Comparison of the environmental impact of three forms of nitrogen fertilizer
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COMPARISON OF THE ENVIRONMENTAL IMPACT OF THREE FORMS OF NITROGEN FERTILIZER

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**Introduction**

Steps towards environmental labelling are gaining pace; indeed, providing environmental labelling for mass consumption products can help consumers turn towards more environmentally responsible ones.

For instance, the French Ministry of Sustainable Development and Ademe\(^1\) are implementing actions and guidelines on the use of environmental information from the production of consumer products to develop environmental labelling. This is predicated on the availability of information related to agricultural production based on methodology that is known to be reliable and whose demonstrable conclusions can be easily understood by all participants, whether they are customers, consumers, certification organizations or public authorities. The methodology used within the framework of environmental labelling is life cycle analysis (LCA), which is a method of assessing the environmental impact of a product throughout its entire life.

The influence of fertilizers, and in particular mineral nitrogen (N) fertilizers, on the environmental footprint of agricultural production makes it a major factor when considering the environmental profile of agricultural products. Optimizing and adjusting the quantities of nitrogen that are spread on the land, through the implementation of agricultural fertilization plans and the use of nitrogen management tools, is a first step. But the link between the nitrogen form and its environmental impact should also be considered.

The aim of this study is to establish whether the choice of the type of nitrogen fertilizer can affect environmental performance during agricultural production. The environmental impacts on wheat crop cultivation of the three main forms of nitrogen fertilizer used in France - ammonium nitrate (AN), urea-ammonium nitrate (UAN) and urea - are compared using the LCA method. The study has been validated by a critical review conducted by an LCA specialist service (Bio Intelligence Service) with recourse to outside experts.

\(^1\) French Environment and Energy Management Agency
I. Life cycle analysis: a global, multi-criteria and standardized method to assess the environmental impact of a product

The life cycle analysis (LCA) method has been selected for this study, as it has the advantage of being standardized and multi-criteria and because it allows recommendations and improvements to be made as part of the eco-design approach.

Life cycle analysis is a standardized method (ISO 14040 defines its principles and framework and ISO 14044 its requirements and guidelines) to quantify the potential environmental impact of a product throughout its whole life. The method involves creating an inventory of all the materials (raw materials consumption, polluting materials emissions) and energy flows coming from the different processes that occur over the product’s life cycle. These materials and energy flows are compiled over the whole product life cycle and then transformed into indicators of potential impact on the environment (impact assessment).

LCA is a multi-criteria methodology, which means that it is possible to calculate a large diversity of indicators. These indicators give a global view of the environmental impact of the product and avoid “transfer of pollution” or “pollution swapping” which can lead to recommendations based only on a single environmental point-of-view. Thus, an LCA study provides the basis for recommendations that make it possible to improve the overall environmental impact of a product.

1) Definition of the system and hypotheses adopted

The aim of this study is to identify possible efficiency differences among different nitrogen mineral fertilizers from an environmental and an agronomic point-of-view. Consequently, it has been decided not to restrict the study solely to the production of nitrogen fertilizer but also to take into account the various levels of nitrogen use efficiency with regard to the nutrition of wheat.

The scope of the study therefore relates to the environmental assessment of mineral fertilization needed for the production of one quintal of wheat on the land under consideration. Accordingly, the results relate to the quintal of wheat produced.

Borealis, a major producer of nitrogen fertilizer in France, has joined forces with InVivo, a national union of agricultural cooperatives, to share their expertise and experience in the production, distribution and use of nitrogen fertilizers in France.

1.1 System borders

The study compares the three main forms of nitrogen fertilizer used in France: ammonium nitrate (33.5% N), UAN (urea-ammonium nitrate, 30% N) and urea (46% N).

It must be noted that the three different forms of nitrogen are not directly equivalent, but all have the objective of providing nitrogen to the crop. There is a large difference between the proportion of these nitrogen sources used in France compared to the global market stemming from industrial, agricultural and agronomic choices.

Urea is the main form of nitrogen fertilizer used on a world scale. The French urea market, however, only represents 1% of the global market. The product currently accounts for 13% of the mineral nitrogen fertilizer market in France (this data is the average of the 2000 to 2010 mineral fertilizer consumption volumes in France: source UNIFA). In 2009, 80% of the urea used in France was imported from Egypt, explaining the choice of this source of supply for the study.
Conversely, ammonium nitrate consumption is very dominant in France and throughout Europe, accounting for 5% and 25% respectively of the global AN market (Cazeneuve, 2010). AN accounts for 50% of the French market (source UNIFA). Ammonium nitrate 33.5 produced in France by Borealis is therefore the product considered in the study.

