application of food-production waste as soil amendments has been investigated as an

ecological strategy to recovery nutrients and enable their reuse (Palansooriya et al., 2023). The addition of wool waste to sandy loam soil altered physical properties such as bulk density (from 11.98% to 9.85%), porosity (from 16.45% to 13.57%), and water retention (from 18.1% to 6.5%) (Abdallah et al., 2019). The use of wool did not negatively affect soil microbial communities, allowing native arbuscular mycorrhizal fungi to remain active, which promoted 33% greater growth of olive plants compared to the control (without wool) (Palla et al., 2022) (Table 1).

Value-added wool fertilizer products

Recent advances in the management of keratin residues for fertilizer production represent strategies that promote ecological development (Korniłowicz-Kowalska y Bohacz, 2011). Sheep wool is highly resistant to environmental factors, insoluble in water, and, resistant to enzymatic lysis by proteases in weakly acidic or alkaline solutions (Shavandi et al., 2017). However, recent methodologies for the extraction and/or solubilization of keratin from sheep wool through chemical, physical, and biological processes have enabled multiple applications of this material (Giteru et al., 2023) (Figure 4).

Table 1. Sheep wool applications as substrate for compost generation and soil amendments.

Direct application of sheep wool	Beneficial effect	Source
Compost piles were prepared: white sheep's wool + horse manure (+straw), white sheep's wool + manure (+straw), white sheep wool + horse manure (+straw) and white sheep's wool + manure (+straw).	The most balanced C/N ratio was obtained in the compost made from Mallorcan sheep wool (with both types of manure) and from Mallorcan red sheep wool combined with chicken manure.	Lechuga (2022)
A mixture of 25% waste wool, 50% vegetable waste, and 25% horse manure was composted for 3 months at an approximate temperature of 66.8° C.	It had a pH between 7.2 and 7.5, and the analysis showed acceptable values of organic matter (OM) and nitrogen.	Hustvedt et al. (2016)
Sheep wool was composted and inoculated with 10% (w/w) fresh cattle manure and 5% (w/w) phosphate, maintaining a constant humidity of 90% for 3 months.	The compost contained 20.6% organic carbon, 10.0% total nitrogen, and 2.06% phosphate.	Tiwari et al. (1989)
Sheep wool pellets were mixed with fir sawdust in sawdust:wool ratios of 2:1 and 1:1 (v/v) to increase soil organic carbon.	The results obtained from the pellet analysis showed high contents of total nitrogen (N) and total organic carbon (TOC), as well as an interesting water retention dynamic.	Dal Prà et al. (2024)
Wool residues from industrial processes (washing and carbonizing) were applied at different residue/substrate ratios of 0, 0.5, 1 and 2% w/w.	No negative impact on soil bacterial communities or AMF activity was observed, and the growth of olive plants was positively affected.	Palla et al. (2022)
Two wool residues (washed and carbonized) were used at different residue/sandy loam-soil ratios of 0, 0.5, 1, and 2% (w/w).	The wool/soil ratio of 2% (w/w) reduced the bulk density of the soil and increased both the total porosity and the available water capacity.	Abdallah et al. (2019a)
Sheep wool residues (SWRs), both charred (BW) and non-charred (WW), were applied to ornamental sunflower in soil mixtures with wool concentrations of 0, 0.5, 1 and 2% (w/w), and to a corn mixture at 1% (w/w), along with the supplementary nitrogen fertilization.	All SWRs-soil mixtures, with the exception of white wool residue at 2%, showed benefits for plant growth and biomass production. In maize, the BW at 1% resulted in optimal plant physiological status and production compared to the control, even without N fertilization.	Abdallah et al. (2019b)
Uncomposted sheep's wool was added at concentrations of 0.67, 1.33, and 2% (w/w) wool/potted substrate.	The concentrations of ammonium and nitrates increased, a higher nitrogen content was also observed in plant tissues, and the amount of microbial biomass was enhanced.	Zheljazkov et al. (2008)
A layer of wool was spread at a rate of 10 g for each of substrate, with a thickness of 5 cm.	It was reported that the addition of wool increased yields by up to 33% higher, especially in tomato and pepper.	Górecki y Górecki (2010)

