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REVIEW

A Systematic Review of the Diverse Applications of Alfalfa and Its Role in Sustainable Agriculture

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ABSTRACT

This comprehensive review synthesizes literature from scientific databases, including ScienceDirect, SpringerLink, and Google Scholar, to critically assess the diverse applications of alfalfa (lucerne; *Medicago sativa* L.). Renowned as a premier forage crop for silage, hay, and grazing, alfalfa delivers exceptional nutritional quality for ruminants, being rich in proteins, vitamins, minerals, and carbohydrates. Beyond its traditional role in animal nutrition, alfalfa is increasingly recognized as a potential functional vegetable for human consumption, with significant medicinal properties, including validated cholesterol-lowering and antidiabetic effects attributed to its bioactive phytochemicals such as saponins and flavonoids. The crop also demonstrates considerable promise for environmental remediation, utilizing its deep

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root system and high biomass to stabilize heavy metals like cadmium and copper while degrading organic pollutants through phytoremediation mechanisms. Additionally, alfalfa offers viable applications in biofuel and fiber production. Its cultivation is integral to organic and sustainable farming systems, providing critical ecosystem services such as enhancing soil fertility, sequestering carbon, promoting biological nitrogen fixation, and supporting agricultural biodiversity including pollinators, beneficial insects, and avian species of conservation concern. By integrating these nutritional, medicinal, environmental, and agronomic dimensions, this paper consolidates current knowledge to highlight alfalfa's integral role in promoting resilient and sustainable agricultural systems while addressing interconnected global challenges related to food security, climate change mitigation, and environmental health.

Keywords: Alfalfa (*Medicago sativa*); Sustainable Production; Nutritional Quality; Multi-Purpose Crop; Organic Farming; Soil Fertility

1. Introduction

Alfalfa (*Medicago sativa* L.), a perennial legume from the Fabaceae family, holds a distinguished place in global agriculture. Its name, derived from the Arabic "Al-Fasfasa" meaning 'father of all plants,' reflects its ancient cultivation history dating back over 3,300 years to southwestern Asia [1,2]. Often termed the "Queen of forages," alfalfa is prized for its high biomass yield, superior forage quality, and its consequent impact on livestock productivity for meat and milk [3,4]. Primarily utilized as hay, silage, and pasture [5,6], its exceptional nutritional profile, characterized by high protein content, essential vitamins (A, B, C, D, E), minerals, and carbohydrates, also positions it as a valuable food source for humans [7–9].

This crop shows remarkable adaptability, thriving in various soil types and climate conditions, including nutrient-poor environments [10]. Its cultivation helps solve the dual challenges of conserving resources and ensuring food security, mainly through symbiotic nitrogen fixation. The agronomic benefits of alfalfa are wide-ranging, including improving soil fertility, enhancing soil structure, increasing soil carbon and nitrogen levels, controlling erosion, and supporting biodiversity [11]. Despite its agricultural importance, consistently high seed yields are still hard to achieve, with success depending on optimized mineral nutrition [12,13], growth regulators [14,15], pollinator activity [16], and planting density [17].

As a cornerstone of sustainable livestock and human nutrition systems [6], alfalfa production remains vulnerable to abiotic and biotic stresses, which can significantly reduce productivity [18]. Current research focuses on understanding and enhancing alfalfa's resilience to stresses such as salinity [19–21], drought [22–24], and contamination from heavy metals like cadmium [25–28] and copper [29–32]. These issues occur within a broader context of global agricultural challenges, including yield plateaus, nutrient deficiencies, declining soil organic matter, and water scarcity [33–37], all worsened by abiotic stresses and climate change [38–41].

The primary aim of this review is to promote the expanded use of alfalfa, not only as a high-quality animal feed but also as a nutritious vegetable, thereby supporting better human nutrition and food security [42]. To place this goal within the context of modern agricultural innovation, it is important to recognize that tackling such complex challenges requires integrated, technology-based solutions. Recent progress in sustainable agriculture includes climate-resilient practices for dryland systems [43], meta-analyses on agronomic management to improve yield and efficiency [44–47], and new strategies for environmental cleanup, such as AI-based heavy metal removal [48–51], nanotechnology for precise agriculture [52–54], and nature-inspired solutions for stress reduction [55–57]. Research on innovative cropping systems [58], bioremediation techniques [59–61], and advanced crop management [62–66] together represent the evolving frontiers of sustainable agri-technology, where alfalfa's role is both important and versatile. The Economic Importance of Alfalfa is shown in **Figure 1**.