Lastly, UAN nitrogen solution fertilizer is also a widely used form in France (32% of the market: source UNIFA). The country is the second largest global consumer after the United States and accounts for 12% of global UAN consumption. Despite this high rate of use, however, the UAN used in France is mainly imported. Egypt exports urea-ammonium nitrate, so this source of supply is again used in the study.

Even though differences in geographic origin has been adopted for fertilizer production (in line with the reality of the French market), only one location has been considered for fertilizer use, in order to standardise transport hypotheses. The location used is land in the region covered by VIVESCIA, a cooperative in the French department of Aube and part of the InVivo network.

For the three fertilizers analysed, the study considers the same stages in the life cycle of the product. These cover the production of the raw materials used in the manufacture of the fertilizer up to the end of the fertilizer’s life cycle with the production of the wheat grain.

1.2 Data sources

In accordance with the LCA methodology, the energy and material flows (consumption of raw materials, emissions of pollutants) that enter or exit the various stages of the life cycle have been recorded in a life-cycle inventory. Real data have been used for these inventories. For this purpose, the partnership between a fertilizer producer and a union of cooperatives (which stores and distributes fertilizers, monitors their use and collects cereal grain) has been productive. Where no actual data are available, the study uses the Ecoinvent inventories, together with those of the GES'TIM guide (Institut de l'élevage - Breeding Institute et al., 2010).

In the ammonium nitrate assessment, a large amount of actual data could be used, namely data relating to energy and raw materials consumption (records of the Borealis plant) and to the emission of pollutants (compulsory declaration), as well as data on logistics and storage (registration by the cooperative). The hypotheses relating to the nitrogen dose and yield associated with the scenario of ammonium nitrate fertilization are based on practices actually observed in the region under investigation and collected by the fertilization management tool used by the cooperative.

With respect to urea production and the production of UAN nitrogen solution, the Ecoinvent inventory has been adapted to incorporate the actual natural gas and steam consumption data from several Egyptian sites, obtained from the bibliography and benchmarks (British Sulphur Consultants, 2001 and 2008; and IFA, 2008).

While the representativeness of the production of urea and the UAN nitrogen solution considered in this study corresponds to an average production of granulated urea and nitrogen solution in Egypt, the representativeness of ammonium nitrate production is limited to that of the Borealis plant in France. A sensitivity analysis overcomes this limitation.

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2 GES'TIM is a methodological guide to assess greenhouse gas emissions regarding agricultural activities. The main French agricultural technical institutes drafted it in 2010.
2) Choice of environmental indicators

After drawing up the inventory, the energy and materials flows are aggregated and then translated into indicators measuring their potential impact on the environment. The impact indicators have been selected on the basis of the issues associated with nitrogen fertilization and according to the potential for differentiation between the fertilizer forms.

The numerous indicators calculated in the study ensure an overview of the issues: global warming potential, non-renewable primary energy consumption, freshwater and marine eutrophication potential, acidification potential, potential impact on human toxicity and potential impact on air, soil and freshwater ecotoxicity.

The potential indicator of global warming (expressed as kilograms of CO\(_2\) equivalent), also known as the carbon footprint, has been chosen because nitrogen fertilization (production of fertilizer and its use in the field) contributes to emissions of CO\(_2\) and nitrous oxide (N\(_2\)O), a gas with a global warming potential (GWP) that is 298 times greater than that of CO\(_2\). It should be noted that the latest IPCC update of GWP (2007) has been used in this study, while the GES'TIM guide uses a GWP of 296 kg of CO\(_2\) equivalent.

The non-renewable energy consumption indicator, expressed in mega joules (MJ), has been selected because production of nitrogen fertilizers is energy intensive. In fact, the synthesis of ammonia, which is the precursor of nitrogen fertilizers, accounts for approximately 4% of the energy consumption of the industrial sector on the planet (Pach, 2007). Primary non-renewable energy consumption is the total amount of energy used throughout the product life cycle: from extracting the raw materials to the end of the product's life. It also takes account of the energy used to produce the energy inputs.

The acidification potential indicator (expressed in kg of SO\(_2\) equivalent) allows an assessment of the impact of ammonia volatilization on the environment. It takes account of the increase in the concentration of acidifying substances in the lower atmosphere that can cause acid rain, which in turn is involved in damage to forests. After spreading nitrogen fertilizer on the field, atmospheric emissions take place due to the volatilization of ammonia.

The eutrophication potential is used to assess the impact of nitrogen losses from the soil (e.g. via nitrate leaching to surface and underground water). It should be emphasised that the form of nitrogen applied in the spring has no direct influence on winter leaching, because during the growing period all forms of nitrogen are converted into nitrates. The risky period, in terms of leaching, is in the winter (the period in which the water table is replenished with drainage water).