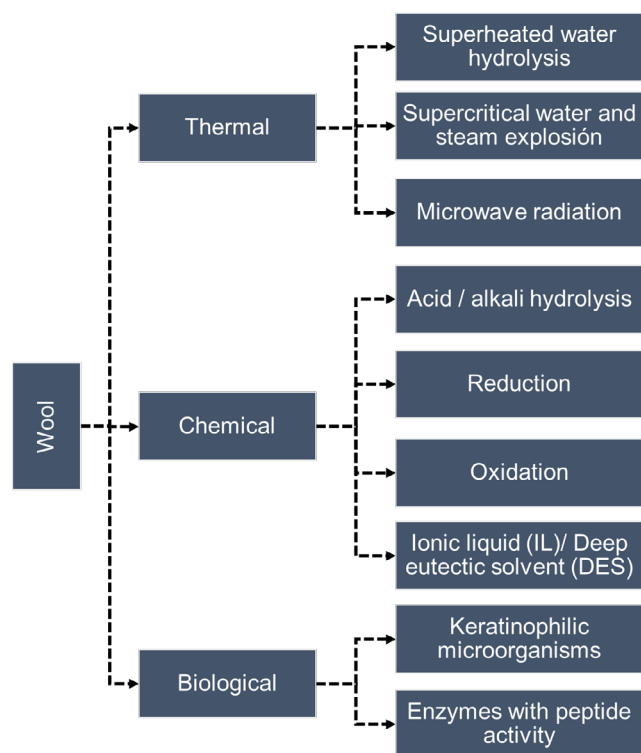


Figure 4. Main methods for solubilization and/or extraction of keratin from sheep's wool [based on Giteru et al. (2023)].

These hydrolysis processes can be either specific (using enzymes) and non-specific (chemical and physical methods) cleavages of the intermolecular or intramolecular bonds in keratin molecules, causing solubilization of the material (Perța-Crișan et al., 2021). Thermal and chemical solubilization methods release nutritional compounds that have been shown to promote plant growth in various crops (Berechet et al., 2020; Bhavsar et al., 2016; Holkar et al., 2016). These hydrolysates have high potential as organic fertilizers. According to the World Fertilizer Use Manual of the Food and Agriculture Organization of the United Nations & International Fertilizer Industry Association (2002), a fertilizer must provide nutrients needed by crops and contain at least 5% of one or more of the three primary nutrients. Wool consists of elements such as carbon (50%), nitrogen (16-17%) and sulphur (3-4%) (Zoccola et al., 2015), which explains the high interest in generating nitrogen fertilizers (Table 2).

Although chemical and thermal processes can be beneficial, they may also generate non-nutritive compounds at high temperatures and deplete nutrients due to chemical reactions, as reported in feather solubilization (Bhari et al., 2021). Recent microbial and

enzymatic hydrolysis methods allows solubilization of wool while releasing bioactive molecules that act as precursors of plant metabolism, promoting plant biostimulation (Calin et al., 2019; Constantin et al., 2022; Gaidau et al., 2021) (Table 2).

According to the European Parliament and of the Council (2019), a plant biostimulant is a product that, regardless of the nutrient content, promotes one or more of the following: 1) nutrient use efficiency, 2) tolerance to abiotic stress, 3) quality characteristics and 4) availability of immobilized nutrients in soil and /or the rhizosphere. Protein hydrolysates (PHs) of animal or plant origin are a group of plant biostimulants (Sani & Yong, 2022), and may contain polypeptides, oligopeptides, and amino acids (Schaafsma, 2009) (Table 2).

Gaidau et al. (2021) developed an alkaline/enzymatic hydrolysis method for sheep wool that generated products with low-molecular-weight protein fractions and amino acids rich in organic nitrogen, which promoted plant growth and exhibited antifungal capacity against *Fusarium* spp. Microbial hydrolysis with fungal isolates not only solubilized wool but also released bioactive compounds from the microorganisms, enhancing crop performance (Calin et al., 2019; Constantin et al., 2022). The use of PHs for plant biostimulation is a sustainable tool that improves the resilience and environmental sustainability of food production systems (Malécange et al., 2023) (Table 2).

DISCUSSION

The reintegration of wool as a substrate for composts and soil amendments is an ecological and inexpensive method (Petek y Marinšek, 2021). However, handling large quantities can lead to material compaction, reducing the contact area between microorganisms and the substrate, which decreases microbial activity and nutrient release (Hustvedt et al., 2016). Wool composts have low nutritional value, so strategies to enhance their contribution include supplementation with nutrients and inoculation of microorganisms that improve plant nutrition (Sánchez et al., 2017). Although compost formulations can increase nutritional value, some effects, such as the use of keratin-rich amendments to suppress soil borne plant diseases by altering microbial communities, remain underexplored (Andreo-Jimenez et al., 2021).

