April 2023

Stopping a Super-Pollutant:

N_2O Emissions Abatement from Global Adipic Acid Production

Authors: Ali Hasanbeigi and Adam Sibal

Global Efficiency Intelligence

Acknowledgements

The author would like to thank Evan Gillespie and Victoria Chu of Industrious Labs, and Jibran Zurbei of Lawrence Berkeley National Laboratory for their valuable input on this study and/or their insightful comments on the earlier version of this document.

Disclaimer

Recommended citation: Hasanbeigi, A.; Sibal, A. 2023. Stopping a Super-Pollutant: N_2O Emissions Abatement from Global Adipic Acid Production. Global Efficiency Intelligence. Florida, United States.

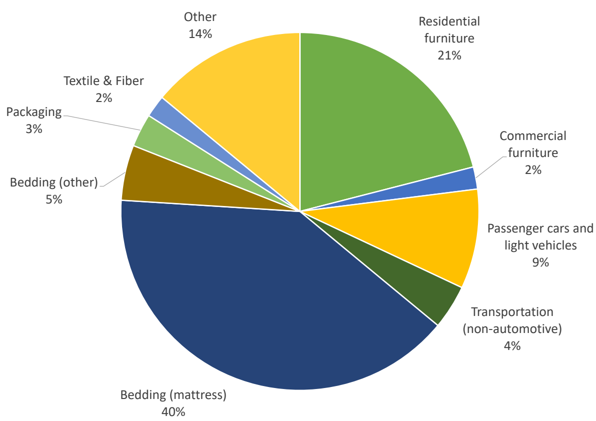
https://www.globalefficiencyintel.com

Executive Summary

Adipic acid is a white, crystalline compound and is primarily used in the production of nylon 6,6. Adipic acid is also used to produce polyurethanes, as a reactant to form plasticizers and lubricant components, and is used in the production of polyester polyols. There are estimated to be 39 operational facilities globally producing adipic acid while almost two thirds of the global adipic acid production takes place in China and U.S. Adipic acid production is one of the largest sources of nitrous oxide (N_2O) emissions. The impact of 1 kg of N_2O on warming the atmosphere is almost 273 times that of 1 kg of carbon dioxide (CO_2). Therefore, N_2O is one of the so-called super pollutants.

The annual N_2O emissions from adipic acid production facilities in China is estimated to be about 134 million tons (Mt) of CO_2eq/yr for 2021 while the rest of the world is estimated to contribute just 8.5 Mt CO_2eq/yr. China accounts for 94% of global annual N_2O emissions from adipic acid production. Thus, ensuring the N_2O abatement technologies are installed and operating in all adipic acid production plants in the China should be considered a priority in this industrial sector. There are widely used commercially mature technologies to reduce N_2O emissions at a low cost. Our analyses indicate that adipic acid emissions reductions are highly cost effective, with high-level controls available at less than \$0.50 per ton of CO_2eq abated, and ultra-high levels of control at less than \$5 per ton of CO_2eq abated.

Adipic acid intermediary products include nylon 6,6, polyurethane, adipate ester, and other products. Nylon 6,6 is by far the most significant product produced from adipic acid with a share of over 83% (over 2,500 kilotons per year (kt/yr)) and polyurethane is the second largest product with a share of over 8% (over 230 kt/yr) of total adipic acid demand globally (Figure ES1).



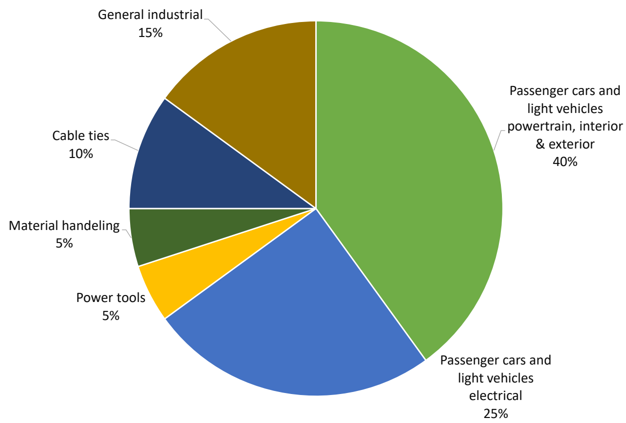


Figure ES1. Share of adipic acid consumed in downstream intermediary industries (left); Share of nylon 6,6 consumed in downstream industries (right)