Finally, and for the sake of completeness, the indicators of the potential impact on human toxicity and ecotoxicity have also been calculated. These indicators are not, however, very reliable due to methodological uncertainty and are not reported here. Only the first three indicators have been selected to enhance transparency for the general public. An LCA study on winter wheat production in the UK by Brentrup et al. (2004) has also demonstrated the particular relevance of these impact categories selected for arable crop production.
II. A life-cycle approach to the wheat chain

A pilot study carried out on behalf of the AFNOR/ADEME platform in charge of environmental labelling in France has pointed out that, for the 150 food products analysed, agricultural upstream activity is responsible for 40 to 90% of the environmental impact (depending on the degree of transformation of the final product). Thus, improving the environmental impact of agricultural raw materials will result in a significant improvement in a life cycle-based analysis.

For this reason, some of the cooperatives in the InVivo network have conducted LCAs for different categories of milling wheat, based on agricultural practices recorded in the field by means of decision support or traceability tools. For example, the fertilization management tool developed by InVivo (Epiciès) enables retrieval of information regarding soil and weather conditions and agricultural practices during the growing period in order to calculate the impact of fertilization within the framework of an LCA. Using these data, it is possible to calculate a LCA result on a plot scale for a cooperative’s whole grain production area.

1) Relevance of mineral nitrogen fertilization in the environmental footprint of winter wheat

Figure 1 shows the LCA results of winter wheat production intended for the milling market. The system downstream boundary is the grain sale by the cooperative to a customer. Thus, the collection and storage stage has been considered in the study. The LCA has been based on practices from agricultural plots totalling more than 45,000 hectares (almost 7,000 plots) located in France covering various agronomic situations.

Regardless of the particular indicator considered, the chart points to a strong dominance of nitrogen fertilization in the environmental footprint of the production of one quintal of wheat. This nitrogen fertilization can be divided into two sub-items: the impact of the production of the nitrogen mineral fertilizer used to produce the one quintal of wheat (this item takes account of the fertilizer manufacturing process as well as transport of the fertilizer to the plot and is called “Fertilizer production” in the chart above); and the impact of the actual use of the nitrogen fertilizer in the field (taking into account the polluting molecules emitted from the field as a result of the fertilizer application, called “Fertilizer use” in the chart).
Regarding global warming potential, both fertilizer production and use are predominant contributors throughout the wheat life cycle, a fact that is also confirmed by other carbon footprint studies on winter wheat production (e.g. Brentrup & Pallière, 2008). The impact of fertilizer use related to this indicator comes from emissions of N₂O. This is a powerful greenhouse gas which is released naturally from the soil, as well as after nitrogen fertilizer application.

As far as the indicator for primary energy consumption is concerned, the major contributor is mineral fertilizer production. The production of nitrogen fertilizers requires natural gas, both as a hydrogen feedstock and as a source of energy for the production process. The consumption of natural gas is mainly related to the production of ammonia, which is the usual precursor for the main forms of nitrogen mineral fertilizer.

Lastly, regarding the acidification potential indicator, field ammonia (NH₃) emissions after nitrogen application has the greatest impact in the production of one quintal of wheat. This phenomenon is called volatilization. Its extent depends on the weather conditions during fertilizer application, the characteristics of the soil, and the type of fertilizer applied.

It is interesting to note that calculating LCA results based on plot data from a substantial sample (more than 45,000 hectares) ensures that the intra-plot variability of the results is clearly apparent. The conclusion is clear: the variability among the plots of a large sample is much higher than the variability of the results between groups of homogeneous plots (similar agronomic situation or wheat quality). This is true regardless of the indicator calculated (Berthoud et al, 2011).

In light of the observation that between 40 to 90% of the environmental impact of wheat production relates to nitrogen fertilization, a significant reduction in environmental impact may be expected when addressing this issue.

2) Differences between the nitrogen fertilizers

A comparison of the environmental impacts of the three different forms of nitrogen fertilizer is possible because their production processes and their behaviour in the field vary. The diversity of fertilizer geographical origins and manufacturing processes from an industrial standpoint suggest that it is also possible to separate the impact of these forms from an environmental point-of-view.

The three forms of fertilizer studied have different compositions resulting from distinct manufacturing processes. Ammonium nitrate (AN) is synthesized from ammonia and nitric acid. Ammonia (NH₃) synthesis consumes natural gas and the synthesis of nitric acid (HNO₃) gives rise to N₂O emissions which can largely be reduced by treatment with specific catalysts. The ammonium nitrate chemical formula is NH₄NO₃ and the N content is 33.5% in this scenario. Urea is also produced from ammonia, which is reacted with carbon dioxide (CO₂) to produce the amide CO(NH₂)₂. Urea N content is 46% in the study. Urea-ammonium nitrate (UAN) is a mix of urea and ammonium nitrate in aqueous solution. Its N content is 30% in the study.

