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The Potential for Hydrolysed Sheep Wool as a Sustainable Source of Fertiliser for Irish Agriculture

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Abstract: Suppressed wool prices in Ireland over the last number of years has led to situations where the cost of shearing animals is greater than the wools' value, leading to net losses per animal for farmers. Populations of sheep in Ireland and nutrient values of wool from literature sources were used to determine the quantity of nutrients that could be produced on an annual basis using hydrolysis techniques. Results of this study suggest that up to 15.8% of the nitrogen required to produce Ireland's cereal crops can be met annually using hydrolysed sheep wool in an economically feasible manner along with considerable amounts of sulphur, zinc, and copper. Most of the cost associated with the process is the purchasing of wool from farmers at an economically favourable level for farmers. Based on the spatial distribution of these animals, the town of Athlone is the most suitable location for a processing facility.

Keywords: sheep; wool; organic fertiliser; soil amendment; sustainable circular economy; hydrolysis

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Citation: Gillespie, G.D.; Dada, O.; McDonnell, K.P. The Potential for Hydrolysed Sheep Wool as a Sustainable Source of Fertiliser for Irish Agriculture. *Sustainability* **2022**, *14*, 365. https://doi.org/10.3390/su14010365

Academic Editor: Theocharis Chatzistathis

Received: 26 November 2021
Accepted: 22 December 2021
Published: 30 December 2021

1. Introduction

The majority of sheep in Ireland have been bred for meat production, with very little emphasis placed on fleece or wool quality. This is evident in a paper by Byrne et al. [1]; when discussing bioeconomic breeding objectives for sheep in Ireland, there was no mention of fleece or wool quality. This trend has continued with a more recent paper by Bohan et al. [2], also making no mention of fleece or wool quality, and instead focussing on lambing and production, and health characteristics. As such, there has been very limited work from an Irish perspective on the amount, type, quality or chemical composition of sheep wool. The global production systems for sheep considerably vary, especially across Europe, due primarily to differences in environmental and climatic conditions, breed types, soil and forage types, animal nutrition, and farm management practices [3–5]. Consequentially, research outputs and information on sheep wool composition from one country, breed or system may not be relevant or applicable in others.

Due to these breeding practices placing an emphasis on meat production and ease of lambing, the value of sheep wool in Ireland has decreased to the point where, based on anecdotal evidence from sheep farmers, the cost of shearing the animals is greater than the economic value of the fleece, with some farmers quoting fleece prices of €0.15 kg^{-1} being achieved while shearing costs were €2.40 head^{-1}. This low economic return for wool has also been seen in countries other than Ireland, with both Corscadden, Biggs [6] and Stiles and Corscadden [7] reporting a similar issue being faced by sheep farmers in Canada. According to the most recently available data from the Central Statistics Office (CSO) [8], the price of sheep wool has fallen steadily since 2015, with the price in 2018 being just 42% of the price in 2015.

With these sustained low prices for wool, alternative uses for this abundant and readily available product have been developed. Alyousef et al. [9] and Dénes, Florea & Manea [10] utilised sheep wool fibres in the production of concrete specimens. Alyousef et al. [9] found that the addition of wool into concrete mixes led to a harsher product with a reduction in workability; however, the tensile strength and flexural strength of samples containing wool increased remarkably compared to plain concrete mixes, with best performances achieved when 2–3% sheep wool was included. Due to the linking actions of sheep wool fibres, better ductility and higher energy absorption was observed in wool-containing samples [9]. Corscadden, Biggs & Stiles [6] found that when sheep wool is used as a sustainable insulation product in the Nova Scotia region of Canada, it has similar thermal properties to other commercially available insulation materials. Parlato and Porto [11] reported that sheep wool has similar thermal insulation properties to more commonly used insulation materials such as glass wool and polystyrene foam. Zach et al. [12] and Parlato and Porto [11] also reported many advantages of sheep wool as an insulating material including hygroscopicity, resistance to fire, and its ability to absorb excess moisture to regulate air relative humidity levels.

Another possible processing option for sheep wool is to hydrolyse it to produce an organic fertiliser/soil amendment. Hydrolysis is a chemical process that can involve the use of acids (e.g., HCl and H_2SO_4), bases (e.g., NaOH and KOH), or enzymes (keratinases) in combination with high temperatures (and associated pressures) to degrade proteins in order to obtain oligo-peptides and amino acids [13–16].

Hydrolysis techniques have been exploited by studies, [14,17,18], to produce fertilisers using sheep wool as a substrate. With the Farm to Fork strategy of the EU's Green Deal aiming to reduce chemical pesticide usage by 50%, fertiliser usage by 20% plus a decrease in nutrient losses by at least 50% [19], the incorporation of hydrolysed sheep wool as a soil amendment and nutrient source may help Ireland to achieve these targets.

The aim of this research is to use data available in the literature to assess the potential amount of fertiliser that would be available to Irish farmers if all sheep wool available was utilised as a feedstock to a hydrolysis process.

2. Materials and Methods

Data for the population of sheep for each county in Ireland were taken from the Department of Agriculture, Food and the Marine (DAFM) sheep census [20], which is carried out annually in December [8]. As part of this census, each registered keeper is legally obliged to return their completed census form each year to the Department of Agriculture Food and the Marine, giving an accurate representation of the sheep population in Ireland each year. The DAFM National Sheep and Goat Census is carried out under EU Regulation 21/2004, which obliges member states to carry out a census of sheep and goats annually. The first census took place in 2005.