The automotive industry consumes about 65% of nylon 6,6 while the bedding mattress segment consumes about 40% of polyurethane. Based on our analysis, the global embodied N_2O emissions from the source of adipic acid consumption for nylon 6,6 and polyurethane production were about 112 and 10.5 Mt CO_2eq in 2021, respectively.
The passenger cars and light vehicles industry sector may have the largest leverage for the installation of the N_2O abatement technologies in its upstream processes. Our analysis

estimates that a passenger car or light vehicle has an average embodied N_2O emissions of 976 kg CO_2eq/vehicle, just shy of 1 tonne CO_2eq per vehicle[1]. About 99% of the source of N_2O emissions embodied in passenger cars and light vehicles is estimated to be from nylon 6,6 production and the remaining is the source of polyurethane. Out of the 74 Mt CO_2eq/yr N_2O emissions embodied in passenger cars and light vehicles, the share of tires, car seats, and airbags are about 20%, 6% and 6%, respectively. The embodied N_2O emissions intensities for these products are shown in Chapter 6 of the report. The embodied N_2O emissions intensity for an airbag, car seat, and tire is estimated to be 28.7, 14.3, and 9.4 kg CO_2eq/product, respectively. Embodied N_2O emissions intensity for cable tie and bedding mattresses are estimated to be 0.2 and 6.2 kg CO_2eq/product, respectively.

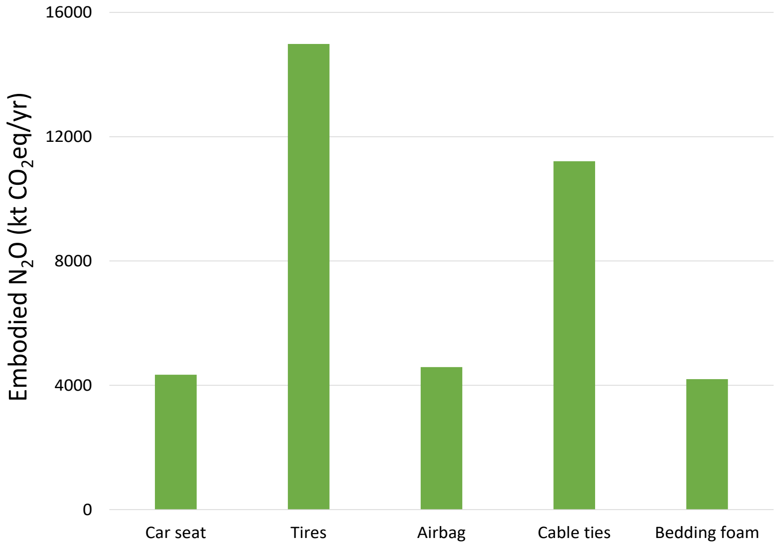


Figure ES2. Embodied N_2O emissions for the selected consumer products in 2021 (Source: This study)

Figure ES3 shows the N_2O abatement cost impact on final products if the cost of N_2O emissions abatement were to increase the price of adipic acid and associated intermediary products (i.e. nylon 6,6 and polyurethane). In terms of the abatement cost per unit of product, the average abatement cost for a passenger car or light vehicle is just $0.4 per vehicle. The abatement cost for airbags, car seats, and tires is estimated to be $0.012, $0.006, and $0.004 per product, respectively. The abatement cost for cable ties and bedding mattresses are estimated to be $0.00007 and $0.0026 per product, respectively.

