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POTENTIAL USE OF WASTE WOOL IN AGRICULTURE: AN OVERVIEW

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ABSTRACT

The review aims to compile the information on recycling of wool wastes in agriculture and to explore future research areas. Wool is a biodegradable fibre and readily recycled with significant benefits accruing from returning to the earth as a nitrogen and sulphur-rich fertilizer. Wool-waste produced in many forms beside shearing waste, carpet disposal, textile industries, wool scour sludge and very coarse wool that cannot be processed. These wool wastes are included in the present evaluation with relevant literature and focussed on applications and potential benefits of wool-waste as a soil amendment and to identify areas where there is insufficient knowledge to implement its usage. Along with growing public concern for the environment and costs of landfill in recent years, it is utmost urgent to look for alternative uses for inevitable wool-waste. Therefore, closed cycle processes without significantly producing waste are being developed for many products and materials, but rarely for fibre products. Recycling technologies are becoming increasingly important and there is clear need to identify an alternative use for this protein-rich product and its by-products.

Key words: Agriculture, Moisture conservation, Organic mulch, Slow release fertiliser, Soil amendment, Waste wool

Total world wool production and its prices in the last two decades have been steadily declining since 1990. As per the recent figures world wool production is 1161 million kg (IWTO, 2015) and accounts for 3.51% of total fibre production (33 million tonnes). In the recent past, wool price in the country has also declined. As a result, many farmers are shifting from wool to mutton in sheep farming. Very coarse wool because of no utility in textiles and also in other sectors ends up by burning or burying it. Coarse wool has become an underrated and underused resource. Belly wool, even from fine-wool sheep, goes unsold and often referred to as 'waste wool'. It accounts for about 20% of the total wool from a sheep; and represents a fair amount of wool that does not generate return to producers (Hargreaves, 2017). Thus, waste and tag wool account a huge amount of wool that is a readily available, inexpensive and considered low-quality because of contamination and stains. Further, nearly 10 to 15% of waste wool produced in woollen industries during wool processes (carding, combing, spinning, wad weaving, etc) is usually discarded or dumped on the ground (Kadam et al., 2014). These wool wastes are voluminous, light weight and rich in protein and cause serious environmental hazards and air pollution. Floating of the fine wool particles from waste wool in air causes severe allergic rhinitis in humans (Wang, 2005). To overcome these problems, there is need to have efficient environment friendly wool waste disposal system. It can be decomposed with other agriculture by-products and used in agriculture as manure.

Recycling technologies are one of the options for best use of waste products and materials, but not much efforts are being made for use of waste wool fibre (Bartl et al., 2005). There is a need to identify an alternative use for waste wool, which is rich in protein (Zheljazkov, 2005). The use of wool-waste from both industries and post-consumers would reduce waste and improve resources conservation (Watson 2005; Miraftab and Lickfold, 2008).

Animal manure and raw organic materials have been traditionally used as a nutrient source for conditioning of soil in agriculture. Organic fertilizers contain a lot of organic nitrogen (N), but it is not mineralized fast enough to meet the needs of the plants during critical periods (Pang and Letey, 2000). Bioconversion has a significant potential for transforming wool-waste into high-value products like manures for organic farming. The concept of 'geo-textile' for waste-wool came from the use of jute for non-woven geo-textiles for soil stabilization and controlling soil erosion in dry, irrigated and rain-fed areas. These fibres can also be used in drainage-bonds and agricultural mulching in Rajasthan. It has been observed that wool waste of woollen mills from Bikaner is traditionally being used by the farmers of Sikar district since ages for improving the crop production. ICAR-Central Sheep and Wool Research Institute, Avikanagar (CSWRI), Rajasthan has initiated research on utilisation of non-profitable / non-utilised coarse wool or waste wool in agriculture for widening its use and increasing its economic value besides reducing pollution and adding profit to farmers from sheep rearing. There is limited number of studies investigating the incorporation of shredded carpet waste directly into soil in the country. The aim of this paper is to present the current management options for utilization of raw wool waste and to review the research on solutions for converting wool waste into useful organic manure for use in agriculture.