In addition to intrinsic differences due to the variety of chemical reactions taking place during synthesis of the different forms of nitrogen fertilizer, there are also process differences related to their geographical origins. The fact that the ammonium nitrate produced in France is subject to the European regulatory framework for the regulation of greenhouse gas emissions (ETS system of quotas) has resulted in investments to optimize the manufacturing process in terms of energy consumption and in specific measures to reduce emissions. The nitric acid production phase, which is used in the production of ammonium nitrate, and also of UAN solution, generates N₂O emissions.
These emissions have been significantly reduced at French ammonium nitrate production sites, and in the EU in general, due to the very strict regulatory restrictions on their release. By using specific catalysts, N₂O emissions have been reduced to 0.35 kg N₂O/tonne nitric acid on the Borealis site, compared to 6 kg N₂O/t of HNO₃ without the catalysts. The EU average for 2010 is 1.56 kg N₂O/t HNO₃ (Fertilizers Europe, 2013).

For energy consumption, differences between the geographic origins of production suggest a different energy purchase price associated with the origin of the supply (the local market for Egypt and the world market for France). Hence, different investment strategies to optimize consumption can be observed.

In the soil, nitrogen is present in different chemical forms (mainly urea, NH₄⁺, NO₃⁻, organic N) with different physico-chemical characteristics and different dynamic behaviours. From an agronomic point-of-view, the different chemical composition of nitrogen fertilizers (table 1) results in differing behaviours after spreading.

<table>
<thead>
<tr>
<th>Form of fertilizer</th>
<th>Ureic nitrogen</th>
<th>Ammonium nitrogen</th>
<th>Nitrate nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium nitrate</td>
<td>0%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Urea</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Urea-ammonium nitrate</td>
<td>50%</td>
<td>25%</td>
<td>25%</td>
</tr>
</tbody>
</table>

Ammonium, ureic and nitrate nitrogen differ not only in terms of their sensitivity to volatilization, nitrification/denitrification and leaching, but also in terms of their ease of uptake by the plant. Ammonium nitrate, urea and urea-ammonium nitrate fertilizers contain different proportions of these chemical forms. In the field, it therefore appears possible to distinguish different behaviours and efficiencies between the three products.
It is possible to take account of the differences between fertilizers when considering the gaseous emissions (\text{N}_2\text{O}, \text{NH}_3) based on the different emission factors of each form. This differentiation is, moreover, recommended by the GESTIM guide for ammonia emission values:

- In the field, \text{N}_2\text{O} emissions are the result of direct emissions caused by nitrification and denitrification of nitrogen products and of indirect emissions caused by the enrichment of the natural nitrogen environment (leaching and volatilization phenomena).

For the direct emissions, different emission factors from Bouwman et al (2002) have been used, based on the form of nitrogen fertilizer applied on the land. For the indirect emissions, the emission factors have been worked out on the basis of IPCC recommendations by incorporating the volatilization potential (variable depending on the form of nitrogen) and the leaching potential (here assumed to be identical for all fertilizers). The final results are shown in Table 2 below:

<table>
<thead>
<tr>
<th>Form of nitrogen fertilizer</th>
<th>Portion of N supplied directly emitted in the form of N-N_2O</th>
<th>Portion of N supplied indirectly emitted in the form of N-N_2O</th>
<th>Value of the global emission factor of \text{N}_2\text{O}/kg of N spread</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium nitrate</td>
<td>0.8%</td>
<td>0.245%</td>
<td>16.4g</td>
</tr>
<tr>
<td>Urea</td>
<td>1.1%</td>
<td>0.375%</td>
<td>23.2g</td>
</tr>
<tr>
<td>UAN nitrogen solution</td>
<td>1.0%</td>
<td>0.305%</td>
<td>20.5g</td>
</tr>
</tbody>
</table>

- Spreading the fertilizer on the field is followed by ammonia emissions through volatilization. The quantities of nitrogen that are volatilized on a plot depend on various factors, including the form of nitrogen used. The different rates of volatilization for different forms of nitrogen fertilizer are the result of a bibliographic summary by CORPEN in 2006, based on the UNECE Guidebook Emission Inventory (CORPEN, 2006). These are summarised below in Table 3:

<table>
<thead>
<tr>
<th>Form of nitrogen volatilization as ammonia</th>
<th>Portion of N volatilised</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium nitrate</td>
<td>2%</td>
</tr>
<tr>
<td>Urea</td>
<td>15%</td>
</tr>
<tr>
<td>UAN nitrogen solution</td>
<td>8%</td>
</tr>
</tbody>
</table>

Over the past few years, an increasing number of investigations have been conducted to examine the differences in terms of efficiency between the forms of nitrogen from an agronomic perspective.