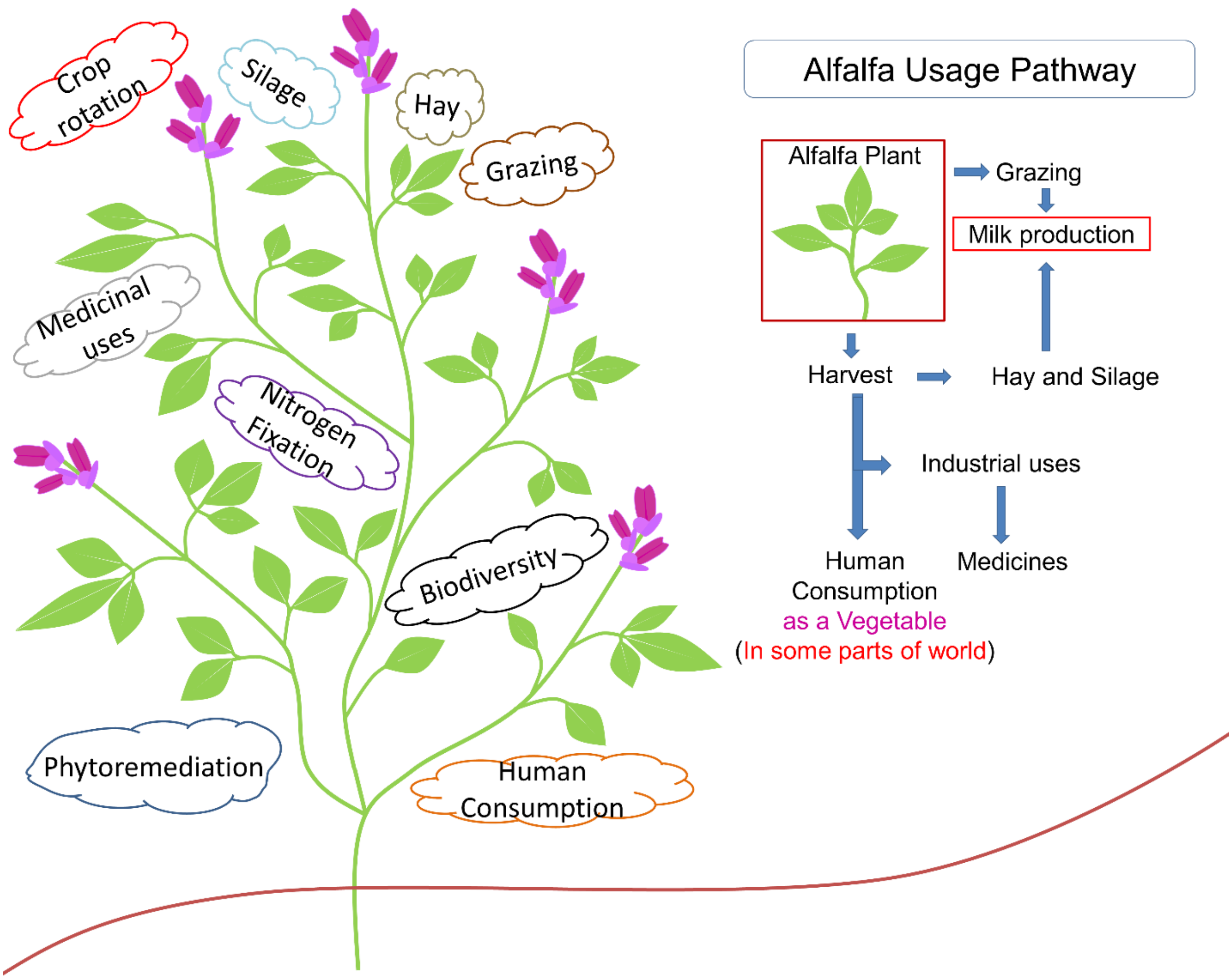

Figure 1. Economic Importance of Alfalfa.