A. Physico-chemical properties of wool

Wool is stable through alpha-keratin peptide linkages and a highly cross-linked network of disulfide bonds. Greasy raw wool is composed of protein 'keratin' with an abundance of carbon (C 50%), nitrogen (N 16-17%) and sulphur (S 3-4%), which play an essential role in plant nutrition (Von Bergen et al., 1963). Wool is not easily degraded in nature and causes serious pollution. Alpha keratin, also known as hard-keratin has higher cysteine content (up to 14%) to form S–S bonds between cross-linking protein chains, contributing ability to resist common proteolytic enzymes such as pepsin, trypsin or papain (Onifade et al., 1998). In addition, the hydrophobic groups of spiral coil in wool make it more difficult for biodegradation (Kornillowicz-Kowalska and Bohacz, 2011). The chemical composition and element analysis of wool waste are presented in Table 1. The waste wool production in promising wool producing countries is given in Table 2 and relative contribution of countries in total wool waste production is depicted in Fig.1.

Table 1. Elemental concentration of wool waste

Wool waste	N (%)	P (%)	K (%)	S (%)	Zn (ppm)	Cu (ppm)	Mn (ppm)	Fe (ppm)	References
Scoured wool and dust	15.78	0.01	0.005	3.21	115.00	25.00	25.00	50.00	Burn et al. (1964)
Un-composted wool and hair waste	0.11	0.08	3.30	5.13	501.00	8.00	21.00	234.00	Zheljazkov (2005)
Shearing waste	-	0.01 - 0.03	0.06-0.08	1.87 - 2.20	73.60 - 88.80	5.30 - 10.30	3.37 - 22.93	22.03 - 513.17	Patkowsa-Sokola et al. (2009)
Machine waste	0.11	0.012	0.02	3.21	230.00	8.54	8.00	12.47	Sharma et al. (2014)
Waste wool	2.37	0.0003	0.76	2.17	94.25	13.39	45.93	914.96	Chaudhary et al. (2018)
Shearing waste	11.80 -12.50	0.01 - 0.02	0.02 - 0.03	2.60 - 3.00	130.00 - 145.00	20.00 - 25.00	23.00 - 28.00	60.00 - 90.00	CSWRI (2018)

Table 2. Estimated waste-wool production (tonnes) in promising countries*

Country	Estimated wool waste	Country	Estimated wool waste
Australia	119623	Turkey	18599
China	58982	Iran	14248
USA	37668	UK	12406
New Zealand	25614	India	7946
Argentina	22224		

**- Estimated value on the basis of total wool production, considering 10 to 15% waste in sorting, scouring and cleaning and 12 to15% waste during wool processing*

B. Biodegradation and composting of wool

Wool is quite resistant to the attack of micro-organisms; only under hydrophilic conditions they are able to breakdown the keratinous fibre. It takes months to degrade the wool. The functional groups of wool start to degrade and convert into biomass after 4 weeks and weight loss up to 33% was reported under hydrophilic conditions during three months (Arshad and Mujahid, 2014). Wool keratin is an ideal substrate for proteases, esterases, lipases enzymes and those that act specifically on disulfide bonds. Microbes and insects can digest wool by secreting extracellular keratinolytic enzymes that catalyze the hydrolysis of peptide linkages leading to release of polypeptides and soluble sulfhydryl-containing amino acids (Cardamone, 2001). Microbial growth depends upon moisture, ambient temperature and assimilable sources of nutrients for the specific organism. Under favourable temperature and humidity conditions, more than 10^4 viable bacteria and 10^3 fungi per g of wool develop and cause biodegradation (Gochel et al., 1992).

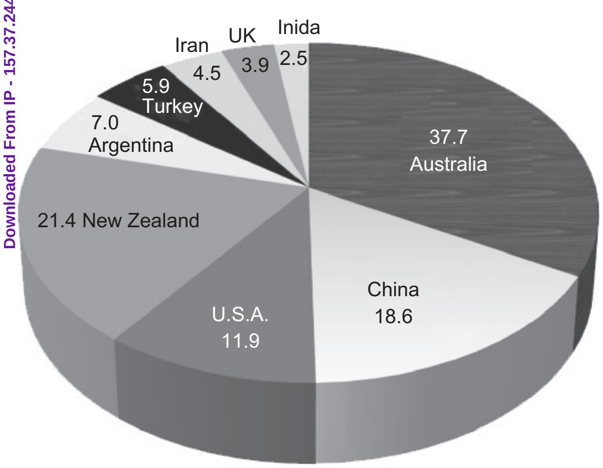

Fig. 1. Relative contribution (%) of countries in total wool waste production

In waste wool, mostly fibres are broken which allow the microbe to attack on the inner cuticle layers and the lipid-rich complex of membrane cells, thereby the innermost structural elements, the cortical cells, become exposed to enzymatic digestion. This enzymatic digestion is further increased if carbohydrates, fats and nitrogen are present in the culture media. Although, environment-friendly and economical methods of microbial degradation are not universally used wool waste, it seems to be an attractive approach to manage these wastes without energy wastage and amino acids loss (Gupta et al., 2012).

