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A Life Cycle Assessment to Evaluate the Environmental Benefits of Applying the Circular Economy Model to the Fertiliser Sector

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Abstract: In recent years, the world has witnessed one of the most severe raw material crises ever recorded, with serious repercussions for maintaining its agri-food supply chain. This crisis risks dramatically impacting the poorest areas of the planet and poses profound reflections on global food security. In this complex geopolitical context, the recovery and recycling of renewable resources have become an obligatory path and, today, more than ever, essential in the fertiliser industry. To achieve these objectives, TIMAC AGRO Italia S.p.A. has undertaken a research activity to review the formulation of fertilisers by diversifying the raw materials used and introducing recycled raw materials. This article carried out a life cycle assessment (LCA) on four fertilisers to identify and quantify whether the changes influenced the environmental impacts, highlighting how applying the circular economy within industrial processes can reduce the pressure on natural resources. The results demonstrate that the global warming potential (GWP) impacts of the different reformulated fertilisers show a considerable variation of 4.4–9.2% due to the various raw materials used, the nitrogen content, and related emissions deriving from environmental dispersion. This study shows the importance of the LCA methodology to analyse and quantify the impact categories generated on the life cycle of fertiliser production and to identify the optimal by-products and end-of-waste for the fertiliser industry to find a synergy between environmental and agronomic performance. It also highlights the relevance of the transition to circular production and consumption systems to reduce environmental pressures and their effects on communities and ecosystems without compromising yields. Finally, the positive results encourage accelerating the circular transition and finding alternatives to virgin-mined raw materials.

Keywords: global warming potential (GWP); life cycle assessment (LCA); fertiliser; circular economy; secondary raw materials

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1. Introduction

Climate change has been the biggest challenge impacting agriculture in the last seven decades due to the greater frequency of extreme events, changing precipitation patterns, and increasing temperatures [1,2]. The observed direct effects are on food security due to increasing crop variability, limiting crop productivity [3,4], and its interlinkage with land degradation and desertification.

Yet, more recently, agriculture has faced several other challenges that have tested the resilience of global food production and security [5,6]. On the one hand, the lack of adaptation strategies and their effective implementations when they exist [7] and the unsustainable management practises threaten the natural capital of soils [8,9]. In particular, in prone areas like the Mediterranean region, various physical (sealing, compaction, erosion), chemical (reduction of soil organic matter, contamination, salinisation, acidification), and biological criticalities related to the decrease in biodiversity threaten the health of agricultural soils [10]. On the other hand, the old continent is witnessing one of the most severe raw material crises, bringing our agri-food chain to its knees [11], with a dramatic impact on the poorest areas of the planet, which poses serious reflections on global food security [12].

In this complex context, which makes prices unstable and supply reliability uncertain, circular economy initiatives linked to recovering minerals and secondary metals linked to different matrices and reducing mined mineral fertilisers nowadays have significant economic, social, and environmental interests [13,14]. The circular economy, first described by kneese [15] and Pearce and Turner [16], is a model that turns all forms of waste into the economic cycle as inputs to minimise dependence on natural resources, reduce waste and emissions, and decouple economic growth from environmental impacts [17–19]. More recently, the European Commission promoted this concept in agriculture under the action plans and strategies of the EU Green Deal, especially the "Farm to Fork" strategy, which aims to reduce nutrient losses by at least 50% and the use of fertilisers by at least 20% by 2030 [20], for sustainable transformation of agriculture [21].

Although this deal has created a favourable context for accelerating the economic transition towards sustainable production systems, the main challenge in agriculture will be to find the right balance between feeding a constantly growing global population and preserving natural resources and the interactions they generate in the biosphere without slowing down economic development [22,23]. Therefore, the role played by raw materials will become increasingly important in maintaining global food security [11], and innovation will become even more critical to finding effective and efficient solutions not to compromise agricultural outputs [24].

The newly published Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 introduces significant changes on the European market in the manufacturing, trade, and compatibility assessment of mineral fertilisers [25]. Indeed, the introduction of seven Product Function Categories (PFCs) and eleven Component Material Categories (CMCs) promotes an increased use of recycled nutrients, contributes further to the development of the circular economy, and allows for a more resource-efficient overall use of nutrients while at the same time reducing the European Union's dependence on nutrients from third countries.

In this context, the knowledge of the environmental effects caused by a fertiliser on its life cycle and their quantification with possible alternatives is essential for decision-making and defining business strategies aimed at continuously improving environmental performance through the mitigation of products on the environment and new designs of new products and processes [26,27].

For the quantification purpose, the Life Cycle Assessment (LCA) methodology—a cradle-to-grave analysis technique—is a potent instrument to capture; estimate; and quantify all the relevant environmental impacts of systems, services, or products at each stage to cover the entire life cycle [28,29]. This thorough inventory of cumulative environmental impacts, through the four distinct but interconnected phases (Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation), helps improve the overall performance of the system, service, or product.