Table 2. Solubilization of sheep wool and its applications in agricultural crops.

Solubilization Method	Effect on crops	Source
Alkaline hydrolysis was performed with 8 % (w/w) KOH at 85° C under constant agitation for 3 h.	An increase in length of treated wheat plants ranging from 10.7 to 18.3 % was observed.	Berechet et al. (2020)
Superheated water hydrolysis: the optimal conditions were identified, resulting in a hydrolysis yield of up to 98.94 % at 187.5 °C for 367.5 min.	Phytotoxicity was evaluated using a germination test of <i>Lepidium sativum</i> L. seeds, which showed a germination rate close to 100 %. The hydrolysate had significant effects on fresh and dry leaf biomass and leaf area of maize at doses of 1.5 mL applied at transplanting.	Bhavsar et al. (2016), Metomo et al. (2024)
Alkaline hydrolysis with KOH:NaOH in a 14:1 ratio, assisted by acoustic cavitation, was compared with a conventional thermal hydrolysis method in an autoclave at 120°C and 5 bar for 15 min.	The treated wheat plants showed increased growth with the conventional method; however, acoustic cavitation represents a more environmentally friendly strategy.	Holkar et al. (2016)
Two-phase hydrolysis was performed: (1) alkaline hydrolysis at 80°C, 2.5 % (w/v) NaOH for 4 h under agitation and a 1:3 solid-liquid ratio, and (2) enzymatic hydrolysis.	It promoted plant growth in corn by 8.4-19%, and good resistance was observed against <i>Fusarium</i> spp.	Gaidau et al. (2019, 2021)
Hydrolysates of wool proteins and chicken feathers were further hydrolyzed using isolated strains of <i>Trichoderma</i> spp.	The isolates were able to utilize keratin hydrolysates as the sole source of carbon and nitrogen, producing secondary metabolites (indole acetic acid and siderophores) that enhanced health and productivity in tomato crops.	Calin et al. (2019)
Gels based on protein hydrolysates (GHC 2-B) were prepared, consisting of 40 % keratin hydrolysate (HKU-B) obtained by alkaline-enzymatic hydrolysis from sheep wool, 40 % collagen hydrolysate (HCE-B), and 20 % leather hydrolysate (GPU-B) obtained by thermal hydrolysis).	Gemination tests on bell pepper and tomato seeds at 1 %, 3 % and 10 % concentrations showed a stimulating effect on tomato seeds at 1 %, where the germination index (Gi) was <100 %. The GHC 2-B variant exhibited the highest stimulant effect (Gi-190.23 %).	Cristea et al. (2024)
Microbial hydrolysis of <i>Paecilomyces lilacinus</i> 112, which possesses keratin-degrading properties and promotes plant growth, was carried out.	The fungus was able to hydrolyze keratin residues and exhibited an inhibitory effect against plant pathogenic fungi, as well as producing secondary metabolites that enhanced growth in tomato plants.	Constantin et al. (2022)

Value-added products, such as organic fertilizers and plant biostimulants offer faster and more homogeneous nutrient availability. However, some chemical and physical hydrolysis methods consume high energy and chemicals that may negatively impact the environment (Malécange et al., 2023). These methods, as observed in chicken feather processing, can produce non-nutritive compounds and reduce nutrient content

(Bhari et al., 2021). Biotechnological strategies using keratinophilic microorganisms and protease enzymes provide environmentally friendly alternatives, promoting the release of organic and inorganic minerals and bioactive molecules that stimulate plant metabolic processes (Calin et al., 2019; Constantin et al., 2022; Hernández-Melchor et al., 2022).

CONCLUSIONS

Sheep wool production is closely linked to Mexico's growing demand for sheep meat. Its economic value depends mainly on its use in the textile sector. However, increasing demand for high-quality fibers and limited markets reduces its economic potential, while accumulation of wool residues creates risks of improper disposal and environmental contamination. Valorization of sheep wool as a raw material for compost, soil amendments, organic fertilizers, and plant biostimulants represents a circular economy strategy for this abundant by-product of sheep farming. Microbial and enzymatic hydrolysis processes release bioactive molecules, providing an accessible and ecological option to enhance crop fertilization directly and/or indirectly. Future research should focus on strategies to study the combined and individual effects of PHs and microorganisms on plant nutrition processes.

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