As the census is conducted in December, it does not take into account any lambs that have been produced on the farm that year, so we have assumed that any sheep that has been included in the census would provide wool the following summer.

A comprehensive literature review was conducted to determine the yield of wool from sheep along with the elemental composition of wool. These values, along with the average of the values, are presented in Tables 1 and 2. These values were used in combination to determine the amount of soil amendment and crop nutritional products that could be produced on an annual basis in Ireland from sheep wool.

Table 1. DAFM 2019 sheep census data.

County	Region	N Flocks	Average Flock Size	Ewes > 12 Months	Rams	Other Sheep	Total Sheep	% of National Flock
Carlow	South East	689	154	71,492	2139	32,293	105,924	2.78
Cavan	Border	943	82	50,182	1900	25,008	77,090	2.02
Clare	Mid-West	573	46	17,443	775	8342	26,560	0.69
Cork	South West	1684	98	117,530	3454	44,573	165,557	4.35
Donegal	Border	6032	87	354,058	11,603	161,048	526,709	13.83
Dublin	Mid-East and Dublin	201	123	18,150	654	5996	24,800	0.65
Galway	West	4057	103	277,951	9262	131,944	419,157	11.00
Kerry	South West	2457	133	243,025	6617	78,259	327,901	8.61
Kildare	Mid-East and Dublin	652	164	68,771	2172	35,754	106,697	2.80
Kilkenny	South East	464	146	44,997	1394	21,412	67,803	1.78
Laois	Midlands	424	110	28,852	1057	16,786	46,695	1.23
Leitrim	Border	1142	101	82,451	2715	30,406	115,572	3.03
Limerick	Mid-West	219	94	13,079	416	7166	20,661	0.54
Longford	Midlands	421	87	25,106	903	10,539	36,548	0.96
Louth	Mid-East and Dublin	361	158	35,170	1141	20,793	57,104	1.49
Mayo	West	4842	89	310,069	9459	111,942	431,470	11.33
Meath	Mid-East and Dublin	989	154	100,413	3262	48,701	152,376	4.00
Monaghan	Border	503	100	30,093	1178	19,232	50,503	1.33
Offaly	Midlands	559	127	44,544	1370	25,333	71,247	1.87
Roscommon	West	1779	103	122,399	3820	57,221	183,440	4.82
Sligo	Border	1588	88	101,350	3391	35,563	140,304	3.68
Tipperary	Mid-West	880	139	75,764	2283	44,630	122,677	3.22
Waterford	South East	409	159	45,559	1244	18,052	64,855	1.70
Westmeath	Midlands	737	114	55,108	2200	26,704	84,012	2.21
Wexford	South East	1035	146	85,001	2827	63,578	151,406	3.97
Wicklow	Mid-East and Dublin	1298	179	152,313	4819	75,168	232,300	6.10
Total	-	34,938	119	2570,870	82,055	1156,443	3809,368	100

Table 2. Literature values for the yield of wool (kg) per sheep.

Author	References	Minimum Yield	Maximum Yield
DeBarbieri	[21]	3.8	5.1
Mounter	[22]	3.5	6.2
Zoccola	[23]	1.5	3
Parlato	[11]	1.5	-
Corscadden	[6]	2.3	3.6
Robards	[24]	2	5
Connolly	[25]	-	5.8
www.iwto.org [1]	-	-	4.5
Alyousef	[9]	2.3	3.6

[1] Access Date: 9 June 2021.

3. Results and Discussion

Data from the 2019 sheep census are presented in Table 1 and show that there were 3.81 million sheep present in Ireland at the end of 2019. The national flock comprised 34,938 flocks, with an average flock size of 119 sheep. Flock sizes varied from 46 sheep per flock in Co. Clare to 179 sheep per flock in Co. Wicklow, with Co. Donegal having the largest number of flocks in a county with 6032 registered flock keepers. Figure 1a shows that, according to the DAFM sheep censuses conducted since 2005, the number of sheep in Ireland declined significantly between 2005 and 2008 from approximately 4 million to 3.1 million, a 22.5% reduction in sheep numbers before recovering to today's population of 3.81 million. The average sheep population in Ireland between 2005 and 2019 was 3.56 million head (with a standard deviation of 305,400). These animals are not evenly distributed across the country as can be seen in both Figures 1b and 2a, with approximately 45% of the 2019 sheep population in just 4 counties—Donegal (13.83% of the total population), Mayo (11.33%), Galway (11%), and Kerry (8.61%), all of which are located on the west coast of the country. Figure 2b shows that the area of land that was designated for cereal and/or crop production, according to Basic Payment Scheme (BPS) data, was located primarily in the east and south of the country. The use of hydrolysed wool as a soil amendment would allow tillage farmers in the east and south of the country to import nutrients from, according to the Teagasc farm income survey [26], lower-income sheep enterprises in the west of the country. If these sheep were grazed on mountainous areas of the west of the country, it would allow for the economic return of the wool to be even greater as there would be very little inputs into the grazing system.