C. Possible application of waste wool in agriculture (Table 3)

i. Moisture conservation: Wool fibres absorb and retain moisture very effectively and this property is beneficial when applied to soils where it can reduce runoff of contaminants such as pesticides and improve water conservation. Wool fibres are lighter and can absorb higher amount of moisture without adding the weight (Nustorova et al., 2006). Karim et al. (2009) reported that wool retained higher amount of moisture due to hygroscopic nature. Wool can absorb up to 30% moisture of its own weight because of polarity of peptide group, salt linkage and its amorphous nature. The peptide group and salt linkages attract water molecule, which readily enter into the amorphous region of the fibre. Coarse wool can act as water conservation medium since wool can retain a substantial amount of moisture (Kadam et al., 2013). On comparing various forms of wool, Kadam et al. (2014) reported higher moisture retention of wool felt due to its consolidated form and uniform density (1000 g/m^2) as compared to other form of wool. The consolidated form of wool restricts movement of moisture due to barrier created between soil layers. The moisture retention in soil was increased by 23.33% over the control (Kadam et al., 2014). Brian Gold from Pineae Green houses in Ogden reported that after seven days, the plant with the wool pellets had retained about 40% more water than those without wool pellets (Hargreaves, 2017). He opined that wool naturally absorbs water about 20 times its weight, so farmers can conserve more water by applying waste wool as mulching material in the soil or bunds.

ii. Organic mulch: Mulch is placed on top of soil around trees and crop plants. The mulch acts as an insulator and keeps the soil cooler in the summer and warmer in the winter. It also helps the soil to retain moisture, limits evaporation and prevents weeds from germination and growth in the mulched areas (Bhardwaj, 2013). Like other mulch materials, wool suppresses weed growth and acts as a source of N, and more resistant to breakdown (lasting longer) than other mulch materials. Wool mulch lasts for two years. The wool absorbs water, herbicides, pesticides and fertilisers, releasing them slowly into the soil. Wool mats are commercially available in developed countries, or one can weave their own mats from unprocessed wool. Wool carpet waste contains nutrient elements that can provide fertilising benefit over and above that of non-biodegradable mulch or simple organic mulch.

Table 3. Use of wool-waste in agriculture and other sectors

Sector	References
Agriculture	
Mulching material for improving soil moisture retention, reducing evaporation and preventing weeds germination	Bhardwaj (2013); Cincinnati et al. (2012); Garton et al. (2013)
Soil amendments for improving soil condition and nutrient content	Govi et al. (1998); Johnson et al. (2003); Pugh (2007); Zheljazkov et al. (2008)
Soil reinforcement amendment	Wang et al. (1994); Wang (1997, 2006)
Compost and organic nutrient source	Plat et al. (1984); Tiwari et al. (1989); Waliczek et al. (2013); Hustvedt et al. (2016); Kadam et al. (2014)
Slow release fertiliser	Mazur and Malicki (1993); Nustorova et al. (2006); Michel et al. (2008); Waliczek et al. (2013)
As substrate amendment in pot cultivation of tomato, sweet pepper and eggplant	Gorecki and Gorecki (2010)
Others	
Conversion of waste wool to protein for the production of fibre, film and injectable gel for biomedical applications	Shavandi et al. (2016)
Use of waste wool in nitrogen fertilisers	Bhavsar et al. (2016); Bhavsar (2018)
Extraction of keratin from waste wool for cosmetic industries	Brown et al. (2016)

Cincinnati et al. (2012) reported that the eggplants (*Solanum melongena*) that received the wool mulch were more resilient to temperature than those that received hay mulch. These eggplants in wool mulch also had darker leaves, greater vitality and higher yield. The soil under the wool mulch is cooler than that under hay mulch. Sweet potato (*Ipomoea batatas*) mulched with wool produced 536 pounds compared to just 145 pounds in the row mulched with hay. Wool mulch had less temperature fluctuation than in hay mulch or no-mulch. Nitrogen levels in the tissue samples were highest in the wool mulch and the lowest or deficient in the hay mulch. At West Virginia University, Morgantown, Garton et al. (2013) reported that in organic tomato production, wool applied as mulch at a depth of 5 cm, yielded significantly higher than other treatments or control. As wool is able to absorb water and biodegrades slowly it makes good mulch, particularly for young trees and shrubs (Pollard-Jones, 2016).

iii. Soil amendment and organic nutrient source: Anecdotal records of gardeners from 1940s had suggested beneficial effects of wool on growth of plants (Waliczek et al., 2013). Earlier, it was believed that wool would not break down in soil. Researchers tried experiments by adding some wool in hanging baskets around plants and compared it with other plants (Hargreaves, 2017). They found beneficial effect on plant growth, further used pellet of wool for making best use of wool in soil amendment. Limited research on the use of poor grade wool for agricultural crops has been carried out (Zheljazkov, 2005). It was reported that amending soil with sheep wool improved productivity of plant species (Zheljazkov, 2005; Zheljazkov et al., 2008).