In the beginning, the LCA method was used to compare and provide rigorous information on the environmental performances of a product and compare it to alternatives, and with time, the applications expanded to include the planning and policy of processes and services [30], covering a wide range of sectors [31,32] including agriculture and agro-food [33,34], industrial activities, tourism, services, healthcare, etc. More recently, different LCA methodologies have been applied to quantify environmental burdens in circular economy strategies and practises [35]. According to the authors, the LCA allows the quantification of circular economy alternatives' environmental benefits to verify alleged claims regardless of the limitations that could emerge.

The literature has indeed intensively applied LCA methods to assess the environmental benefits of circularity in the built environment, also known as the construction industry and components [36,37]. However, there is no evidence of its application to evaluate the fertiliser sector's circularity.

Therefore, this research is the first attempt to implement the LCA method according to the ISO 14040-44:2006 [38,39] standard to analyse, compare, and evaluate the evolution of the formulations of fertiliser products and the environmental performances following the circular economy model's application and by-products' integration to replace some of the raw materials used for their production. This assessment allows estimating the potential benefit of greenhouse gas (GHG) emissions change after the industrial transition is carried out, helps evaluate the overall environmental performance, and supports product development and the implementation of improvement strategies. Finally, the results present the first evidence of LCA's potential to assess fertiliser sector circularity and fill a big research gap towards the sustainable transition of this strategic sector.

2. Materials and Methods

This study adopted the Life Cycle Assessment (LCA) method according to the ISO 14040-44:2006 standard [38,39], given its proven importance in implementing the life cycle thinking approach for agriculture and agri-food and facilitating a quantitative assessment of human health, emissions, and resource use [40]. The LCA also has some applications for evaluating circular economy impacts [41] and agricultural input assessment [42–44]. The product system processes were modelled within SimaPro LCA software (version 9.5).

2.1. Case Study

TIMAC AGRO Italia S.p.A., a subsidiary of the French group Roullier, has been operating on Italian territory for over thirty years. Born in 1991 in Milan, the company began its commercial activity in Italy by selling fertilisers produced by Roullier Group plants outside Italy. After three years, the company expanded its presence in the national territory. This rapid expansion within the Italian market incentivised the group to increase its investments in Italy for its significant agricultural and agri-food know-how, the considerable number of customers, and the diversification of distribution channels, characterised by private traders, cooperatives, and farming consortia.

Indeed, in 1998, TIMAC AGRO Italia acquired the production plant in Ripalta Arpina (CR), in the Lombardy region (Figure 1a), situated in the heart of the South Adda River protected area, and in 2001, that of Barletta (Figure 1b). The aim was to start production on-site, thus strengthening its strategic positioning in the Italian market.

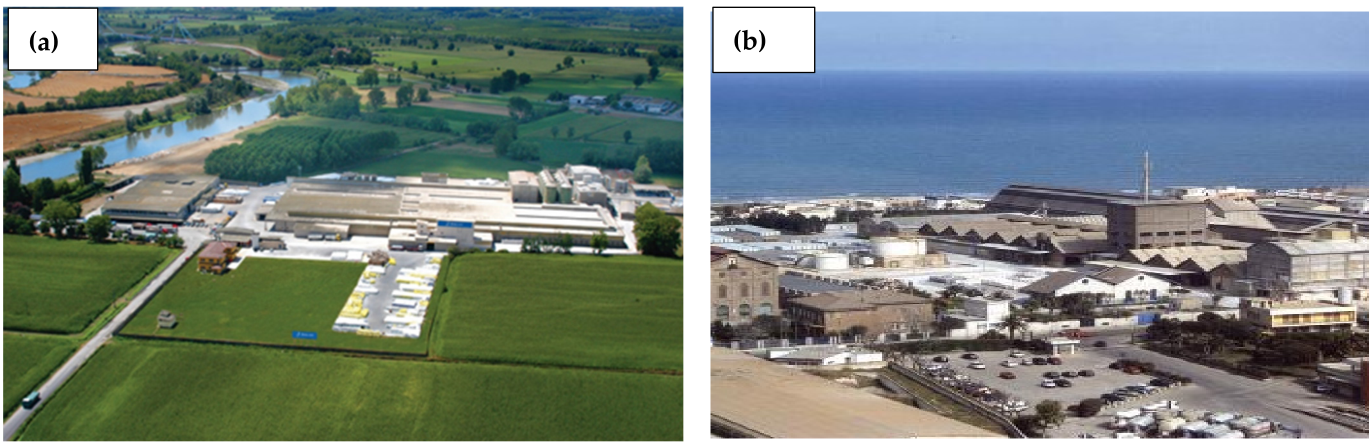

Figure 1. (**a**) Aerial picture of the production site in Ripalta Arpina (to the left); (**b**) Aerial picture of the production site in Barletta (to the right).