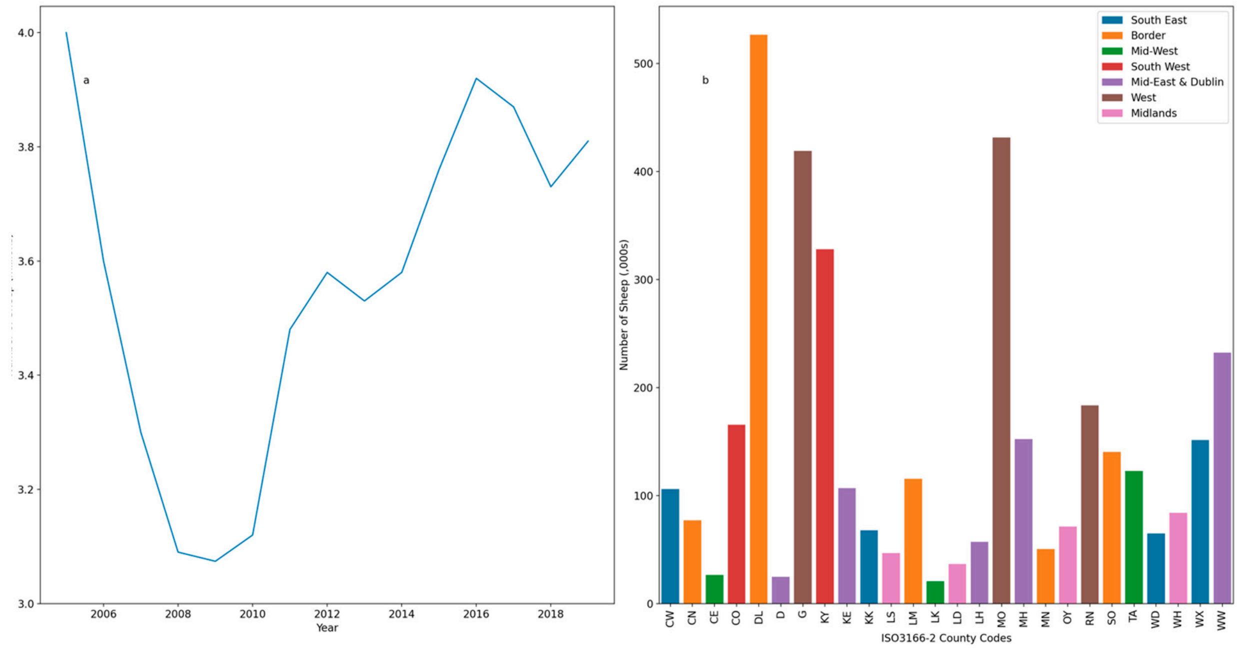

Figure 1. (**a**) Irish sheep population between 2005 and 2019; (**b**) number of sheep per county in 2019.

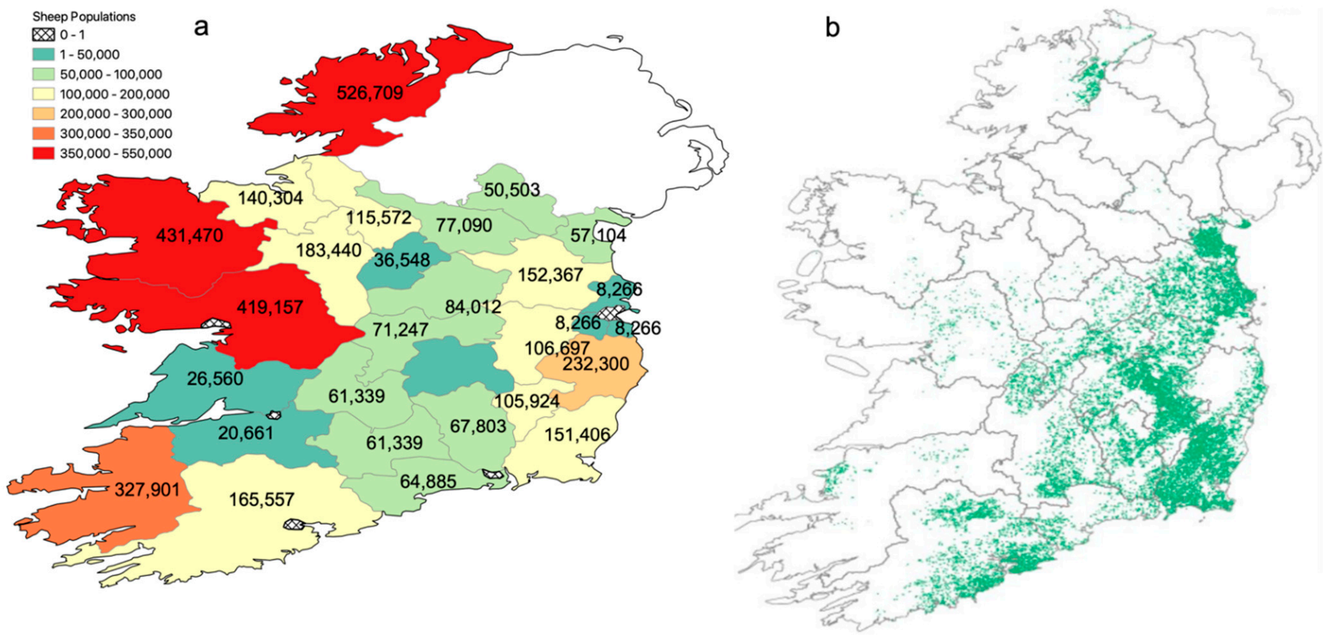

Figure 2. Map of (**a**) the 2019 number of sheep per county, and (**b**) land cultivated with cereal crops (wheat, barley and oats) in 2020 (source: DAFM BPS cropped area).