Wool is a rich source of important nutrients which are necessary for plant growth (McNeil et al., 2007). It contains high quantities of N, S and C. Sheep wool hydrolysate improves growing conditions by increasing contents of total N, C, and P in the soil (Govi et al., 1998). In an experiment on the use of waste wool carpet to improve the pasture land, Johnson et al. (2003) found increased levels of sulphur by 25%, magnesium by 17%, potassium by 15%, nitrogen by 10% and phosphorous by 7% in grass after 10 weeks of seeding on soil with ground-up wool carpet compared with grass grown on soil with no wool. The dry weight of grass after 15 weeks was 24% more from the carpet-fertilised area. The wool in carpet contains significant amounts of N and S. Major elements reported for carpet wool waste are 5.5 to17.0% N, 1.2 to 3.5% S and 10.8% Ca (McNeil et al., 2007; Mesman et al., 2007). Out of which N and S contents are comparable to farmyard manure, but it has low contents of phosphate, potash and magnesium (Pugh, 2007). Further, McNeil et al. (2007) found suitability of wool wastes as fertiliser with elevated levels of essential elements such as N (19%), S (19%) and Mg (7%) in the grass grown on wool fertilised plots as compared to the control. The addition of wool-waste to the growth medium increased Swiss chard (*Beta vulgaris*) and basil (*Ocimum basilicum*) tissue N, and NO_3-N and NH_4-N relative to the un-amended control (Zheljazkov et al., 2009a).

There is significant evidence that incorporation of carpet waste may improve some structural characteristics of soil as well as water-holding capacity. In a series of research papers, Wang et al. (1994) and Wang (1997, 2006) investigated the use of fibres in soil and recorded an increase in tri-axial compressive strength that have relevance in unstable and sandy soils.

In an experiment with the hydrolysed wool, Nustorova et al. (2006) found that the C:N ratio in treated soil increased with increasing doses of wool. This was also reflected by an increased mineralization of hydrolysate by microorganisms in the soil. Zheljazkov (2005) and Zheljazkov et al. (2008) reported that addition of wool waste to soil increased NH_4-N and NO_3-N in soil and stimulated soil microbial biomass. They further observed that high rates of wool addition to soil resulted in shifts of microbial composition, while a low rate of wool-waste addition did not affect the microbial composition relative to the un-amended. Amendment-fertilisation of grassland contributes to the reduction of soil degradation, including erosion. Pot experiment involving waste wool have proved it as a good source of N (Hodnik et al., 2008).Coarse wool provided significantly higher quantity of available nitrogen, phosphorus and potash for plants. However, micronutrient availability and other soil properties like soil organic C and pH were unaffected by wool application in any form (Kadam et al., 2014). Another advantage, wool soaks up in the soil, it fluffs up and expands, increasing soil porosity and improving the soil's ability to retain oxygen (Kadam et al., 2014; Hargreaves, 2017).

iv. Composting of waste wool: It is one of the best options for soil amendments and provides farmers with additional income, and provides communities that depend on sheep for best use of waste wool. Wool-waste requires composting prior to use as soil amendments, largely to provide appropriate substrate qualities for plant growth, including lowering of C: N ratios and the provision of available plant nutrients (BSI, 2005). Tiwari et al. (1989) used wool-waste compost at 10 t/ha in a growth study involving chickpea and wheat crops and found a trend in response with the reduction in C: N ratios. Waliczek et al. (2013) constructed compost piles incorporating wool-waste with proportions of various other feedstock ingredients including animal manures, food waste, invasive river plants and horticultural plant green waste, as well as tree-pruning waste and livestock bedding and straw.