2.2. Goal and Scope Definition

This section describes the product system regarding boundaries and the functional unit. This study's primary goal is to evaluate the environmental load of producing granular mineral and organo-mineral fertiliser (Figure 2) at the production site of TIMAC AGRO Italia S.p.A., located in Ripalta Arpina (Cremona, Italy), and compare and evaluate the evolution of fertiliser formulations adopted following the optimisation made within the path of the circular economy model and integrating secondary raw materials from other industrial processes. The assessed products are listed in Table 1, which shows the change in formulation between the old and updated formulae.

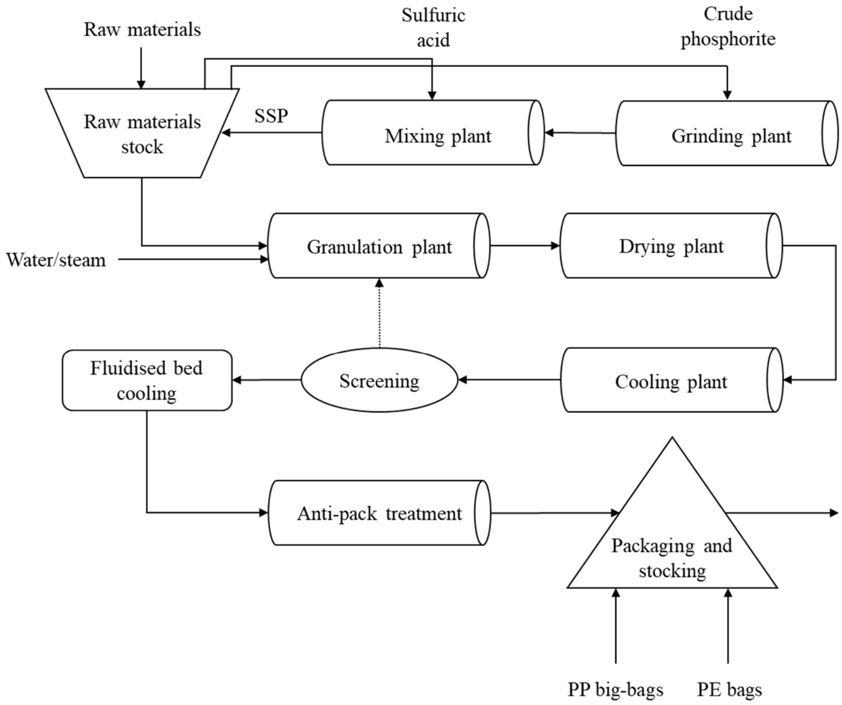

Figure 2. The production process of granular fertilisers at TIMAC AGRO Italia S.p.A.

Table 1. The assessed products include the old and updated formulations.

Product	Old Formulation (N-P-K)	New Formulation (N-P-K)
TIMATECH	5-7-16	5-6-12
EUROCOD	18-5-8	16-5-6
PRIME	8-18-0	6-16-0
MAGNIFIQUE	14-7-12	13-7-10

The Polluter Pays Principle (PPP) has been applied, and the production processes for secondary raw materials have been modelled accordingly, so that processes of waste processing are assigned to the product system that generates the waste until the end-of-waste state is reached.

The system boundaries are specified by the Product Category Rules of the International EPD® system [45] for a complete cradle-to-grave LCA, including the upstream, core, and downstream processes (Figure 3).

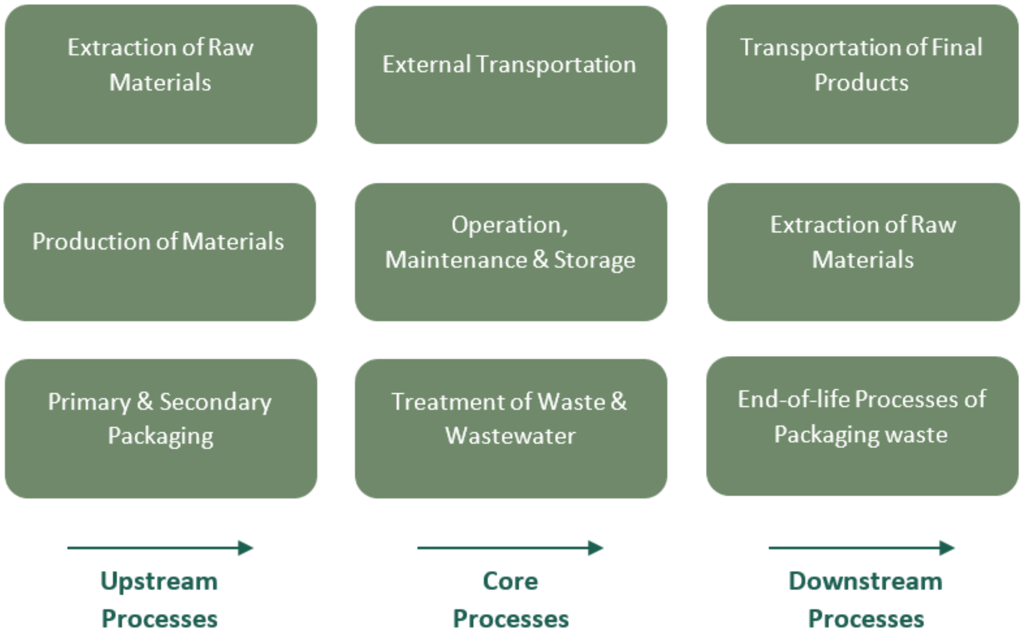

Figure 3. The system boundaries of the production system extend from cradle to grave.