3.1. Amendment Quantity

The results presented in Table 2 show that the amount of wool that can be obtained per animal ranges between 1.5 and 6.2 kg of wool per sheep. Using an average value of 3.58 kg of wool per sheep and the sheep population of 3.81 million from the DAFM sheep census, 13,637,537 kg of wool is available on an annual basis in Ireland. This value ranges from

5,714,052 to 23,618,082 kg when the 1.5 and 6.2 kg values, respectively, are used. Table 3 presents the elemental composition of sheep wool based on literature studies. These data show that sheep wool, being primarily keratin, is a source of nitrogen, with up to 0.25 kg of N kg sheep wool^{-1} available [11] and an average of approximately 0.131 kg N kg wool^{-1} (Table 3). Using the sheep population of 3.81 million and the average values for the yield and N content of wool, 1,788,790 kg of nitrogen could be produced in Ireland on an annual basis, with up to 5,904,520 kg available when the maximum N content of wool (Table 3) and the maximum yield of wool (Table 2) are used (assuming a 100% recovery rate of the elements). A popular fertiliser, particularly for grassland, is calcium ammonium nitrate (CAN), with a nitrogen content of 27%. Using the maximum values for the yield and nitrogen content of wool, there is potential for hydrolysed sheep wool products to replace up to 21,868,594 kg of the fossil-based CAN fertiliser. Table 4 illustrates the cultivated areas and suggested nitrogen application rates for each of the main cereal crops produced in Ireland. Using these values and the average amount of nitrogen that can be recovered from sheep wool (1,788,790 kg), the nitrogen requirements for the entirety of either the winter or spring oats or the spring wheat areas can be met. Using the average value of nitrogen recovered from sheep wool, 4.78% of the entire cereal crop demand in Ireland can be met; this value rises to 15.78% when the maximum recovered nitrogen amount is utilised. The elemental values for the content of sulphur in sheep wool can be even higher than nitrogen with a maximum value of 0.32 kg S kg wool^{-1} (Table 3), with the average S content of wool from the values presented in this paper being 0.078 kg S kg wool^{-1}. The high S and N contents of wool are mainly due to strong disulphide bonds of amino acids making the wool water-insoluble and resistant to different chemical agents [27]. This would suggest that 1,065,676 kg of S can be produced on average in Ireland annually with potential for up to 7,557,786 kg S to be produced. N and S constitute the largest portion of sheep wool on an elemental basis with other nutrients, in descending order, including calcium (Ca), potassium (K), zinc (Zn), phosphorus (P), iron (Fe) and copper (Cu) (Table 3). Figure 3 shows the amount of these elements that would be available on an annual basis in Ireland using the mean values for wool yield and the elemental composition (Figure 3a) and the maximum values for the wool yield and elemental composition (Figure 3b). It can be seen that the two largest products that can be obtained are Ca and K, depending on whether the mean or the maximum values are used. Using the highest literature value for the K content of sheep wool and the current sheep population of 3.81 million 77,940 kg of K can be produced annually. The next largest element that can be recovered is Zn, with an average of 4451 kg available. In cereal crops, Zn is required for protein synthesis, sugar formation and optimal photosynthesis levels [28,29]. Rehman, Farooq [29] reported that that wheat yields in Turkey increased by 32% when Zn-deficient soils were amended with adequate Zn fertilisation. Roques, Kendall [28] report that barley crops (grain only) remove 0.03 kg t^{-1}. This suggests that, using the mean values for wool yield (Table 2) and Zn content of wool (Table 3), hydrolysing wool and utilising the product as a soil amendment would provide enough Zn to meet the offtake needs of 5.3 million ha of barley with an average yield of 10 t ha^{-1}. The central statistics office [8] report that barley is the crop with the largest cultivated area in Ireland, with an average of approximately 182,000 ha of Barley year^{-1} cultivated between 2017 and 2019. Zn from wool hydrolysate significantly outweighs the annual barley requirements in Ireland. Therefore, Ireland could either use the soil amendment for grassland production or it could export the product to crop-producing regions deficient in Zn. Wool hydrolysate could also produce approximately 87,280 kg of Cu annually. As barley has a Cu offtake of 0.009 kg t^{-1} [28], the crop requirements of 9.7 million ha of barley could be met through the application of wool hydrolysate soil amendments. Cu is an important parameter for the production of viable pollen for grain production, CO_2 assimilation, and ATP production [28,30].

Table 3. Literature values for the elemental composition of sheep wool (all values presented in mg kg^{-1}).