Plat et al. (1984) suggested the utilization of wool-waste in compost form, as N source for plants and Tiwari et al. (1989) reported a marked response in chickpea and wheat growth using wool-waste composts and they further noted maximum responses in nodulation and pod formation in chickpea and also in yield of wheat crop by the application of 10% dung and 2% rock phosphate treated wool-waste compost. The composting in this way results in an immediate immobilization of nutrients, especially N. Further, Zheljazkov et al. (2009b) used un-composted wool-waste as a nutrient source for both container grown crops and field crops and concluded that wool-waste as an excellent soil amendment that increased plant yields and essential nutrient contents. Mubarak et al. (2009) found that decrease in water movement in sandy soils amended with organic residues including carpet wool wastes, offered better chance for crops to absorb water and nutrients. They found an increase in plant yields up to 28% dry matter (DM). It is also interesting to note that wool has greater imbibition for water since soil moisture content at harvest was greater than without wool amendment, which emphasizes wool ability to stabilise soil. Recent research has established that wool or hair incorporated into the pot plant environment can improve the water-holding capacity of the soil as well as act as a slow-release fertiliser (Waliczek et al., 2013). Hustvedt et al. (2016) determined that a 25% waste wool, 50% grass clipping, and 25% horse stall waste mixture provided the optimal results for composting. Compacted wool, if transported in wrapped bundles, proved better decomposition of the waste wool. The authors recommended a ratio of sheep wool-waste, fallen tree leaves/weeds and grasses (agricultural farm waste/crop residues) and sheep faecal pellets at 30:20:50 for its efficient composting and quality manure production.

ICAR- CSWRI, Avikanagar has conceptualized the idea of utilization of waste wool in agriculture for its safe disposal by composting with sheep manure and other agricultural by-products (S.C. Sharma, L.R. Meena and R.C. Balai, 2012; S.C. Sharma, R.C. Balai and A. Sahoo, 2017, Personal communications). A series of experiments were carried out and obtained encouraging results in terms of moisture retention and higher biomass yield. In an incubation study in 2012, sheep manure: wool dust (1.00:1.00 part) when incubated for 45 days resulted in improvement in pH, N (1.31 to 3.03%), P (0.42 to 1.47%), K (0.93 to 1.43%), Fe (33.45 to 95.2 ppm) and Cu (21.03 to 48 ppm) of sheep manure. In subsequent years, waste- wool-based manure has been developed by composting 50% sheep manure, 30% waste wool, 20% crop residues/dry tree leaves with compost inoculants and named as 'Avikhad'. The Institute has also got 'copyright' for 'Avikhad and 'Organic Certification' from Rajasthan Organic Certification Agency (ROCA), Jaipur in 2016. It has multiple benefits: a) use as fertiliser, b) improves retention of water to facilitate its slow release of nutrients to the crop, c) minimises frequent watering due to longer duration of moisture retention, d) for organic produce and finally, e) reducing environmental pollution (Fig. 2). This has opened up wide use of wool waste application in urban horticulture/ floriculture, pot-culture (indoor and outdoor ornamental plants in pots) and making of green environments in multi-storey buildings/malls, corporate offices, airports and other establishments in metro-cities. Further, in 2016 and 2017, comparative scientific evaluation on the use of Avikhad, sheep manure and waste wool was made on plant growth performance involving oats and barley crops in Rabi season (S.C. Sharma, A. Sahoo and L.R. Meena, 2018, Personal communications). Two types of wool-waste i.e. shearing waste and wool processing machine waste at 40 and 60% soil moisture saturation level were studied. It was observed that height of crops and dry matter accumulation increased considerably

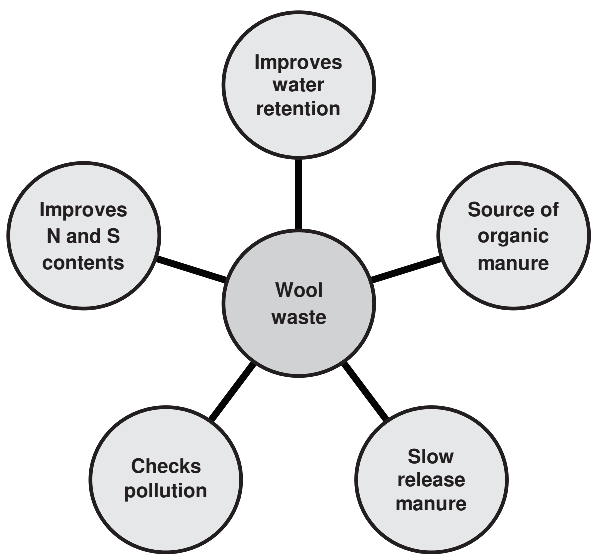

Fig. 2. Multiple benefit of wool-waste in agriculture

with Avikhad in comparison to sheep manure under both type of waste-wool application in low-carbon sandy soil of Rajasthan.

