Carbon footprint of fertilizer technologies

K. Chojnacka[1,*], Z. Kowalski[2], J. Kulczycka[2], A. Dmytryk[1], H. Górecki, B. Ligas[1],
M. Gramza[3]

[1]Department of Advanced Material Technologies, Faculty of Chemistry, Wrocław University of Science and Technology, Wrocław, Smoluchowskiego 25, 50-372, Poland
[2]The Mineral and Energy Economy Research Institute of the Polish Academy of Sciences, Cracow, Wybickiego 7, 31-261, Poland
[3]Grupa Azoty Zakłady Azotowe Kędzierzyn S.A., Kędzierzyn-Koźle, Mostowa 30 A, 47-220, Poland
[*]Corresponding author: e-mail katarzyna.chojnacka@pwr.edu.pl, tel. +48 71 320 43 25,
fax +48 71 320 34 69

Abstract

Purpose: The methodology for life cycle assessment (LCA) of carbon footprint in fertilizer technology was elaborated while considering greenhouse gases (GHG) assimilation during vegetation of fertilizer-treated plants.

Methods: LCA analysis included the comparison between two crop cultivation systems – with and without the fertilizer use. 1 Mg of plant biomass produced was proposed as a functional unit. Both GHG emission and CO_2 absorption were determined using CO_2 equivalents per unit mass of nitrogen applied with the fertilizer. For the former, best available technology data for fertilizer production and agrotechnical treatments were selected as input values, yet primarily balance sheet data concerning individual fertilizer technology would be required. CO_2 assimilation by plants will be assessed according to the current agricultural knowledge.

Results: Proposed LCA methodology is considered for comprehensively evaluation of the actual environmental effect of both production and use of fertilizers. It was estimated that fertilizing at 170 kg N/ha would result in the plant yield about 8 Mg/ha followed by absorption of 75 kg CO_2 equivalent per each N kg applied.

Conclusion: LCA along with the analysis of life cycle costs would provide more reliable determination of the amount of fee charged on fertilizer manufacturers. Also, the verification of similar fertilizer technologies in different installations is expected to identify of bottlenecks in terms of the ecological, technical and economic evaluation.

Keywords: LCA analysis, CO_2 emission, European Union Allowances, crop cultivation, photosynthesis

1. Introduction

In the current European economy, when considering the production profitability, the essential roles play various environmental fees. The integrated environmental permit includes the agreed limits on CO_2 emissions, together with purchasing emission allowances (European Union Allowances) for the price regulated by the stock market.

Based on European Commission report, "the overall amount of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions (...) associated with a product along its supply-chain, use and end-of-life recovery and disposal" is designated under the name *carbon profile* or *carbon footprint* (CF) [1]. Carbon footprint – originally conceived by Rees [2] as the concept of ecological footprint – is currently a critical environmental indicator [3, 4], one of the environmental footprints [5], regulated by

ISO 14067. Besides CO_2, CF involved methane (CH_4), nitrous oxide (N_2O) and fluorinated gases [6]. As the Intergovernmental Panel on Climate Change (IPCC) has established, quantitative determination of CF is referred to global warming potential (GWP) – the key indicator showing the effect of "the potential relative climate change per kg of a greenhouse gas over a fixed time period" [7]. In other words, CF quantifies an individual contribution to global warming from industrial and human activities, expressed in CO_2 equivalents [8].

Although the determination of carbon footprint generally reveals the impact of the product – meaning both good and services [9], on the environment, GHG emissions affect oceanic and atmospheric systems – hence, an indirect influence on human health might also be indicated [10]. There are various methodologies to estimate CF [11], yet, the life cycle assessment (LCA) is the most common approach [12] as it enables reliable evaluation of burdens and improvements corresponded to various environmental matters [13, 14]. In addition, the LCA analysis is often required for environmental certificates – especially those issued in Western European countries.

Two international standards – ISO 14040 [9] and 14044 [15], specify LCA itself. Since the life cycle is defined as "the consecutive and interlinked stages of a product system, from raw material acquisition, or generation from natural resources, to final disposal" [9], the primary stage of performance testing by LCA involves detailed statement of material and energy consumption. The execution of such research enables to reduce not only the negative environmental impact, but also measurable financial savings – e.g. by identifying, and then improving, the least efficient operational stages. The method of LCA works based on quantitative data, interpretation of which – particularly in relation to the environmental effect, is quite complex, and thus it should be complemented with the analysis and elaboration of inputs-outputs from the production process. The approach justifies the inclusion of the enhancement in plant growth – hence carbon dioxide metabolism *via* photosynthesis (CO_2 assimilation), by the fertilizer application the overall CO_2 balance.