Due to the variable degree of volatilization from the field depending on the form of fertilizer used, for the same dose of nitrogen applied in different forms, a variable quantity of nitrogen will actually be available to the plant. From Table 3 it can be anticipated that, where urea or UAN nitrogen solution are used, the quantity of plant-available nitrogen will be less.

Hence the three forms of fertilizer do not have the same degree of nitrogen efficiency. This has been confirmed by a series of agronomic trials.
A synthesis of 120 tests on Arvalis wheat was published in Perspectives Agricoles (Le Souder, 1997) comparing ammonium nitrate fertilization with nitrogen solution (UAN) fertilization. Carried out in different regions and on different types of soil, the synthesis showed a difference in favour of ammonium nitrate:

- At the same rate of nitrogen, according to the type of soil there was a yield reduction of between 2.4 to 3.9 quintals per hectare when using the nitrogen solution.
- The optimum nitrogen dose rate was higher with the nitrogen solution by 14-16%.

The InVivo network has implemented response curve comparisons between ammonium nitrate and urea for three nitrogen rates for wheat and maize, putting the emphasis on their impact on the yield and the quality of the grain. Results have been compiled for four years for both crops and have demonstrated a difference of efficiency in favour of ammonium nitrate at different N rates:

- The first advantage of ammonium nitrate over urea is a higher yield. A better efficiency of nitrogen inputs is also observed in a number of cases, meaning that an equivalent yield is reached with a smaller amount of nitrogen.

The synthesis of these 10 replicates on wheat shows an average yield gain of +3.7 quintals per hectare in favour of ammonium nitrate and a lower optimal dose (in other words the smallest dose ensuring the best yield within 3 quintals) for this form, meaning that ammonium nitrate has a higher nitrogen use efficiency (see Figure 2). Furthermore, these experimental results are consistent with the bibliography on the subject (Le Souder et al, 1997 and Yara, 2006).

![Figure 2: Results of yield comparisons at different nitrogen rates between ammonium nitrate and urea on soft wheat, Pool Fertil (10 replicates) InVivo Agro network annual results 2007-2011](image)

- Regarding quality, ammonium nitrate reveals a different protein rate. The recognized threshold of 11.5% for high quality bread wheat is either reached or exceeded in 75% of the cases, against 50% of the cases in which urea is used.
• Finally, the experimental approach reveals efficiency differences between the fertilizer forms in relation to soil and weather conditions. For example, the 7 replicates and 21 tests on maize shows that, according to the field indicator APM measuring the quantity of nitrogen that can be mineralized in a soil (“Azote Potentiellement Minéralisable” in French), the difference between the forms is more or less marked.

Using an immediately plant-available nitrogen form such as ammonium nitrate in soil with low mineralization potential provides a benefit of 9q/ha for the crop compared to the other forms. Although it is not very obvious in other situations (Figure 3), this effect is reinforced at the optimal dose.

![EFFECT OF THE NITROGEN FORM ON YIELD (q/ha)](image)

*Figure 3: Comparison of yield differences between ammonium nitrate and urea on soils with different nitrogen mineralization potential, Pool Fertil Invivo Agro network*

Given this agronomic difference in efficiency, for the purpose of this study it has been decided to use the yield reduction value of 3.9 quintals per hectare at the same nitrogen dose rate for urea and the UAN nitrogen solution in relation to ammonium nitrate. A sensitivity study has been carried out on this hypothesis.
III. Environmental indicators results

1) Results of three main indicators

In general, analysis of all the potential impact indicators (global warming, non-renewable primary energy consumption, acidification, drinking water eutrophication, marine eutrophication, human toxicity and ecotoxicity in the air, ground and water) demonstrates a better environmental performance from the French ammonium nitrate compared to the imported urea or the UAN nitrogen solution. The advantage of ammonium nitrate is explained by:

- An optimized industrial production process, which consumes less energy and produces smaller quantities of greenhouse gases.
- Reduced N losses in the form of N\textsubscript{2}O and NH\textsubscript{3} in the field.
- Different agronomic efficiencies between the three forms due to a much greater proportion of nitrate nitrogen in ammonium nitrate, a nitrogen form that is immediately taken up by the growing plant.

It is important to note that, despite the various geographical origins, the fertilizer transport phase has very little influence on the greenhouse gas emissions generated throughout the life cycle of the fertilizer. The relative importance of the production and utilization phases varies according to the indicator:

- The production phase has the most significant impact on the energy consumption indicator.
- The field use phase has the most important impact on the acidification and eutrophication potential indicator.
- Both phases have an impact on the greenhouse gas emissions indicator.