v. Slow release fertiliser: Most of the inorganic fertilisers are nowadays costly and subjected to many types of losses resulting in poor use efficiency. Further, these fertilisers are hazardous when used in excess causing soil pollution. However, as organic fertiliser from wool-waste is a rich source of important nutrients (N, S and C) for plant growth, it is imperative to explore its environmental-friendly usage. The wool and its by-products are richer in organic N (over 5%) and C (30 to 50%) than manure and compost (Baker, 1991). Sweat wool before processing contains fats, dirt, and other compounds like weeds, faeces, etc. As the presence of fats delayed microbiological decomposition, raw wool is less suitable for amending growing substrates in short-term vegetable cultivation under glass. Also, sweat wool is hydrophobic, so the amount of water and nutrient solution, it absorbs is smaller (Mazur and Malicki, 1993;, Michel et al., 2008). As mentioned, one of the main qualities of wool is biodegradability, when buried in soil, the keratin biopolymer is degraded by microorganisms and releases nutrients essential to the crops. Because wool slowly decomposes in soil it can be used as a slow-release fertiliser, and act as a source of N-based nutrients and S over a longer period than conventional fertilisers. Low grade raw wool or wool waste can be used as agricultural amendments, laid directly in the bottom of the plant pits, or added to the compost mixture, to improve the N content and water retention. Green hydrolysis using super-heated water is an emerging technology to turn waste wool into amendment-fertilisers for the management of grasslands and other cultivation purposes (Zoccola et al., 2015). In this way wool keratin is degraded into simpler compounds, increasing the release of nutrients to plants.

Scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis demonstrated that wool wastes decompose slowly under field or greenhouse conditions, and act as a slow release S, N, P, and K fertiliser. These results, along with the measured concentrations of NO_3-N in soil at harvest, suggested that addition of wool or hair waste @ 3.3 g/kg of soil supports two to five harvests of crops under greenhouse conditions and two to four seasons in the field, and improved soil biological and chemical characteristics (Zheljazkov, 2005). Hargreaves (2017) reported 9%N, 1%P, and 2% K in wool pellets, which takes months to break down, and act as a natural, slow-release fertiliser.

D. Effects on plant chemical composition, growth and yield

The use wool or its hydrolysate on chemical composition and performance of plants has been presented in Table 4. Zheljazkov (2005) reported that addition of wool-waste to soil increased total N (and protein) content in plant tissue. Wool-waste additions to soil altered slightly the content and composition of plant secondary metabolites (essential oils or alkaloids); however the overall constituents remained within the normal range for the respective crops. McNeil et al. (2007) found that content of Ca did not change in ryegrass plants due to fertilising with post-consumer wool carpet, content of Mg did not change or increased 7% (depending on the number of days after planting), whereas content of P (35 and 10%) and K (8 and 8%) decreased. On the other hand, Nustorova et al. (2006) reported that due to the amendment of wool hydrolysate, content of K, Mg, and Ca increased in the biomass of ryegrass collected during the first mowing, whereas content of these elements in the biomass of ryegrass from the second mowing decreased. Gorecki and Gorecki (2010) reported that due to wool amendment to the substrate, content of N-NO_3 and K decreased by 49 and 42%, respectively in tomato leaves, whereas content of P, Mg, and Ca increased by 19, 15, and 25%, respectively. It may be concluded that waste wool is a valuable fertiliser in production of many species of plants. Applied hydrolysed wool also improved emergence and plant growth (Nustorova et al., 2006). The addition of unwashed and cut wool showed similar positive results on marigold and basil plants (Zheljazkov et al., 2009b).

Wool, when added to the soil, greatly increases the yield (wet and DM) of grass. The known disadvantages of wool-wastes in grassland are inherent handling problems, lack of ready availability nutrients, weed problems and low bulk density (Das et al., 1997). Zheljazkov (2005) reported that addition of wool waste to soil increased yields of basil (*Ocimum basilicum* L. 'Trakia'), thorn apple (*Datura innoxia* Mill. 'Inka'), peppermint (*Mentha* x *piperita* L. 'Black Mitchum') and garden sage (*Salvia officinalis* L. 'Desislava'). Plants cultivated in wool-amended soil yielded 40-142% more yields. Literature shows that wool, when used as a fertiliser, increased the DM yield of grass between 24 to 82%. The grass grown on plots fertilised with wool appeared a dark shade of green than the grass grown on the control plots (suggesting a healthier state), with elevated levels of essential elements such as N (19%), S (19%) and Mg (7%). The increase in N in the fertilised grass showed that the N in the decomposing wool, which is an essential element for grass growth. The increased S in the fertilised grass is valuable for wool growth in sheep, as S is a major component of wool, representing about 3% by weight (McNeil et al., 2007).