In this study, we also forecasted the total N_2O emissions of the global adipic acid industry up to 2050 under different scenarios by applying varying adoption rates for abatement technologies. In the business-as-usual (BAU) scenario, total N_2O emissions of the global adipic acid industry will increase by about 92% between 2021 and 2050. Under the Advanced scenario, our analysis shows that higher deployment of single and dual abatement technologies will result in significant abatement rates for the global adipic acid industry resulting in the estimated annual N_2O emissions reductions by 90% and 94% up to 2035 and 2050. If we assume half of Chinese adipic acid plants are running N_2O abatement technologies, then the 2021 emissions starting point would be lower.

1 For comparison the embodied CO_2 emissions associated with steel used in a passenger car is around 0.9 and 1.8 tonne CO_2 per car if manufactured using steel produced in the U.S. and China, respectively. Around 900 kg of steel used in a passenger car (worldsteel, 2022). The average CO_2 emissions intensity of the steel industry in the U.S. and China are 1.0 and 2.0 tonne CO_2 per tonne crude steel (Hasanbeigi, 2022).

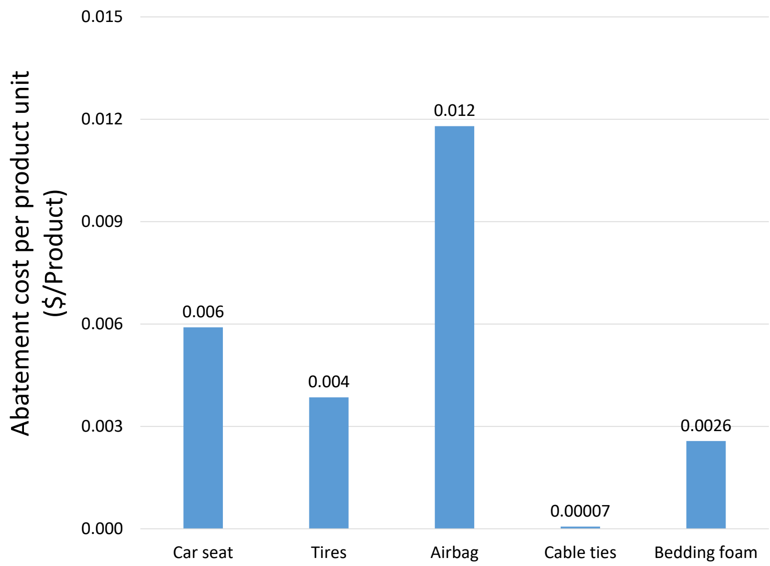


Figure ES3. N_2O abatement cost impact on the selected final products (Source: This study)

In summary, reducing N_2O emissions from adipic acid production is relatively easy and cost-effective, and the technology is already available and widely used. With the right set of policies and partnerships between industry, policymakers, and other stakeholders, the global adipic acid manufacturing industry can move towards net-zero N_2O emissions from the adipic acid production at a very low cost. Global car manufacturing companies can play a significant role in providing the demand pull for this net-zero N_2O emissions adipic acid production.

Table of Contents

1 Introduction

Adipic acid is a white, crystalline compound and is primarily used in the production of nylon 6,6. Adipic acid is also used to produce polyurethanes, as a reactant to form plasticizers and lubricant components, and is used in the production of polyester polyols. Around 2.5 million tons of adipic acid are produced annually. Almost all adipic acid is produced by nitric acid oxidation of ketone-alcohol (KA) oil with a mixture of cyclohexanone and cyclohexanol. The nitric acid oxidation reaction unavoidably generates nitrous oxide (N_2O) emissions.

N_2O is long-lived in the atmosphere because of its low solubility in an aqueous solution. Moreover, N_2O is classified as a longed lived greenhouse gas (GHG) that contributes to climatic changes 273 times more potent than CO_2 according to the IPCC. The estimated atmospheric lifetime of N_2O is 150 years. The impact of N_2O on the ozone layer depletion increase is estimated to be about 6% (Capece, 2018). Therefore, N_2O is one of the so-called super pollutants.