Following PCR 2010:20, Version 3.01, we did not consider the packaging of raw materials or the production of bags. Further, we divided the system into sub-processes and collected the data for each sub-process where possible. Where this was not possible, we based the allocation between different products and co-products on physical relationships, i.e., the mass (t) of the products, unless otherwise stated. Finally, we did not include data contributing to the life cycle inventory of less than 1% of the total product flows (mass and energy).

The declared unit equals 1 tonne of fertiliser (packaging included).

The impact categories used are as follows:

- Global warming potential (GWP);
- Acidification potential (AP);
- Eutrophication potential (EP);
- Ecotoxicity (ET);
- Land use (LU);
- Water deprivation potential (WS);
- Resource use, fossils (RU);

The LCA results are potential impacts and cannot predict impacts on endpoint categories, exceeding thresholds, safety margins, or risk.

2.3. Inventory

This section, considered the most time- and work-consuming step of an LCA study, determines the quality of the LCA study. It consists of data collection and compilation in a Life Cycle Inventory (LCI). It identifies all the inputs and outputs throughout the life cycle of the product system defined in the previous section [46].

The data inventory saw the collection of primary plant data relating to 2018, particularly industrial formulations for the identification of raw materials, energy consumption, water consumption, waste, packaging, and transport (specific data). All data were modelled with specific processes derived from Ecoinvent database v3.8 [47], guaranteeing high data quality in terms of geographical, time, and technological representativeness. Specific methodologies were then applied to assess additional data related to the Agronomic efficiency and Uptake Index, as proposed by the Product Category Rules of the International

EPD® system (PCR 2010:20 v.3.01, "Mineral or Chemical Fertilisers") [45] to estimate the efficiency of fertilisers.

As the actual formulas are protected by industrial secrecy, fertiliser names are generically listed and described according to their NPK (nitrogen-phosphorous-potassium) content in Table 1.

Within the old formulations, the nitrogen content was mainly derived from urea coming from North Africa and transported by ship. On the other hand, new formulations foresee the use of secondary ammonium sulphate produced in Lombardy, starting from sulfuric dioxide, generated as a by-product of the plastic industry.

The use of by-products indeed aligns with the requirements of circular economy principles but also allows for an impact reduction in the production of such raw materials. Nevertheless, the expected benefits are to be tested at the level of fertiliser production. To perform so, raw materials were modelled in line with the different formulations, whereas energy inputs and auxiliary materials in the granulation step were kept the same.

The Ripalta Arpina plant produces and packages simple phosphatic mineral fertilisers, NPK compound mineral fertilisers and NPK organo-mineral fertilisers. The manufacture of the products takes place through three sub-plants:

- Superphosphate production plant (semi-finished product);
- Nitrogen melting plant (semi-finished product);
- Granulation plant.

The superphosphate (SSP) production plant is composed of a sulfuric acid storage and mixing plant, a crude phosphorite grinding plant, and a dilute acid and ground phosphorite mixing plant, at the service of which a wet washing plant is installed for the abatement of the vapours generated by the exothermic reaction.

Two dry systems with bag filtration are technically connected to the granulation plant.

The production data for 2018 is shown in Table 2.

Table 2. Production at the Ripalta Arpina plant (annual value for 2018).

Fertiliser Type	Produced Quantities [tonne]
NPK fertilisers	124.252
Superphosphate	57.947
Nitrogenous super calcium	2.269

Aside from the needed pre-treatment steps for the production of the aforementioned semi-finished products, the steps of the granulation plant are described as follows.

When they arrive at the company, the solid raw materials for fertiliser production are stored primarily in bulk in areas suitable for subsequent use. In contrast, the phosphorites are kept in silos. The liquid substances are stored in special silos and containers for subsequent use in production plants. The solid raw materials are recovered from the heap using a mechanical shovel and placed in the dosing hoppers. Then, they are dosed, transported by belts, and fed into a granulation cylinder.

In the granulator, with the dosed addition of water/steam in the right quantities, an optimal aggregation of the raw materials and a constant granulometric structure of production are obtained. At the exit of the granulator, the product is unloaded and, via conveyor belts, sent to the drying section, where the granule formation and consolidation process continues. The drying phase of the product takes place under the suction of a centrifugal fan and at pre-set temperatures, employing a co-current heat exchanger with hot air derived from direct fumes from a cogeneration plant's exhaust. At the exit of the dryer, the product is sent via a belt to a cooling section.

The cooling/stabilisation phase of the product takes place under the suction of a centrifugal fan through a counter-current exchange of cold air (at ambient temperature). At the discharge of the cooler, through a belt and a bucket elevator, the product is sent to two screens, which separate the fertiliser into the fractions of:

- Big product;
- Fine product;
- Good product (with the right granulation).