Source	References	Nitrogen	Sulphur	Phosphorus	Potassium	Calcium	Zinc	Iron	Copper
Parlato	[11]	250,000	30,000	-	-	-	-	-	-
Holkar	[14]	165,000	35,000	-	-	-	-	-	-
Gogos	[17]	21,000	86,000	-	310	400	44	4.8	-
Gogos	[17]	38,000	320,000	-	710	670	63	5.8	-
Zoccola	[23]	165,000	35,000	-	-	-	-	-	-
Grace	[31]	-	-	-	-	-	80	-	-
Grace	[31]	-	-	-	-	-	300	-	-
Wyrostek	[32]	-	-	-	-	-	86	-	-
Wyrostek	[32]	-	-	-	-	-	98	-	-
Ragaisiene	[33]	148,000	10,000	-	-	-	-	-	-
Sahoo	[34]	-	31,000	120	3300	323	114	42	3
Hawkins	[35]	-	-	-	-	-	670	-	5
Hawkins	[35]	-	-	-	-	-	2200	-	9
Scott	[36]	-	-	-	-	-	195	-	-
Patkowska-Sokola	[37]	-	-	148	643	1790	74	22	5
Patkowska-Sokola	[37]	-	-	284	755	2900	89	510	10
Minimum		21,000	10,000	120	310	323	44	4.8	3
Average		131,167	78,143	184	1144	1217	334	117	6.5
Maximum		250,000	320,000	284	3300	2900	2200	510	10
SD [a]		86,615	109,135	88	1218	1110	613	220	3
N		6	7	3	5	5	12	5	5

[a] SD, standard deviation.

Table 4. Areas and nitrogen requirements of the main cereal crops cultivated in Ireland [a].

Crop	Area (ha)	N_a (kg ha^{-1}) [b]	N_{req} (t)	% Replaced
Winter Wheat	35,000	190	6650	26.9
Winter Barley	51,500	166	8549	20.9
Winter Oats	8300	146	1212	147.3
Spring Wheat	11,500	130	1495	119.7
Spring Barley	141,700	125	17,713	10.1
Spring Oats	17,200	105	1806	99.1
Total	265,200	-	37,424	4.78

[a] Source for the cropped area of each crop type is www.cso.ie (Access date; 12 August 2021, while the nitrogen application rates are from Dillion et al. (2018). [b] N_a, nitrogen application rates used on Irish cereal crops; N_{req}, amount of nitrogen, expressed in terms of tonnes, required to cover the entire area cultivated in Ireland.

3.2. Location of Processing Site

As the sheep are not evenly distributed across the country, the centroid point and the sheep population of each county were used to determine an appropriate weighted location for a processing facility to handle and hydrolyse the wool. Figure 4 shows that based on the sheep populations the processing site would be located in an area to the west of the town of Athlone on the Roscommon/Westmeath border (coordinates; 53.43, −8.01). This location is well serviced by motorways and national roads such as the M6, N61, N55 and N62 allowing for easy movement of the wool from farms to the processing location and then on to end users after processing. If the produced soil amendment is to be used on tillage land for crop production purposes, the location of Athlone town allows for wool to move in a south westerly direction from the sheep dense counties of Donegal, Mayo and Galway to more arable based counties such as Wexford, Kilkenny and Carlow (Figure 2b). The town of Athlone is well connected to these regions, allowing for rapid transport of the processed material to crop-producing regions of the southeast.

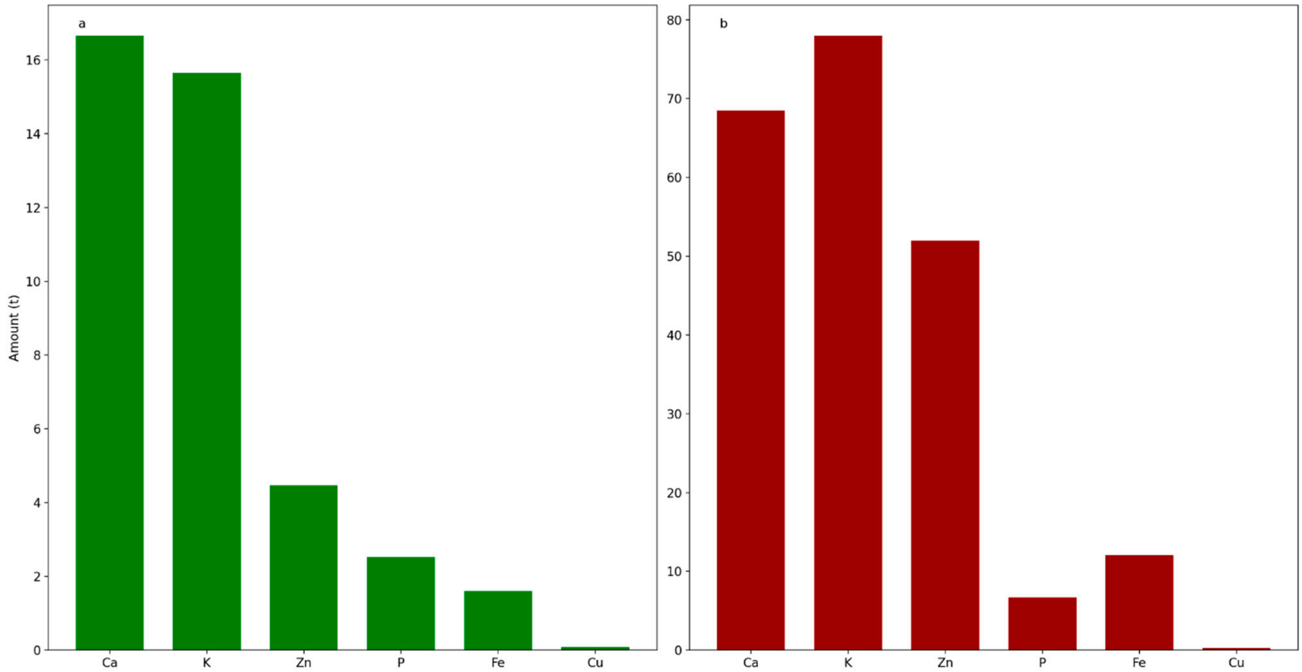

Figure 3. Amounts of elements available on an annual basis in Ireland using the (**a**) mean values for both the wool yield and the elemental composition and (**b**) the maximum values for both the wool yield and elemental composition. Please note the different scales used between (**a**,**b**).