2. Nutritional Profile and Human Consumption

Alfalfa stands out for its exceptional protein yield per unit area compared to conventional crops, underscoring its potential as a strategic food resource [67]. For populations in low-income segments, underutilized crops like alfalfa offer an affordable yet nutritionally dense option. The food industry has a pivotal role in transforming public perception and commercializing alfalfa through diverse product formats, such as fresh, frozen, or ready-to-eat meals, supported by consumer awareness campaigns [68]. The crop's nutritional, medicinal, and feed applications are systematically summarized in **Table 1**.

Beyond the components listed in **Table 1**, alfalfa is a significant source of vitamin K, calcium, carotene, and chlorophyll [79,72]. It contains a diverse range of bioactive compounds, including saponins, flavonoids, alkaloids, sterols, coumarins, vitamins, proteins, amino acids, sugars, and minerals. Its high dietary fiber content helps lower cholesterol levels. Research on tropical alfalfa (*Kacang Ratu* BW) in duck diets (3–10% inclusion) showed no negative effects on production performance but improved feed conversion ratios [71,72,80–82]. Notably, it reduced cholesterol in meat (66.4 to 33.7 mg/100 g), liver (176.8 to 117.3 mg/100 g), and blood (163.1 to 133 mg/100 g), while lowering LDL (82.90 to 67.0 mg/dL) and increasing HDL (53.7 to 72.94 mg/dL) [73]. In laying hens, a 2% dietary inclusion resulted in eggs enriched with vitamin A (4,933.8 vs. 4,381.8 µg/100 g), beta-carotene (1,819.2 vs. 1,513.61 µg/100 g), iron (5.7 vs. 4.8 mg/100 g), zinc (3.5 vs. 1 mg/100 g), and antioxidants [76]. The schematic diagram showing phytoremediation of environmental pollutants is shown in **Figure 2**.

Table 1. Nutritional, Medicinal, and Livestock Feed Applications of Alfalfa (*Medicago sativa* L.).

Category	Application/Effect	Key Findings	References
Medicinal Use	Cholesterol Reduction	Alfalfa seeds reduced LDL and normalized serum cholesterol in patients with Type II hyperlipoproteinemia and protected monkeys from atherosclerosis.	Mölgaard et al. [69]
	Diabetes Treatment	Alfalfa in diet (63 g/kg) or water (25 g/L) reduced hyperglycemia in diabetic mice, exhibiting insulin-like activity linked partly to its high manganese content.	Gray and Flatt [70]
Poultry & Livestock	Duck Performance & Meat Quality	Supplementation with tropical alfalfa (up to 10%) reduced meat cholesterol (66.4 to 33.7 mg/100 g) and blood cholesterol while increasing HDL levels.	Suwignyo et al. [71], Suwignyo et al. [72], Suwignyo et al. [73], Suwignyo et al. [74], Samur et al. [75]
	Egg Quality	Dietary inclusion of 2% tropical alfalfa in laying hens significantly enriched eggs with Vitamin A, beta-carotene, Iron, Zinc, and antioxidants.	Sulaiman and Al-Sardary [76]
Human Consumption	Food Fortification	Alfalfa powder enhances the protein, vitamin, mineral, and dietary fiber content of wheat flour and dough.	Hao et al. [77]
	Phytochemicals	Sprouts and leaves are rich in bioactive compounds (saponins, flavonoids) and nutrients (Vitamin K, calcium); saponins can impart a bitter taste.	Mattioli et al. [8], Sen et al. [67], Oleszek [78]