The fine product is recycled directly by returning to the granulation cylinder, while the big one is re-introduced after grinding into a breaking mill. The product, respecting the quality standards of granulation size, undergoes further cooling and an anti-packing treatment in a special cylinder before being sent to the warehouse.

The granular finished products can follow two paths according to the packaging and selling size required. The entire loading, screening, weighing, and bagging system is kept under suction while the screened part is conveyed inside a specially sealed chamber.

Finally, the products are sent inside a filming plant (self-tightening hood) and deposited by forklift for storage in the yard or directly on a truck.

The collected data are all reported in Tables 3–5. In addition, the plant is supplied with 124,149 litres of diesel used for internal transportation.

Table 3. Primary and secondary packaging supply and consumption (annual value for 2018).

Packaging Type	Material	Quantity (kg)	Distance from Suppliers to Plant (km)
Big Bag	PP	36,113	2113
Big Bag	PP	16,477	666
Big Bag	PP	95,500	566.5
PPH bags	LDPE	97,839	55.7
PPH bags	LDPE	71,417	55.7
Silage film	LDPE	38,216.6	55.7
Coverstretch	PVC	28,145	1362
Pallet	Wood	249,546	150

Table 4. Consumption of natural gas (annual value for 2018).

Heating System	$Stdm^3$	kWh (Thermal)
Boiler 1	2,050,185	20,076,436.61
Boiler 2	57,969	567,661.43
Boiler 3	30,066	294,421.31
Boiler 4	23,652	231,612.21
Cogeneration system	1,664,113	6,909,430.46

Table 5. Electric energy generation and consumption (annual value for 2018).

Electric Energy	kWh
Purchased from the grid	1,884,519
Sold to the grid	165,852
Net production from cogeneration	6,022,893

The water consumption—derived from wells—consists of 8529 m^3 for superphosphate production and 22,526 m^3 for the overall production of NPK fertiliser. Despite the consumption, no water discharge is present as the water is completely evaporated. Air emissions of pollutant substances—derived from gas combustion and dispersive process emissions—are reported in Table 6. Not being monitored along with pollutants, CO_2 emissions are evaluated according to database values for gas burning.

Table 6. Air emissions (annual value for 2018).

Emission	Quantity [tonne]
SO_2	2092
NOx	37.46
Particulates	3824
VOC	12.23
CO	0.042

Waste transport and treatment are also considered (Table 7).

Table 7. Waste production and treatment (annual value for 2018).

Category	EoL Treatment	Quantity [kg]
Non-hazardous waste	Disposal	104,747
	Recycling	307,810
Hazardous waste	Disposal	5775
	Recycling	-

Concerning the remaining downstream processes:

- A distribution distance of 200 km by lorry (Euro 4, 16–32 t) has been considered for the final product;
- An overall recycling rate of 44.5%, an energy recovery rate of 43%, and a disposal rate of 12.5% have been applied for the end-of-life scenario of the primary packaging [48].

For the emissions deriving from nitrogen application, it is important to clarify that fertilisation efficiency is crucial to reducing the environmental impacts of agriculture. In crop production, efficiency is defined as the "quantity of useful dry substance (commercial production) received from each nutrient unit that is given or from each nutrient unit that is assimilated" [49] and determined by the elements' bio-availability, their dynamics in the plant/soil/water ecosystem, and their use efficiency [50]. The literature describes different indicators to evaluate the efficiency and bioavailability of nutrients; we adopt the Uptake Index (UI) and the Agronomic Efficiency Index (AEI) as follows [51]:

$$\mathrm{UI(x)} = \frac{\text{Nutrient (x) uptaken in the fertilised option (kg/ha)} - \text{Nutrient (x) uptaken in the unfertilised option (kg/ha)}}{\text{Nutrient Unit (kg/ha)}} \times 100 \quad (1)$$

$$\mathrm{AEI} = \frac{\mathrm{Yield}_{\mathrm{Fertilised}} - \mathrm{Yield}_{\mathrm{Unfertilised}}}{\mathrm{nFU}} \quad (2)$$

where:

UI = Uptake Index
x = Nutrient Element
AEI = Agronomic Efficiency Index
UI = Uptake Index
nFU = Applied Fertilisation Unit of (x)

Uptake Index

The amount of nitrogen released into the environment for the use phase was calculated considering the Uptake Index (UI) average value of different field trials [52]. For this purpose, we assume that a fraction of phosphorus and potassium released into the environment remains immobilised in the soil. Therefore, they will not be considered released into water or air.

In accordance with the reference PCR (PCR 2010:20 v.3.01 "Mineral or Chemical Fertilisers"), in the case of fertilisation with 100 nitrogen units, 68% of the quantity is immobilised in the soil, the plant absorbs 27%, and 5% is dispersed. The unstable value is 27%, which is replaced with the UI characteristic of the products [52]. The quantities of immobilised and dispersed nitrogen were kept in a 68:5 ratio to calculate the quantity dispersed in the environment. The latter was divided in relation to the different molecular weights in emissions: in the air as NH_3, NO, N_2O and in water in the form of $N_{organic}$, NH_3, NH_4^+, NO_3^-. The total nitrogen released into the environment is shown in Table 8.