McNeil et al. (2007) found the suitability of ground-up wool carpet as fertiliser in cultivation of Italian ryegrass (*Lolium multiflorum*). Fertilised grass yielded 33 to 95% higher (depending on the number of days after planting). Bohme et al. (2008) successfully used wool - coconut fibre slabs for cucumber cultivation. In general, cucumbers grown in wool yielded 19-42% more than plants cultivated in coconut fibre slabs. In cucumber plants in wool-containing slabs, additionally treated with bio-stimulators, yield increased by 130%. Also, alkaline hydrolysate of waste wool used as soil fertiliser increased biomass of ryegrass and seed germination, as well as improved microbial life of soil (Gousterova et al., 2003; Nustorova et al., 2006). Zheljazkov et al. (2008) conducted pot and field experiments to assess un-composted wool-wastes as a nutrient source for non-edible high-value crops/plants. They inferred that in the pot experiments, addition of un-composted wool to soil increased yields from marigold (*Calendula officinalis* L.) and valerian (*Valeriana officinalis* L.). In the field experiment, wool-waste when added to purple foxglove (*Digitalis purpurea* L.) at rates of 0, 15.8 and 31.7 t/ha increased yields in two seasons by 1.7 to 3.5 times compared to the control. The addition of un-composted wool-waste at 0.33% by weight to soil meet the requirements of nutrients for at least 2 to 3 harvests of crops, without the addition of other fertilisers. Thus, un-composted wool can be used as a nutrient source for high-value crops. Zheljazkov et al. (2009a) reported that un-composted wool-wastes could be used as nutrient source and growth medium constituent for container-grown plants. Total basil yield from the five harvests was 1.6-5 times greater than un-amended control, while total Swiss chard yield from the four harvests was 2-5 times greater compared to un-amended control.

In a study of tomato, eggplant and pepper in an unheated greenhouse, Gorecki and Gorecki (2010) observed that substrate amendment with wool contributed to a significant increase in tomato fruit yield. The effects were taller plants, higher fresh weights of plants and more green appearance of leaves. Also, prolonged the vegetation period and delayed ageing. They further reported that addition of clay soil to the basic peat substrate decreased tomato plants fruiting, but enrichment of this substrate with sheep wool increased the yield by 29% as compared to the control substrate. In the case of eggplant, the addition of wool to culture substrate did not increase the yield, but insignificantly increased the number of fruits (by 14%). Pepper responded to wool amendment into substrate and yielded 30% more and fruit number by 16%. Voncina and Mihelic (2013) observed highest soil N and asparagus (*Asparagus officinalis* L.) yield in the first year following incorporation of wool. Further, NO_3-N content in the asparagus crop was low reflecting the good synchrony of N mineralization and consumption of N in wool incorporation.

Table 4. Effects of adding waste-wool to soil on crop performance at various locations

Crop	Effect on crop performance	Reference
Swiss chard (*Beta vulgaris*), basil (*Ocimum basilicum*)	The addition of wool-waste to the growth medium increased tissue N	Zheljazkov et al. (2009a)
Ryegrass (*Lolium multiflorum*)	Amendment of wool hydrolysate increased K, Mg and Ca content in the biomass of ryegrass	Nustorova et al. (2006)
	Wool fertilised grass yielded 24 to 82% more DM with elevated level of N (19%), S (19%) and Mg (7%)	Gousterova et al. (2003); McNeil et al. (2007)
Tomato (*Solanum lycopersicum*)	Wool amended plot resulted in 19, 15 and 25% higher content of P, Mg, and Ca, respectively in tomato leaves	Gorecki and Gorecki (2010)
Basil (*Ocimum basilicum*), thorn apple (*Datura innoxia*), peppermint (*Mentha piperita*), garden sage (*Salvia officinalis*) cucumbers (*Cucumis sativus*)	Wool-amended soil yielded 40-142% more yields	Zheljazkov (2005)
	Cucumbers grown in wool containing slabs yielded 19-42% more yields	Bohme et al. (2008)
Foxglove (*Digitalis purpurea*)	Wool additions to soil increased foxglove yields over the next two seasons by 1.7 to 3.5 times	Zheljazkov et al. (2008)
Basil (*Ocimum basilicum*), Swiss chard (*Beta vulgaris*)	Wool amended plots gave basil and Swiss chard yield 1.6-5 times greater than the unamended control	Zheljazkov et al. (2009a)
Eggplant (*Solanum melongena*), tomato (*Solanum lycopersicum*), pepper (*Piper nigrum*)	Wool amended substrate increased number of eggplant fruits by 14%, tomato yield by 29% and pepper yield by 30% and fruit number by 16%	Gorecki and Gorecki (2010)
Barley (*Hordeum vulgare*)	Growth, green fodder and grain yield markedly increased using coarse wool at different depth under soil	Kadam et al. (2014)