The current enterprises pay significant fees for the CO_2 released from fertilizer production – which are expected to increase during the coming decades. As a results, the profitability of European production of fertilizers would be questionable because of hampered prices. At the same time, limitation of agricultural treatments would indirectly reduce CO_2 assimilation when lowering crop yield, and thus adversely affecting the environmental level of carbon dioxide. Since GHG emission strongly corresponds to overpopulation and overconsumption [16], the actual balance of CO_2 in the environment is a very important issue of modern fertilizer industry.

In the current work, a new approach of life cycle assessment to determine the carbon footprint in production of fertilizers with the consideration of their further involvement plants vegetation is presented. The paper discusses the main assumptions of CO_2 balance in the fertilizer industry – taking into account the removal of CO_2 from the environment by plants in the process of photosynthesis.

2. Greenhouse gases emission and carbon footprint in fertilizer production

2.1. The intensive crop production

The population growth is strongly correlated with agricultural technology, including fertilizing [17]. Nitrogen (N) was the major limiting nutrient in cropping systems until, in the 1950s, the development of the Haber-Bosch process started the large-scale production of synthetic fertilizers [18-20]. For the last 40 years, the use of synthetic N-containing fertilizers (N fertilizers) increased 4 times [21] providing a nitrogen consumption of 10.5 Mt – 3.9-4.4 fold higher than K_2O and P_2O_5, respectively, in 27 EU member countries [20]. Agrotechnical treatments with N fertilizers provide food for 48% of the global population [22]. Based on current estimations, there will be further 50-80% increase in agricultural demand by 2050 [23, 24].

At the same time, agronomic and economic optimum of nitrogen application rates has already been exceeded [25, 26]. Among severe environmental effects, involvement of N fertilizers as major contributors to GHG emission in crop production [27, 28] is of particular interest since it impairs the principles of sustainable development [21]. The discussion about climate change directs an attention to enhance crop production while decreasing CO_2 released from agricultural activity [28, 29].

2.2. The environmental and economic indicators for intensive crop production

In addition to the fertilizer use increase, since 1970 – a high confidence in anthropogenic CO_2 emission has begun which finally, in 2010, led to double the result from previous 220-year long period [30]. Considering food production chain, the total GHG emission corresponds to the combustion of fossil fuels and industrial process [8]. According to IPCC, aapproximately 78% of total GHG increase observed in the atmosphere during high confidence, has been induced by CO_2 emission from these two sources. Beside energy production and electricity, agricultural system is considered as one of the main anthropogenic emission source as along with forestry and other land use sector releasing about 30% GHG [1, 30, 31].

The contribution of the synthetic fertilizer use to the total GHG emission differs depending on the area, and is about 2% for 15 EU member countries [31] while 7% for China itself [21]. In each year beginning from 1970, anthropogenic GHG emissions have included approximately 25% of non-CO_2 gases [30], among which nitrous oxide (N_2O) is of great interest because of its specific GWP – 298-fold higher as compared to CO_2. Also, agricultural activity releases above 60% of anthropogenic N_2O releases [32], mainly during microbial nitrification and denitrification of fertilizer residues inefficiently recovered by crops [33].

Improvement in management of nitrogen rates in cropping requires to take into account both environmental and economic indicators such as the product carbon footprint (PCF) and the gross margin (GM), respectively [34]. Such approach shows significantly positive influence on the PCF, while its effect on GM is only marginal. Yet, the yield loss by 10% would affect PCF slightly, having a strong detrimental impact on farmers income. The bottleneck of reliable management implementation is then dissemination of advanced strategies for sustainability maintenance which will limit neither yield nor the profitability of the crop production [35]. A number of agricultural systems have been verified to mitigate GHG emission [36-39], the technologies need to be developed to meet the efficacy requirements, though.

3. Carbon footprint assessment in fertilizer production and application

The quantification in LCA of GHG emission in a production chain is performed according to different guidelines – GHG Protocols [40-42], depending on whether product (when one of the products is evaluated throughout its life cycle) or corporate level is considered [43]. The former is related to ISO 14067 [6], while the latter involves ISO 14064 [44]. Furthermore, there three scopes related to corporate carbon footprint (CCF): “1) direct emissions, 2) indirect emissions from electricity production and other services, and 3) indirect emissions upstream and/or downstream on the production chain” [41-43]. In the literature, PCF is reported rather than CCF [43]. Typically, CFP studies take into account only one period of one single crop since agriculture systems are complicated [45]. Not all material flows can be quantified [12].