Table 8. The total nitrogen dispersed into the environment from each formula.

Product		N Content (kg/tonne)	UI (%N) §	N Dispersed (%)	N Dispersed (kg)
TIMATECH	Old Formula	50	47.8	3.5	1.8
	New Formula	50			1.8
EUROCOD	Old Formula	180			6.3
	New Formula	160			5.6
PRIME	Old Formula	80			2.8
	New Formula	60			2.1
MAGNIFIQUE	Old Formula	140			4.9
	New Formula	130			4.6

§ The percentage uptake is the average uptake index calculated from different field trials.

3. Results

The Life Cycle Impact Assessment (LCIA) quantifies and calculates the environmental impacts arising from inputs and outputs identified at the inventory stage (Section 2.2) of the Life Cycle Assessment (LCA) study [53]. During the LCA, raw emissions, waste, and material production data are collected, allocated to specific impact categories, and then quantified with appropriate characterisation models for interpretation.

The results from implementing the LCIA on the investigated products are divided by impact category and summarised in Table 9 and Figure 4.

Table 9. The results of the LCIA are divided by impact categories and by formulation.

Product		Impact Category						
		GWP	AP	EP	ET	Land Use	WS	RU
		kg CO_2eq	kg SO_2eq	kg SO_2eq	CTUe	Pt	m^3 eq	MJ
TIMATECH	Old formulation	1816.26	12.12	1.75	68,915.25	6196.77	1052.28	47,162.50
	New formulation	1649.28	11.52	1.69	68,287.47	6073.04	883.06	45,662.88
EUROCOD	Old formulation	2107.99	10.39	2.93	66,528.08	3086.22	326.45	30,341.27
	New formulation	2001.42	10.74	2.77	70,965.22	3741.31	361.94	33,859.51
PRIME	Old formulation	1922.71	18.18	2.11	79,286.04	10,887.72	654.26	76,184.50
	New formulation	1783.62	17.97	1.99	87,871.94	11,115.99	678.85	77,172.94
MAGNIFIQUE	Old formulation	1871.52	11.06	2.40	56,230.34	4481.99	355.22	37,976.37
	New formulation	1789.11	10.71	2.33	60,701.46	4379.02	364.45	36,961.32

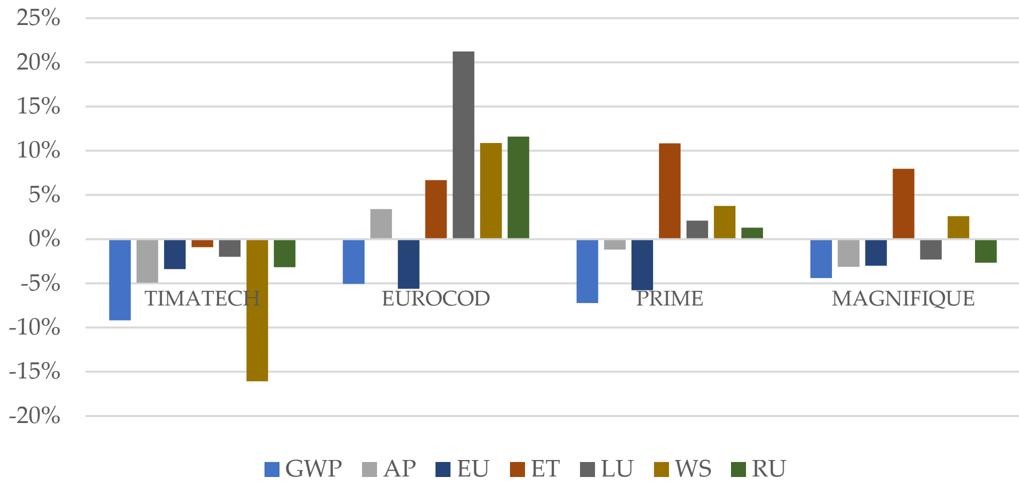

Figure 4. Impact variation from old to new formulas.

The results of all impact categories for all fertiliser products show considerable variation. In particular, the new formulations' GWP presented a varying but relevant improvement in environmental performance between 4.4% and 9.2%:

In the case of EUROCOD, an impact reduction on GWP of 5.1%;

In the case of PRIME, an impact reduction on GWP of 7.2%;

In the case of MAGNIFIQUE, an impact reduction on GWP of 4.4%;

In the case of TIMATECH, an impact reduction on GWP of 9.2%.

The interpretation and analysis of the results show that the GWP variation (Figure 5) is mainly due to the different raw materials used (upstream processes) and, above all, to the variation in nitrogen content and related emissions deriving from environmental dispersion (downstream processes). The core processes do not show significant differences between the fertilisers under examination, thanks to the management of heat and electricity already sufficiently optimised by the cogeneration units, which does not offer particularly sustainable alternatives for the industrial plant in question, limiting the possibilities for improvement to only electricity purchased from the grid. A similar variation is given for EP, as the emission of nitrogen compounds into water is similarly reduced in the use phase.