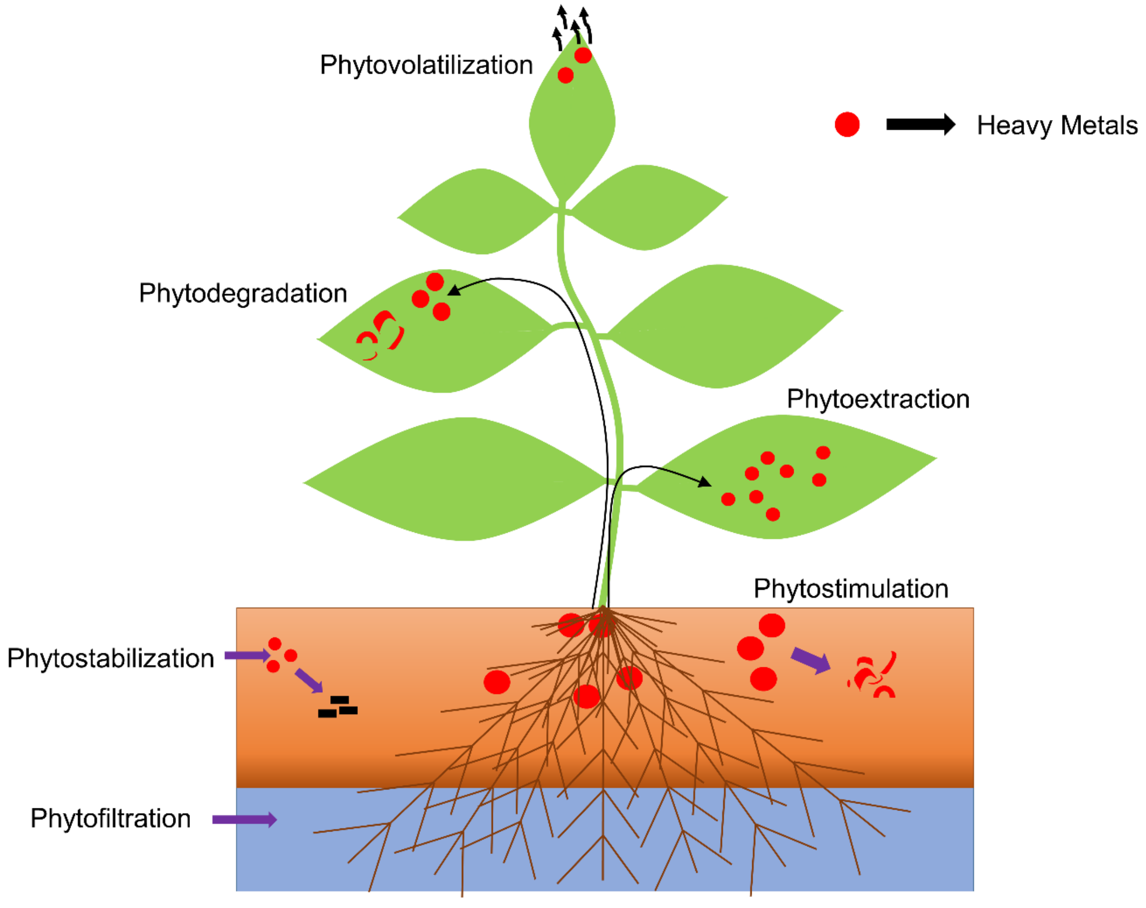

Figure 2. Schematic diagram showing phytoremediation of environmental pollutants.

Culinarily, alfalfa is versatile, used in salads, puddings, soufflés, purees, soups, teas, tortillas, and croquettes [83,84]. It is consumed as a green vegetable in parts of the Americas, Russia, China, and South Africa, often as a spinach substitute [85]. In China, farmers traditionally regard it as a vegetable [77]. Fortifying wheat flour with alfalfa powder improves its nutritional density [77], while raw sprouts are commonly used in salads and sandwiches [86]. Despite its benefits, sensory acceptance can be hindered by a bitter taste attributed to saponins, notably zahnic acid tredismoside [67,78,87]. However, processing methods like preservation can improve its palatability [88].

3. Phytoremediation Potential

In an era of escalating environmental pollution and resource depletion [89], phytoremediation, the use of plants to extract, stabilize, or degrade contaminants, has emerged as a sustainable cleanup strategy [90–92]. This process employs mechanisms like phytoextraction, phytovolatilization, rhizofiltration, and phytostabilization [93].