LCA is the most suitable tool to assess emissions related to the production and use of fertilizers. The production of nitrogen fertilizers requires fossil fuels that are also required in the application during various farming operations. CFP focuses on agricultural processes, and thus – to simplify, it might be limited to “cradle to farm gate” rather than “cradle to grave”, meaning that the system boundaries are set at the farm gate and end with crop harvest, but including by-products e.g. organic manure [46]. Considering agricultural processes, some of their key parameters are still underexamined as depending on local and climate conditions [47]. Thus, the methods of reliable CFP quantification is still developed.

4. The new concept of carbon footprint assessment in fertilizers production with the consideration of plant vegetation

The first phase of LCA analysis is to define its purpose and scope. Essential is development of a methodology for the ecological life cycle assessment of the production and use of fertilizers with particular emphasis on emissions and absorption of greenhouse gases (especially CO_2) based on detailed model assessments for the production and use of nitrogen fertilizers. In the first phase of the LCA analysis, the production system and its boundaries should be defined. The functional unit would be 1 Mg of produced biomass of cultivated plants as the result of fertilizer application (as compared to non-fertilized field). The analysis should be a comparison of systems:

1) without the use of fertilizers – it is assumed to carry out a full life cycle inventory (LCI) in the plant-growing phase, especially the amount of CO_2 absorbed by the plants for the crop and crop area should be determined;
2) with the use of fertilizers – it is assumed to carry out a full LCI for the life cycle of these products, ranging from input streams of materials and energy to fertilizer production to product output and cultivated plant biomass.

This would to compare the individual ecological indicators (including, for example, GHG emissions), the production and use of fertilizers with organic indicators of plant biomass production without fertilizing.

The production, transportation and use of fertilizers cause, for example, the emission of GHG – carbon dioxide and nitrous oxide, in particular. At the same time fertilizing increases the productivity of plant production and stimulates the increase of CO_2 absorption by plants. This causes that it would be possible to avoid the need to expand the crop area which affects the avoidance of GHG emissions due to increased crop use.

The production of fertilizers requires energy, the main source of which is natural gas. For each fertilizer product, cumulative energy consumption will be calculated, which will then be converted to kg CO_2-eqv, respectively. Best available techniques (BAT) data for fertilizer production may be used for the calculation of individual indicators, but primarily balance sheet data for individual fertilizer production unit should be prepared. Fertilizers are transported to the user by various means of transport. For transportation, average European volumes of BAT 0.1 kg CO_2-eq per kg N will be adopted.

Nitrogen introduced into the soil, whether in organic or inorganic, is subjected to microbial transformation in the soil leading to the formation of N_2O emitted into the atmosphere. Indicators of this issue will be calculated on the basis of BAT data.

Plants assimilate large amounts of CO_2 during vegetation. Optimal fertilization of the fields can increase the production of plant biomass and thus the absorption of CO_2 by 4-5 times as compared to non-fertilized fields. For example, plant production of 8 Mg/ha achieved at 170 kg N/ha, absorbs 12,800 kg CO_2/ha, that is equivalent to 75 kg of CO_2 per kg of N used, i.e. -75 kg CO_2-eqv. per kg N.

The final result of LCA analysis will be the development of a methodology for assessing the production and use of fertilizers in plant cultivation, which will allow for comprehensive ecological quality assessment of the whole cycle of production and use of fertilizers, especially in terms of environmental impacts (such as net greenhouse gas emissions – including CO_2). Based on the LCA, a comprehensive economic assessment of the whole cycle of production and use of fertilizers can be made, especially in terms of the impact on greenhouse gas (including CO_2) emissions. The assessment of life cycle costs in the production system will allow for a more objective assessment of the effects of manufacturing processes. A new justification for greenhouse gas emission charges system will be proposed, including CO_2 for fertilizer manufacturers, taking into account the beneficial effects of fertilizer use associated with CO_2 uptake by increased fertilizer biomass. Analysis of similar fertilizer technologies in different fertilizer installations will allow comparison of the ecological, technical and economic indicators of the applied and dependent nodes or unit operations that should be upgraded.

7. Conclusions

The concept for the main assumptions of CO_2 balance in the fertilizer industry was presented, taking into account the removal of CO_2 from the environment by plants in the process of photosynthesis (CO_2 assimilation). In the balance, it is assumed that fertilizer use intensifies photosynthesis by ca. 4.5 times. This assumption is based on field trials with and without fertilizer use. Also, the emission of other greenhouse gases and calculation as CO_2 equivalents is considered (e.g. nitrification processes on the field). The balance of CO_2 emission during production, transportation, use and plants vegetation are presented. Detailed GWP and LCA analysis might be used by fertilizer companies to justify the reduction of fees for CO_2 emission.

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