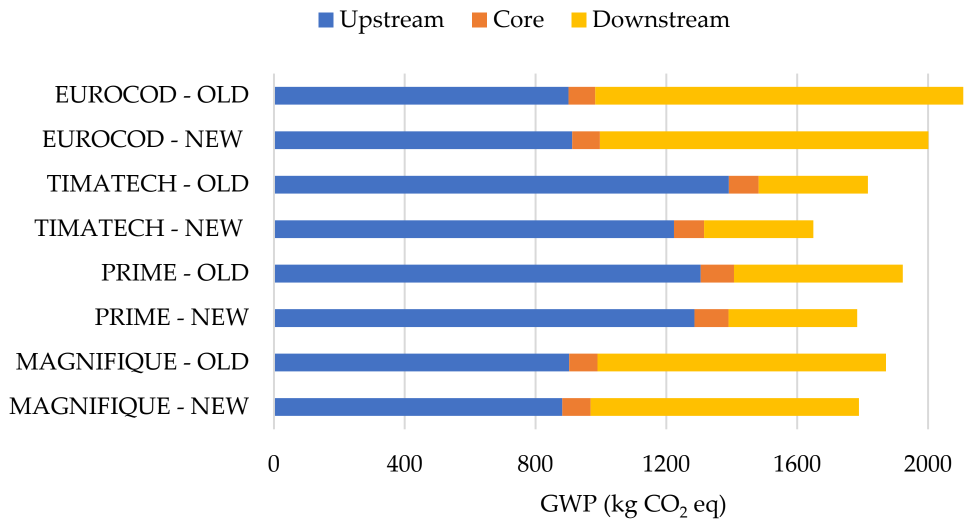

Figure 5. The GWP impacts of different fertiliser products at each process step.

Indeed, the discriminant within the upstream processes is the origin and variation of the raw materials used for the new formulations' production, which improved environmental impact by up to 12%, according to the formulation (Figure 6a). Within the downstream processes, the discriminant is the variation in nitrogen content and related emissions deriving from environmental dispersion. According to the formulation, environmental impact decreased by up to 24% (Figure 6b).

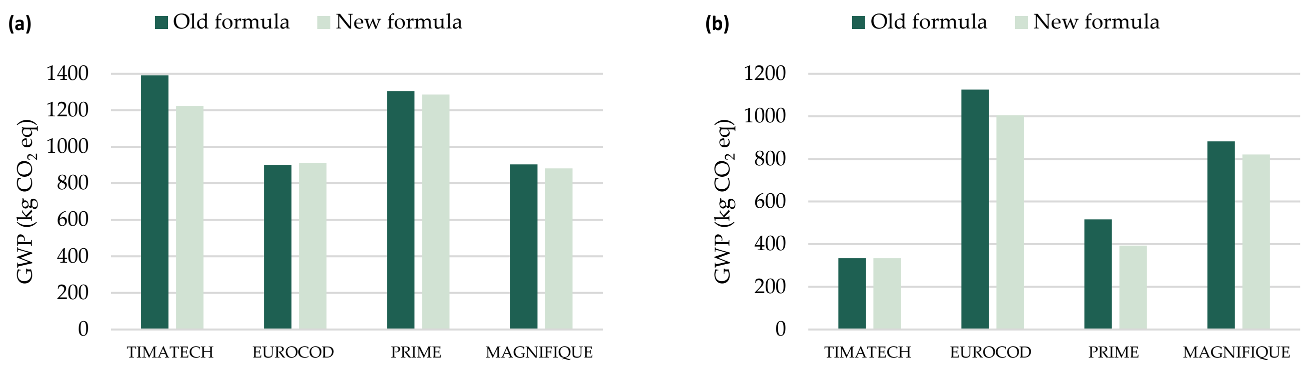

Figure 6. (**a**) GWP contribution for each product at the upstream processes (to the left); (**b**) GWP contribution for each product at the downstream processes (to the right).

The upstream impact reduction on the global GWP is due to the greater circular use of ammonium sulphate, produced locally from sulfuric dioxide, as a by-product of the plastic industry. Above all, this reduction is due to changing the geographical position of production and the consequent transport of urea—virgin raw material purchased from Egypt—and ammonium sulphate—produced as a by-product in Milan (Italy)—to the TIMAC AGRO Italia plant in Ripalta Arpina (Cremona province in Lombardy, northern Italy). Figure 7 highlights how the different origins and production of the raw materials change the GWP impacts in the upstream processes.