In a study of tomato, eggplant and pepper in an unheated greenhouse, Gorecki and Gorecki (2010) observed that substrate amendment with wool contributed to a significant increase in tomato fruit yield. The effects were taller plants, higher fresh weights of plants and more green appearance of leaves. Also, prolonged the vegetation period and delayed ageing. They further reported that addition of clay soil to the basic peat substrate decreased tomato plants fruiting, but enrichment of this substrate with sheep wool increased the yield by 29% as compared to the control substrate. In the case of eggplant, the addition of wool to culture substrate did not increase the yield, but insignificantly increased the number of fruits (by 14%). Pepper responded to wool amendment into substrate and yielded 30% more and fruit number by 16%. Voncina and Mihelic (2013) observed highest soil N and asparagus (*Asparagus officinalis* L.) yield in the first year following incorporation of wool. Further, NO_3-N content in the asparagus crop was low reflecting the good synchrony of N mineralization and consumption of N in wool incorporation.

Kadam et al. (2014) reported that the plant growth of barley crop in terms of plant height, tillers/plant, leaf area and number of leaves/plant was better for the felt wool at soil depth of 30 cm than 15 cm. It might be due to the higher moisture retention by the application of wool. The wool felt had more pronounced effects upon plant growth as compared to other forms of wool. The leaf area of wool felt plot and control plot differed significantly, while plant height and number of leaves/plant were significantly in felt plot over mat plot. This increase might be due to better root growth and higher moisture availability. It was reported that higher root growth, distribution in mid and deep soil improved the uptake of water from deep soil (Kwabiah, 2004; Lalitha et al., 2010). Addition of coarse wool in different forms and at depth in soil resulted in significant ($P<0.05$) improvement of green fodder and grain yield of barley. It could be attributed to consolidated and stable form of wool felt which had provided required moisture for plants during the growth stage. Delayed degradation of wool often has advantage in the second cropping cycle as the follow-up degradation provides significantly more N than the same dose of N from farm yard manure.

E. Other agricultural benefits

Non-woven wool mats are placed around seedlings to inhibit weed growth when the plants are young and then it breakdown and fertilise the soil as the trees grow (Johnson et al., 2003). Wool in non-woven form can be also used as weed-mats (Hempe, 2014). Pollard-Jones (2016) also mentioned that wool mulching helped in keeping the weed competition low for water and nutrients as it acts as barrier for weeds. It serves as a natural repellent (Cincinnati et al., 2012). Hargreaves (2017) reported that wool can be used to repel snails. Composting also removes parasites and pathogens and to some extent degrades potential contaminants (Cogger, 2005).

F. Conclusion

Waste sheep wool is a valuable fertiliser for the plants and has got enormous possibility of organic manure production that ultimately helps in organic animal produce. Both sweat and washed wool (also wool carpets) and its hydrolysates appeared to be valuable and environmental friendly fertilisers. The feasibility of recycling of used carpet / waste wool to the soil as a fertiliser, help to grass growth and thereby help to grow more wool in a closed-loop system, i.e. Grass Wool Carpet Grass. Composting is generally used both as a waste management alternative and a horticultural and agricultural resource. It is a low-energy-input system and the biodegradability properties have potential applications in geo-textile products. To increase the economic, environmental and social sustainability of wool production, composting the waste wool into soil amendments and landscaping can provide producers additional income, and pride to sheep farming communities in the value of all parts of the life cycle.

This literature review has shown that there is limited but significant evidence to show wool-waste, a likely and promising source to provide benefits as a soil amendment, in terms of improving physical characteristics and soil fertility. Nitrogen contents are relatively high and S could be added to soil without lowering pH. Clearly the use of waste wool as a fertiliser is a new concept. Further studies are required to establish the most effective application rates and the dynamics of N release in order to synchronise the complex interaction of its availability and demand by the plants.

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