For all the indicators, uncertainty analysis provides a definition of the significance of the differences in the environmental impact of using ammonia nitrate, urea or UAN nitrogen solution fertilizer to produce a quintal of wheat.

1.1 Greenhouse gas emissions

The ammonium nitrate produced in France has a more optimized manufacturing process, due to strict European regulatory standards on quotas for greenhouse gas emissions and to lower energy consumption due to a higher gas purchase price. It is also characterized by lower field emissions. Differences between the three forms related to fertilizer use are due to several factors:

- Urea has a much higher field NH\textsubscript{3} volatilization rate than ammonium nitrate and urea-ammonium nitrate. This also favours indirect emissions of N\textsubscript{2}O (a greenhouse gas with a high global warming potential). Urea-ammonium nitrate has an intermediate rate between ammonium nitrate and urea (CORPEN, 2006).

- Direct field N\textsubscript{2}O emissions are slightly higher for urea than for ammonium nitrate, with urea-ammonium nitrate again being intermediate for this criterion (Bouwman et al, 2002). However, if the N source is not known, the default IPCC emission factor for N\textsubscript{2}O from the soil does not differentiate between the N source applied and suggests an average emission rate of 1% N\textsubscript{2}O-N per unit of organic or mineral N.
The agronomic difference in efficiency between the three fertilizer forms is key to explaining the difference in the LCA results, because they are scaled so that each represents the production of a quintal of wheat. Indeed, the 80 q/ha yield obtained using ammonium nitrate is slightly higher than the 76.1 q/ha obtained with urea and urea-ammonium nitrate for the same amount of nitrogen applied. The denominator value changes and can explain a slight difference in favour of ammonium nitrate in comparison with the two other forms. Also, the different emission factors for N$_2$O emissions from the soil contribute to the different carbon footprints of the three fertilizer products.

In spite of the different geographical origins, transportation of the fertilizer from the plant to the plot where it is to be applied is not really significant in terms of greenhouse gas emissions over the fertilizer life cycle.

1.2 Energy consumption
Considering primary energy consumption (see Figure 5), a higher efficiency in the manufacturing process and a higher agronomic efficiency in the field explain the advantage of the ammonium nitrate produced in France over the other two nitrogen forms. As mentioned earlier, the transportation and logistics stages, as well as the application, hardly have an impact on the three scenarios when compared to the fertilizer production stages.

1.3 Acidification

There are significant differences between the nitrogen forms in respect of the acidification potential indicator (see Figure 6) due to differences in the volatilization of ammonia. Urea is the form which volatilizes the most NH₃ after spreading. Furthermore, this loss of nitrogen as NH₃ is one of the factors explaining the difference in terms of agronomic efficiency between urea and ammonium nitrate, due to a reduction in the quantity of nitrogen effectively available to the plant.

It is important to note, however, that only the form of nitrogen has been kept as a differentiating criterion regarding emissions values during application, as recommended in the GES'TIM (2010) methodological guide. The soil type and the weather conditions during application are parameters which can impact emissions, but there are insufficiently precise data to take them into account.

Volatilization rates according to product form are sourced from a bibliographical synthesis produced by CORPEN in 2006 based on the UNECE Emission Inventory Guidebook.

![Figure 6: Comparative LCA results for the three forms of nitrogen showing the effect on the environment acidification indicator](image-url)
2) Sensitivity analysis

Sensitivity analysis has been conducted in order to test the “sensitive” hypotheses of the study, in particular those for which it was difficult to collect precise information. Moreover, the analysis enables consideration of the impact of changes in practices or processes over the life cycle of the products. Finally, the analysis provides a more general scope for the study by using less specific hypotheses and by measuring the sensitivity of the final results.

2.1. Sensitivity analysis of the energy consumed for ammonia synthesis

The difficulty in collecting data on natural gas consumption in the Egyptian plants, together with the diversity of values found for this item in the bibliography, justify a sensitivity analysis. The following are thus compared:

- The data used in the study for the product referred to as “Egyptian” urea, resulted from actual values (averaged out and weighted) of natural gas consumption recorded in several Egyptian plants.
- The data from the Ecoinvent inventory (“Ecoinvent” urea).
- The data from the ammonia synthesis module of the ammonium nitrate plant in the study: (“Borealis” urea).