Alfalfa is a promising candidate for phytoremediation due to its deep root system, rapid growth, high biomass, and adaptability to various soils [94]. It has demonstrated effectiveness in stabilizing and adsorbing heavy metals such as copper [32,95] and cadmium [28,96], and in degrading organic pollutants such as polychlorinated biphenyls (PCBs) [97,98] and polycyclic aromatic hydrocarbons (PAHs) [99,100]. Additionally, alfalfa plays a key role in managing soil nitrogen. It efficiently absorbs nitrates from deep soil layers, reducing leaching risks [101,102]. Although alfalfa fields emit nitrous oxide (N_2O) at rates of 0.66–1.44 kg N_2O-N/ha/year, intermediate between fertilized and unfertilized grasses—these emissions can increase in subsequent crops [103,104]. Importantly, alfalfa cultivation greatly contributes to soil carbon sequestration, aiding in the reduction of atmospheric carbon levels [105].

4. Medicinal Properties

Alfalfa has a long history in traditional medicine, often administered as powdered pills [84]. In Chinese and Hindu practices, young leaves are used to treat conditions such as edema, arthritis, and digestive issues, while seed poultices are used to treat boils. In Colombia, it relieves coughs and has been used for kidney stones and gastric ulcers. Its phytoestrogen content is associated with regulating menstrual cycles and enhancing lactation [69].

A key validated medicinal benefit is cholesterol management. Alfalfa seeds have been shown to lower low-density lipoprotein (LDL) cholesterol and apolipoprotein B in patients with type II hyperlipoproteinemia [69]. Additionally, alfalfa exhibits antidiabetic properties. Studies in streptozotocin-induced diabetic mice found that dietary or aqueous supplementation reduced hyperglycemia, demonstrating insulin-like activity partly attributed to its high manganese content [70], corroborating its traditional use as an anti-diabetic tea in South Africa.

5. Agronomic Management and Environmental Benefits

5.1. Silage and Hay Production

Optimal harvest management is essential for balancing yield, quality, and stand longevity. The first cut is usually taken at the bud stage, with subsequent cuts every 5–8 weeks. In European systems, wilting for 1–3 days is common for silage, while hay needs 3–6 days to reach <20% moisture. Because alfalfa has low sugar and high buffering capacity, pre-wilting to about 35% dry matter is crucial for successful ensiling. Additives like molasses may be necessary. For baled silage, preventing soil contamination and reaching 50–60% dry matter density (~200 kg DM/m^3) are key to avoiding clostridial spoilage. Although haymaking is traditional, it can cause significant field losses (>30%). Techniques such as mowing in the morning, conditioning to crush stems, and careful tedding or raking during dew can reduce leaf loss. More advanced methods, such as barn-drying with warm air or industrial dehydration, can produce high-quality, consistent feed but require greater infrastructure investment [11].

5.2. Benefits in Crop Rotations

Integrating alfalfa into crop rotations offers multifaceted advantages. It biologically fixes substantial nitrogen (300–400 kg N/ha/year) [106,107], with approximately 165 kg N/ha stored in roots and crowns for subsequent crops [108,109], providing a nitrogen replacement value of 100–200 kg/ha [110–113]. Residual nitrogen benefits can extend into the second year following alfalfa [114,115]. Although nitrogen rhizodeposition from alfalfa is relatively low (3–5% of fixed N) compared to other legumes [116,117], it contributes slowly to soil nitrogen pools, linked more to fine root turnover than nodule exudation [116,118,119]. While alfalfa improves soil structure and fertility, its deep water extraction can create short-term water deficits for subsequent crops in dry regions [120]. The timing of stand termination also affects nitrogen availability, with autumn termination favoring greater nitrogen mineralization for the next crop than late winter termination [120,121] (**Table 2**).

Table 2. Environmental Impact: Phytoremediation, Soil Fertility, and Biodiversity Support of Alfalfa.