3.3. Economic Analysis

There is very limited published work available of the economic costs associated with hydrolysis of non-lignocellulosic by-products. Following a review of the literature, the economic returns associated with hydrolysis of sheep wool could not be found. Solcova et al. [38] conducted an economic evaluation of using malic acid (a weak organic carboxylic acid) as a green hydrolysis method for the processing of waste chicken feathers in the Czech Republic. In this study, Solcova et al. [38] used an 8000 L reactor to process 340 kg of feathers per batch. The total time to process a batch including the time required for the handling of the feathers and process material was 24 h. For this paper, the costs of hydrolysis reported by the Solcova et al. [38] study (Table 5) were used to estimate the economic return from processing sheep wool in Ireland. If the feedstock, in this case sheep wool, can be achieved with zero associated costs, then the cost of processing a batch (340 kg) is €116.7. As there is a cost is associated with the fleece, the largest portion of the costs of processing are associated with the purchasing of these fleeces. The ranges for feedstock costs displayed in Table 5 refer to the number of fleeces that would be required to fill the 340 kg reactor based on the fleece weight (cf. Table 2). As such, it will take a larger number of lighter fleeces to fill the reactor resulting in a higher cost if the price is paid on a per fleece basis, with up to €680 required to purchase 227 of the 1.5 kg fleeces to fill the reactor at a price of €3 fleece^{-1}. Figure 5 illustrates both the costs associated with purchasing and processing of the fleeces that would be produced annually in Ireland and the sales value of the nutrients that can be recovered from these fleeces. The costs of processing ranges from €1.9 million to €19.54 million depending on the fleece weight and the price paid to farmers for the feedstock material. The price point in Figure 5 refers to the fleece price paid in relation to the costs and refers to the value of the nutrients in relation to the sales (Table 6). For the nutrients, the market value of each nutrient was calculated, this value was then increased by 50% and 100% (price point 2 and 3 in Table 6, respectively) to refer to the increased value associated with the product being an organic and sustainable nutrient source. The dashed lines in Figure 5 refer to the costs associated with processing the average fleece weight and the average nutrient contents of the wool for the sales value. Given that the sales associated with the nutrients recovered from sheep wool can surpass the costs associated with the processing of the feedstock depending on the nutrient values and fleece prices, there is an argument that hydrolysis of sheep wool for use as a soil amendment or nutrient source could be an economically feasible alternative to fossil-based fertilisers. The results of this work suggest that the cost of production for 1 kg of N from hydrolysed sheep wool ranges between €2.60 kg^{-1} N and €17.89 kg^{-1} N (Table 5) depending on the costs associated with the purchasing of the feedstocks. For context, several local fertiliser suppliers (Republic of Ireland) are quoting CAN prices in the region of €600 t^{-1} (€2.22 kg^{-1} N) and urea around €900 t^{-1} (€1.96 kg^{-1} N) due to increased natural gas prices, making hydrolysed sheep wool a viable alternative to fossil-based fertilisers. The economic feasibility of utilising sheep wool as a sustainable fertiliser source is further improved if the costs associated with the processing can be reduced through both economies of scale and optimisation of the process. Argo and Keshwani [39] found that using a fed-batch process to convert cellulosic biomass to ethanol in a 2000 tonne dry biomass day^{-1} facility reduced facility costs by 41% and capital costs by 15% compared to a batch process for a facility of the same size. Argo and Keshwani [39] also found that increasing the fed-batch plant capacity from 2000 tonne day^{-1} to 2500 t day^{-1} decreased the cost of ethanol production from \$2.35 $gallon^{-1}$ to \$2.29 $gallon^{-1}$. Other cost-saving technologies such as the use of solar panels on the roof facility can reduce electricity costs and recycling of heat to preheat the feedstock can reduce the natural gas costs. Excess heat produced during the process could also be sold to surrounding residential or industrial buildings to further increase the feasibility of the facility.

Table 5. Overview of material and energy costs to process a 340 kg batch [a].

Input	Amount	Cost	Cost	Cost	Cost
Fleece Price	-	0	1	2	3
Feedstock Costs [b]	340	0	55–227	109–453	164–680
Natural Gas	0.71 (MWh)	27.7	27.7	27.7	27.7
Water	2.5 (m^3)	4	4	4	4
Electricity	100 (kWh)	8	8	8	8
Malic Acid	18 (kg)	75	75	75	75
Other Costs	-	2	2	2	2
Total Costs [b]	-	116.7	172–343	226–570	281–796

[a] Data taken from Solcova et al. (2021). [b] Cost ranges (all presented in €) account for the minimum and maximum fleece weights. cf. Table 2.

Table 6. Market values of nutrients obtained from hydrolysed sheep wool (€ kg^{-1}) [a].

Nutrient	Price Point 1	Price Point 2	Price Point 3
N	1	1.5	2
S	0.4	0.6	0.8
P	2	3	4
K	0.83	1.25	1.7
Ca	0.5	0.75	1
Zn	2.5	3.4	5.1
Fe	0.17	0.25	0.34
Cu	7.7	11.5	15.4

[a] Nutrient value based on a combination of information from Teagasc, market values, and fertiliser product prices from local suppliers.