It transpires from this study (Table 4) that, whatever the scenario investigated with respect to the two indicators in question, the impact of ammonium nitrate on the environment is far less harmful than that of urea.

| Table 4: Results of the sensitivity analysis on natural gas consumption for ammonia synthesis needed to produce urea |
| --- | --- | --- | --- |
| | Global warming potential | Non-renewable energy consumption |
| | kg CO$_2$equiv/q wheat produced | Difference compared with AN | MJ/q wheat produced | Difference compared with AN |
| “Egyptian” urea | 32.1 | +58% | 298 | +99% |
| “Ecoinvent” urea | 28.8 | +42% | 229 | +53% |
| “Borealis” urea | 30.3 | +49% | 240 | +60% |

However, the use of the Ecoinvent data or Borealis module for the synthesis of ammonia tends to reduce the differences between ammonium nitrate and urea.

2.2. Sensitivity analysis of the hypotheses of the nitrogen dose applied and associated yield

It seems relevant to see the effect of a change on the agronomic performance hypotheses when comparing the three forms of nitrogen fertilizer:

- “higher dose” scenario: several agronomic references show that, on average, the optimum dose of urea and nitrogen solution must be increased by 10 to 15% in order to achieve the same output as that obtained with the optimum dose of ammonium nitrate. Three dose rates are thus tested (ammonium nitrate at 189 units/ha, urea at 217 units/ha and the nitrogen solution at 208 units/ha) for the same yield of 80 q/ha.
• equivalent N-rate scenario: in this case, no difference in efficacy is considered between ammonium nitrate, urea and UAN nitrogen solution; in other words, using the same dose (189 units/ha) and the same yield (80 q/ha).

It can be seen in Table 5 that, for all indicators, a change in the hypotheses of the difference in efficiency between the forms of nitrogen does not alter the classification order between ammonium nitrate and the two other fertilizers. The hypothesis of “same yield and higher dose” increases the difference between ammonium nitrate and the other two fertilizers.

<table>
<thead>
<tr>
<th>Study</th>
<th>Global warming potential</th>
<th>Non-renewable energy consumption</th>
<th>Acidification potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg CO₂ eq/ q wheat</td>
<td>MJ/q wheat</td>
<td>kg SO₂ eq/ q wheat</td>
</tr>
<tr>
<td></td>
<td>Difference compared with AN</td>
<td>Difference compared with AN</td>
<td>Difference compared with AN</td>
</tr>
<tr>
<td>AN</td>
<td>20.2</td>
<td>150</td>
<td>1.12 E-1</td>
</tr>
<tr>
<td>Urea</td>
<td>32.1</td>
<td>298</td>
<td>6.53 E-1</td>
</tr>
<tr>
<td>UAN</td>
<td>33.9</td>
<td>274</td>
<td>3.75 E-1</td>
</tr>
<tr>
<td>“Higher dose”</td>
<td>35</td>
<td>326</td>
<td>7.13 E-1</td>
</tr>
<tr>
<td>Urea</td>
<td>+58%</td>
<td>+99%</td>
<td>+413%</td>
</tr>
<tr>
<td>UAN</td>
<td>+68%</td>
<td>+83%</td>
<td>+210%</td>
</tr>
<tr>
<td>Equivalent scenario</td>
<td>30.5</td>
<td>+117%</td>
<td>+489%</td>
</tr>
<tr>
<td>Urea</td>
<td>+50%</td>
<td>+91%</td>
<td>+204%</td>
</tr>
<tr>
<td>UAN</td>
<td>+60%</td>
<td>+74%</td>
<td>+134%</td>
</tr>
</tbody>
</table>

2.3. Sensitivity analysis of N₂O emissions level for nitric acid

During nitric acid production, which is necessary for the production of ammonium nitrate and UAN nitrogen solution, quite varied emissions of N₂O can be produced depending on the abatement technologies used. It is therefore relevant to check the sensitivity of this data.

The value used in this study is 0.35 kg N₂O/tonne HNO₃ produced, because this corresponds to the result with a new catalyst used in the Borealis plant which achieves an excellent reduction in N₂O emissions. The benchmark achieved by Fertilizers Europe (EFMA, 2007) indicates an average value of 1.24 kg N₂O/t HNO₃ for the 10% most efficient nitric acid production plants in Europe (Best Available Technologies BAT EU).

A scenario has also been constructed based on the hypothesis of an emission of 0.15 kg N₂O/t HNO₃ (GCLDD, 2010). This scenario is highly optimistic compared with the emissions from the Borealis plant, which are already considered as being extremely low and which are the result of major investment, but its analysis enables validation, or otherwise, of potentially important paths for improvement within the life cycle.