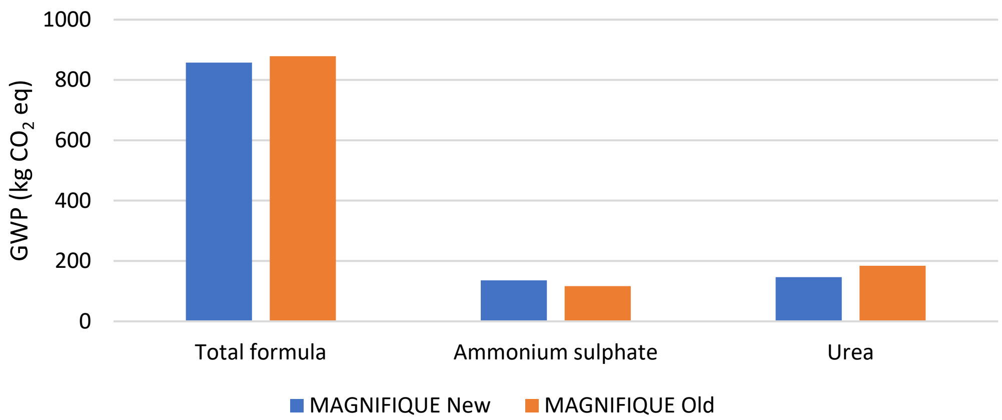

Figure 7. The GWP impacts are due to raw materials' production and origin.

From another side, within the downstream processes, which include the use, end-of-life packaging, and distribution phases, it is evident that the real discriminant in quantifying the total impacts derives from the fertilisers' use phase (uptake index).

In fact, the improvement in environmental performance of the new formulations is due to reduced nitrogen content. No improvement was obtained for TIMATECH, as there was no change in the formulation of the nitrogenous element. The effects of the variation in the uptake index are proportional to the nitrogen content and are quantified as follows:

- In the case of EUROCOD, there was an impact reduction on GWP in the fertiliser use phase of 11.0%;
- In the case of PRIME, there was an impact reduction on GWP in the fertiliser use phase of 25.2%;

- In the case of MAGNIFIQUE, there was an impact reduction on GWP in the fertiliser use phase of 7.2%.

4. Discussion

The LCA methodology has been applied in the fertiliser sector to compare different fertiliser types and their environmental burdens on the life cycle [43]. Yet, there is no evidence in the literature of its use to assess the impacts of circular economy models in the sector. This study is the first attempt to fill this scientific and technical gap in the fertiliser sector. The results confirm the importance of the LCA method in enhancing the transparency of implementing the circular economy and its comprehensiveness for the fertiliser industry. They will also accelerate the sustainability transition of the sector and the adoption of a more circular model of production. This is in line with the results achieved by Lei et al. [36] on the built environment.

However, previous studies that analysed LCA methods applied to the circular economy, particularly in the built environment, mentioned limitations to address that hamper their application. Specifically, the weaknesses could be related to [35,36]:

- The consistency of functional units and system boundaries
- The accessibility and quality of life cycle inventory data;
- The reliability of impact allocation methods.

Such limitations do not strictly apply to the case study presented. Indeed, the functional unit, system boundaries, and characterisation methods were set following the guidelines of well-recognised documents [45]. Moreover, the LCI can rely on an optimised data collection system within the company.

Limitations can arise from the methodology applied in evaluating air and water emissions in the use phase, as only N-compounds are assessed. Due to varying formulas, the lack of assessment for P-components may limit the overall analysis of potential burden-shifting in some impact categories—such as eutrophication.

Still, such a limitation does not apply to most analysed categories, such as GWP.

Finally, the results show that a careful and coherent application of LCA methods, considering the limitations specific to each sector, is fundamental for developing, adopting, and implementing circular economy models in economic sectors.

5. Conclusions

This research implemented the LCA method according to the ISO 14040-44:2006 standard to analyse and compare the evolution of the formulations of fertiliser products produced by TIMAC AGRO Italia S.p.A. and evaluate the environmental performances following the circular economy model's application and by-products' integration to replace some of the raw materials. This study is in line with the corporate commitments to optimise resources and reduce waste undertaken to reach the goals of the 2030 Agenda.

This study showed the importance of the LCA methodology to analyse and quantify the impact categories generated on the life cycle of fertiliser production in a circular economy model. This helps identify the processes and the phases within each process that present the most significant contribution to environmental impacts and, consequently, plan corrective strategies and actions. For instance, guaranteeing a high degree of environmental and agronomic performance for the finished product is essential, highlighting the possibility of a compromise or synergy between the two.

The LCA outcomes demonstrated the greatest contribution to the environmental impact categories derived from the procurement of raw materials (transport) and emissions generated from nitrogen dispersed in the environment during the use phase of fertilisers. The results confirm that pursuing circular schemes can lead to lower consumption of natural resources and lower environmental impacts. However, the circular economy still marginalises the demand for resources linked to industrial production for some products.

Finally, this study represents a cornerstone for TIMAC AGRO Italia S.p.A., which will assist in identifying the optimal by-products and end-of-waste for the fertilisers' industry available on the local market, which can find the required synergy between environmental and agronomic performance. Based on the positive outcomes, it recommends accelerating the circular transition and finding alternatives to virgin-mined raw materials.

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