Environmental Function	Target/Mechanism	Observed Benefits and Mechanisms	References
Phytoremediation	Heavy Metals (Cu & Cd)	Effective stabilization and removal of heavy metals; silicon application enhances cadmium tolerance.	Kabir et al. [25] Yang et al. [28] Ju et al. [32] Chen et al. [95]
	Organic Pollutants (PAHs & PCBs)	Demonstrates capability to accumulate and degrade persistent organic pollutants.	Teng et al. [97] Tu et al. [98] Alves et al. [99] Alves et al. [100]
Soil Fertility & Rotation	Nitrogen Fixation	Fixes 300–400 kg N/ha/year; ~165 kg N/ha stored in roots/crowns benefits subsequent crops.	Kelner et al. [106] Angus and Peoples [107] Rasse et al. [108]
	Carbon Sequestration	Contributes to significant carbon accumulation in soil profiles, mitigating atmospheric CO_2.	Mortenson et al. [105]
Biodiversity Support	Insects and Pollinators	Supports diverse insect communities, including ~30 wild bee species in France and up to 8.8 butterfly species in managed fields.	Rollin et al. [122] Thiebeau et al. [123]
	Avian Habitat	Provides critical breeding and feeding grounds for birds of conservation concern (e.g., skylarks, Montagu's harrier, little bustard).	Kragten et al. [124] Salamolard et al. [125] Berthet et al. [126]

5.3. Biodiversity Enhancement

Alfalfa fields serve as important agroecosystem habitats. While they can host pest insects [127], they also support beneficial populations, including wild bees (30 species recorded) [122] and grasshoppers [128]. These, in turn, support small mammals like voles [129] and higher trophic levels, including birds. Large-scale alfalfa cultivation provides habitat for skylarks [124], raptors like Montagu's harrier [125], and threatened species such as the little bustard [126]. Proper management, including adherence to agri-environment schemes, can significantly increase species richness (e.g., grasshopper density quadrupling) and is vital for maintaining ecosystem services and conserving biodiversity at landscape scales [11]. The preservation of such biodiversity is increasingly supported by soil remediation strategies that mitigate heavy metal toxicity, as demonstrated by the use of organic and inorganic amendments to alleviate cadmium stress and stabilize contaminants in agricultural soils [130–134]. Furthermore, the integration of sustainable agronomic practices, including the application of humic acid and optimized sowing methods, has been shown to enhance crop performance and soil health in diversified cropping systems that support both productivity and ecological function [135–138]. Finally, the long-term ecological resilience of alfalfa-based landscapes is underpinned by broader conservation agriculture principles, such as no-tillage and intercropping, which improve soil water dynamics and system productivity while also depending on the sustained availability of essential nutrients like bioavailable silicon within watershed ecosystems [139–141].

6. Conclusions

This review consolidates the extensive evidence supporting alfalfa (*Medicago sativa* L.) as a cornerstone of sustainable agriculture. Its unparalleled value stems from a unique combination of attributes: a high-yielding, nutrient-dense forage that enhances livestock productivity; a potential source of human nutrition and nutraceuticals; a versatile phytoremediator for soil health; and a keystone species supporting agricultural biodiversity.

The practical implications are profound. Alfalfa cultivation directly contributes to sustainable agriculture by reducing reliance on synthetic fertilizers through nitrogen fixation, improving soil organic matter, and preventing erosion. It advances food security by offering a dual-purpose crop that supports both animal protein production and direct human nutrition, particularly in resource-limited settings. Its role in environmental management is underscored by its capacity for carbon sequestration and for cleaning up contaminated lands.

To fully realize this potential, future efforts should focus on: (1) **Genetic and Agronomic Innovation**: Breeding programs for enhanced stress tolerance (drought, salinity, heavy metals), improved palatability for human consumption, and optimized biomass for bioenergy. (2) **Value-Chain Development**: Encouraging food industry investment in developing and marketing alfalfa-based products for human diets, alongside awareness campaigns. (3) **Policy and Systems Integration**: Promoting alfalfa inclusion in crop rotations through incentives and integrating its ecosystem services into climate-smart agricultural policies. (4) **Interdisciplinary Research**: Further investigating the synergies between alfalfa cultivation, soil microbiome health, and biodiversity conservation in different agroecological zones.

In conclusion, alfalfa is far more than a forage crop. It is a multi-purpose biological tool whose expanded, strategic use is critical to developing resilient, productive, and environmentally sound agricultural systems for the future.

Author Contributions

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The authors declare no conflict of interest.

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