Only the results having an impact on climatic change are shown (Table 6) because the N₂O emissions do not impact on other indicators and thus no difference is observed when changing the level of N₂O emissions.
Table 6: Results of the sensitivity analysis of N₂O emissions during the manufacture of nitric acid for ammonium nitrate production

<table>
<thead>
<tr>
<th></th>
<th>N₂O emissions (kg CO₂ eq/kg of AN produced)</th>
<th>% variation compared with AN Borealis</th>
<th>Global warming potential on wheat production (kg CO₂ eq/q wheat)</th>
<th>% variation compared with AN Borealis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borealis unit</td>
<td>1.15</td>
<td>0 %</td>
<td>20.2</td>
<td>0%</td>
</tr>
<tr>
<td>10% BAT EU unit</td>
<td>1.36</td>
<td>+18 %</td>
<td>21.7</td>
<td>7%</td>
</tr>
<tr>
<td>Theoretical improvement unit</td>
<td>1.1</td>
<td>-4 %</td>
<td>19.9</td>
<td>-1%</td>
</tr>
</tbody>
</table>

The new Borealis nitric acid unit produces a highly significant 18% reduction in N₂O emissions compared to the best 10% of units in the Fertilizers Europe benchmark.

The scenario based on the hypothesis of an additional 15% reduction in greenhouse gas emissions during the ammonium nitrate production phase only leads to a 1% improvement in impact over the entire ammonium nitrate life cycle. In fact, this improvement only takes place during the production phase, whereas the utilization phase of the fertilizer also has a great impact on the climatic change indicator. Hence, planned improvements for the future must relate to emissions in the field in order to encourage agricultural practices that minimize the risk of emissions.

It should be noted that the GES'TIM guide uses 5.5 kg/t HNO₃ as a default value for N₂O emissions, which is very high, given the technological progress which has been made in current European ammonium nitrate production plants and which has led to an average emission rate of 1.56 kg N₂O/t HNO₃ in 2010 (Fertilizers Europe, 2013).
Conclusions

Improvements in agricultural practice must today pass through a new filter: the environmental impact of production. Life Cycle Analysis (LCA) methodology quantifies the different environmental impacts of manufacturing any product, taking into account not just the manufacturing process itself but also the impact of the production of the raw materials and the energy sources, etc. used in the process.

The environmental footprint related to the production of wheat is mainly due to the use of nitrogen fertilizers. But nitrogen is a principal element of plant nutrition and, as such, it is directly correlated to production performance. Basically, it is not a reduction in nitrogen input but its optimization that is the key to environmental improvement without lowering yield.

Over the last few years, decision support tools have been developed to assist farmers to make their nitrogen management more efficient and avoid inaccurate fertilization. As a global indicator of environmental impacts, this LCA of different forms of mineral nitrogen is a major new tool to improve fertilizer practice on farm. It enables the identification of the nitrate form - ammonium nitrate - which is the most readily available to plants and which is characterized by the lowest adverse side-effects on the environment. The final step in the minimization of environmental impact is to raise awareness among stakeholders of the best practices and to present the results to farmers.

Awareness of the differences in environmental and agronomic efficiency between nitrogen fertilizer forms will improve the environmental impact of agricultural production within cooperatives. For instance, a cooperative-customer relationship system can be envisaged that is based on both the agronomic performance and the environmental record of marketed materials. To reach this goal, the cooperative has decision support tools to help farmers to optimize their cropping systems through improved nitrogen fertilization management. It can also advocate a fertilizer form with the lowest environmental impact. The product’s wider use will significantly improve the overall environmental performance of agricultural production.

Implementing a labelling approach to create awareness among the general public, regarding the environmental impact of products they are using, requires the involvement of all the different stakeholders in the production chain. For agricultural production, it is necessary to convey this information to farmers in order to raise their awareness and potentially change their practices. This is important, as today the choice of a nitrogen fertilizer is often based more on the purchase price rather than on agronomic, environmental or technical optimization.

Communication with farmers is taking place through leaflets and a website aimed at farmers and their advisers (www.bienchoisirsonazote.com). Moreover, as farming cooperatives have a supporting and advisory role with farmers, Borealis and InVivo believe that it is useful and innovative to use the results of this study in a tool for recommending forms of nitrogen. This tool, known as Top’Az®, enables the farmer to compare the various forms of nitrogen fertilizer from a technical and economic, as well as an environmental, perspective.

In addition, Borealis and InVivo have decided to extend this study to other crops (rapeseed, maize and barley). In parallel, technical investments are still being made to enable refinement of these results based on further field references.
Bibliographical references


GCLDD, January 2010, State, outlook and stakes of the fertilizer market - Study commissioned by the Ministry of Food, Agriculture and Fisheries.


Fertilizers Europe represents the majority of fertilizer producers in Europe and is recognized as the dedicated industry source of information on mineral fertilizers. The association communicates with a wide variety of institutions, legislators, stakeholders and members of the public who seek information on fertilizer technology and topics relating to today’s agricultural, environmental and economic challenges. The Fertilizers Europe website provides information on subjects of relevance to all those interested in fertilizers contribution to global food security.

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