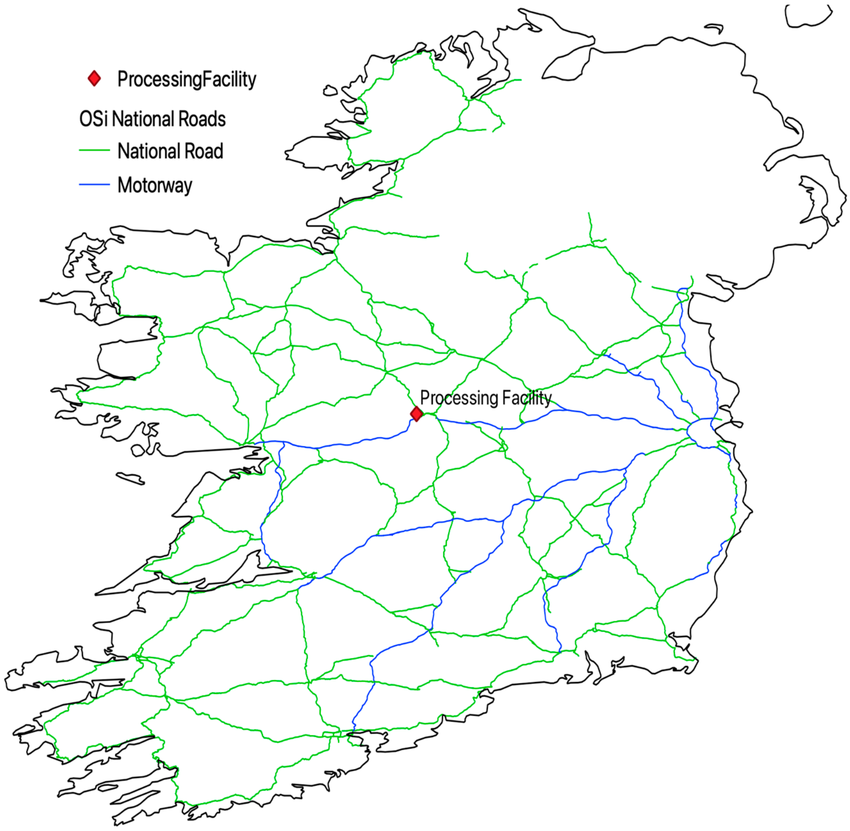

Figure 4. Location of a processing facility based on the centroid point and sheep populations of each county.

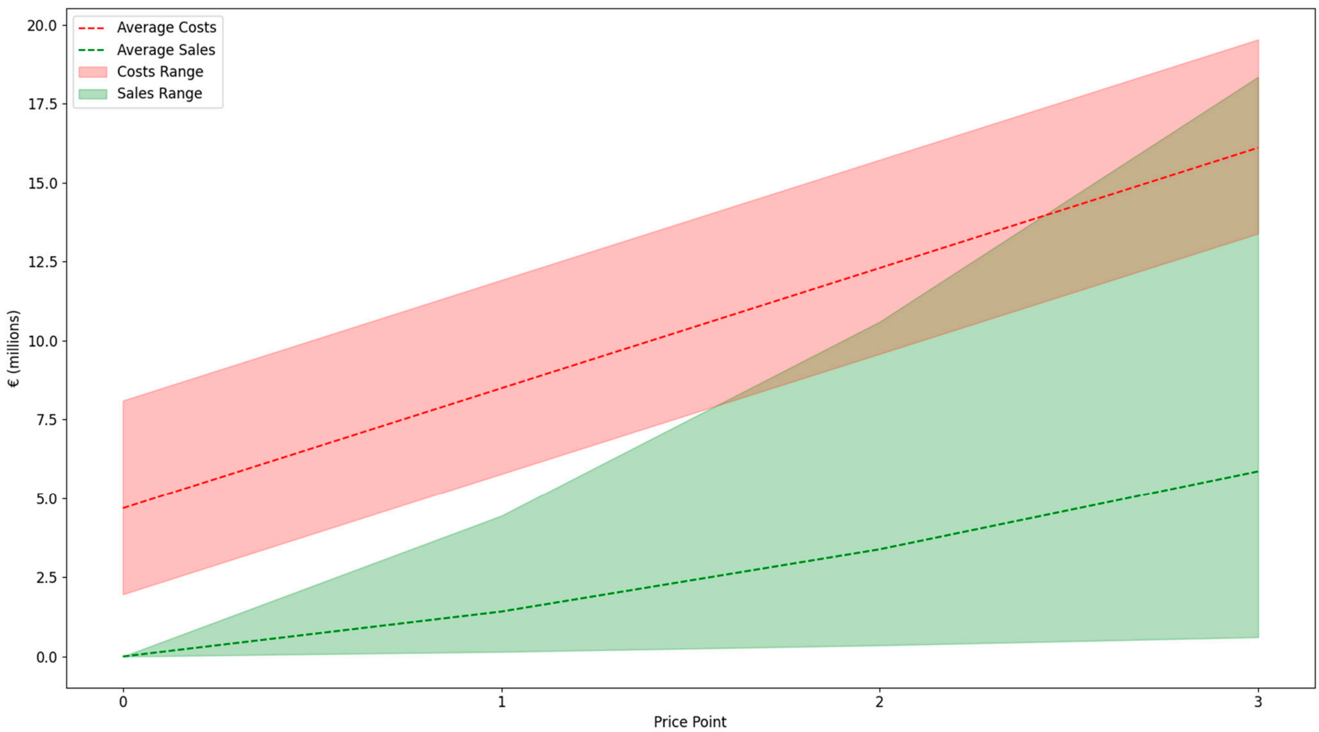

Figure 5. Economic values associated with the costs of purchasing and processing of sheep wool (red) and sales of nutrients recovered from hydrolysed wool (green).

3.4. Future Work

Due to the emphasis being put on meat production and lambing characteristics of the Irish national flock [1,2], future research into this area would require a more detailed assessment of the yield and quality of wool fleeces that are available in Ireland. The results of the current work are for a primary study and as such there are limitations to the research. As such, a comprehensive review of the quality of wool that is available on a regional basis with variations in flock management practices needs to be undertaken. As was mentioned by McLaren, McHugh [3], environmental, breed and management variations can have an effect on sheep product production. The concentration of macro- and micro-nutrients is likely to change due to differences in soil type and forage compositions across states and regions, and therefore, the quantity and composition of wool from upland and lowland breeds in a more detailed regional approach should be looked at. Another aspect that would need to be considered is the effect of soil type and underlying rock type on the chemical composition of the wool produced. For example, does wool produced by upland sheep in the granite dominated Wicklow mountains have a markedly different chemical composition to lowland sheep in the limestone (karst) dominated Burren region of the west of Ireland. Baroni et al. [40] used canonical correlation analysis to demonstrate a significant correlation between the chemical-isotopic profile of beef meat and soil type for sites in Argentina ($r^2 = 0.93$), and therefore it is likely that the composition of sheep wool is likely to also be correlated with soil type and this correlation should be addressed in future research. By assessing this compositional variation in wool, the location of the processing facility that was determined (Figure 4) may change if an emphasis is placed on a particular element, for example zinc (Zn). This paper also only looked at wool produced in the Republic of Ireland, if sheep wool from Northern Ireland or poultry feathers (another keratin source) were to be included the location of the processing facility (Figure 4) would likely be located further to the north as a large proportion of the poultry farms in Ireland are located to the north of the country. Research on the hydrolysis process for poultry feathers would need to be undertaken to ensure it is compatible with a primarily sheep wool based facility. Ashraf and Schmidt [41] found that the combined processing (using enzymatic hydrolysis) of green and woody biomass was more economically feasible than separate processing when using Bermuda grass, Jasmine hedges and date palm fronds as feedstocks. An assessment should be made to determine if the combined processing of sheep wool with other keratin sources, such as waste chicken feathers, leads to a similar synergy compared to processing of the feedstocks separately. In the current research heavy metal contents of sheep wool was not considered, future analysis of sheep wool should also assess the levels of heavy metals present in wool fibres to avoid contamination of soils following prolonged usage. However, the results of heavy metal contents in Ireland are likely to be lower than the results found by Patkowska-Sokola et al. [37] due to the absence in Ireland of heavy industries that are present in Germany and Poland, the regions that that paper focussed on. This paper focusses on wool shorn from sheep, it did not consider fleeces resulting from the butchery of lambs for meat consumption. The amount and composition of soil amendment that may be obtained from the hydrolysis of these products would need to be assessed separately as the chemical composition is likely to be different due to the age and diet of the animals.

The current study conducts a preliminary economic assessment of the feasibility of processing sheep wool to produce soil amendments using data available from literature sources, and further work needs to be conducted to determine the most rapid, sustainable, and economically feasible method of processing the feedstock (e.g., chemical, thermo-chemical or enzymatic). Abdallah et al. [42] found that using scoured sheep wool as a soil amendment increased the total porosity of a sandy loam soil by 16.45%, while reducing the bulk density of the same soil by 11.98%. The soil amendment resulting from hydrolysis also needs to be fully assessed in terms of nutrient availability, the effect on soil flora and fauna, and soil physical characteristics across a range of soil types and conditions before we can fully recommend the use of hydrolysed sheep wool as a fertiliser source.

4. Conclusions

Commercially, the cost of shearing animals is greater than the value of the fleece, hence this paper looked at alternative uses for sheep wool. Hydrolysis is a potential processing technology for value addition to sheep wool by producing nutrients and soil amendments. This study found that utilising hydrolysis could potentially produce 1,788,790 kg of nitrogen, 1,065,676 kg of sulphur, 236 kg of copper, and 51,960 kg zinc annually, which could replace fossil-based fertilisers. Results indicate that hydrolysis of sheep wool could aid with the development of a circular bioeconomy in Ireland. Future work should assess spatiotemporal variabilities of nutrient contents and yields of wool.

Author Contributions: Conceptualisation, G.D.G. and O.D.; methodology, G.D.G.; formal analysis, G.D.G.; investigation, G.D.G.; writing—original draft preparation, G.D.G. and O.D.; writing—review and editing, K.P.M.; visualisation, G.D.G.; supervision, K.P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data for the Annual Sheep and Goat Census can be found at the following link: https://www.gov.ie/en/search/?q=sheep+census (Access date: 31 October 2021). All other data required to complete the calculations used in this paper can be found in the presented tables and figures.

Conflicts of Interest: The authors declare no conflict of interest.

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