The production of adipic acid and nitric acid are the two industrial processes contributing the most to global N_2O emissions. N_2O emissions from adipic and nitric acid production contribute to about 0.2% of global GHG emissions (approximately 142 Mt CO_2eq), which is equivalent to 24% of non-CO_2 greenhouse gas emissions from key industrial processes (Capece, 2018).

Regulating N_2O emissions from adipic acid production is one of the most cost-effective, fast mitigation opportunities to reduce (GHG) emissions. Utilizing existing "end-of-pipe" abatement technologies at just 12 global facilities can lead to cumulative reductions of over 3.5 Giga tons of carbon dioxide equivalent (Gt CO_2eq) by mid-century, or approximately 1% of the remaining carbon budget to meet the Paris Agreement 1.5°C goals.

Companies that rely on adipic acid in their supply chain can be encouraged to reduce their Scope 3 emissions by demanding the adipic acid producers in their upstream to reduce their N_2O emissions at a negligible cost impact to company or the end user. This study aims to present a better understanding of the adipic acid value chain, the value chain for products using adipic acid in their production; nylon 6,6, polyurethanes, and other products. We additionally present who are the major buyers of these products, how supply chain measures can be used to reduce N_2O emissions from adipic acid production, and how abatement measures might impact nylon 6,6 or polyurethanes' costs for final product retail cost.

This study aims to shed light on the N_2O emissions in the global adipic acid industry value chain. We analyzed N_2O emissions in the global adipic acid industry by country and made a forecast up to 2050. Then, we discussed the fully commercialized N_2O emissions control technologies that adipic acid production plants can implement to reduce their N_2O emissions to near zero. We investigated the N_2O emissions in the adipic acid value chain and the embodied N_2O emissions in intermediary products (e.g. Nylon 6,6, and polyurethane) and final consumer products in downstream of adipic acid value chain. We then quantified the N_2O abatement cost impact on adipic acid intermediary products and final consumer products.

2 Global Adipic Acid Production

China and the U.S. are the two leading countries in the production of adipic acid. Figures 1 and 2 illustrate the global production of adipic acid for 2021 in kilotons (kt) per year (CLIMATE STRATEGIES, 2022). Almost two third of the global adipic acid production takes place in China and the U.S. Other leading adipic acid-producing countries include Germany, France, South Korea, Japan, Italy, and Brazil.

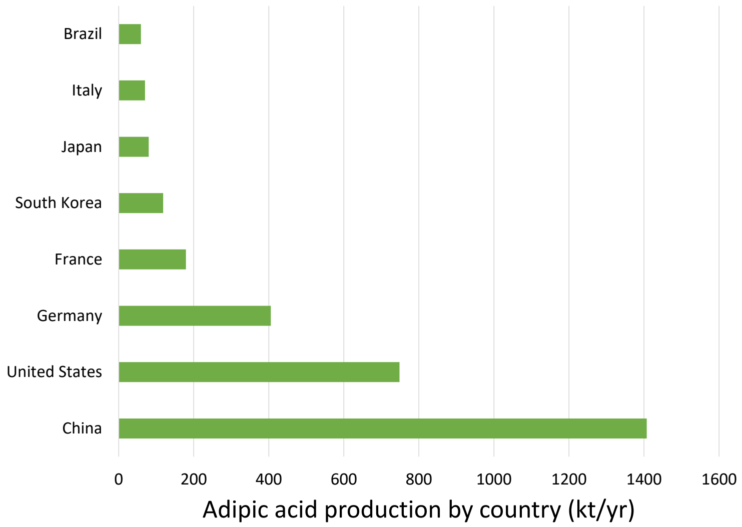


Figure 1. Adipic acid production by the country in 2021 (Source: CLIMATE STRATEGIES, 2022)

At the facility level, adipic acid producers can be categorized based on production capacity higher than and less than 100 kt/yr. Globally there are 39 operating facilities producing adipic acid of which 13 facilities have a production capacity greater than 100 kt per year accounting for 60% of the global production capacity.

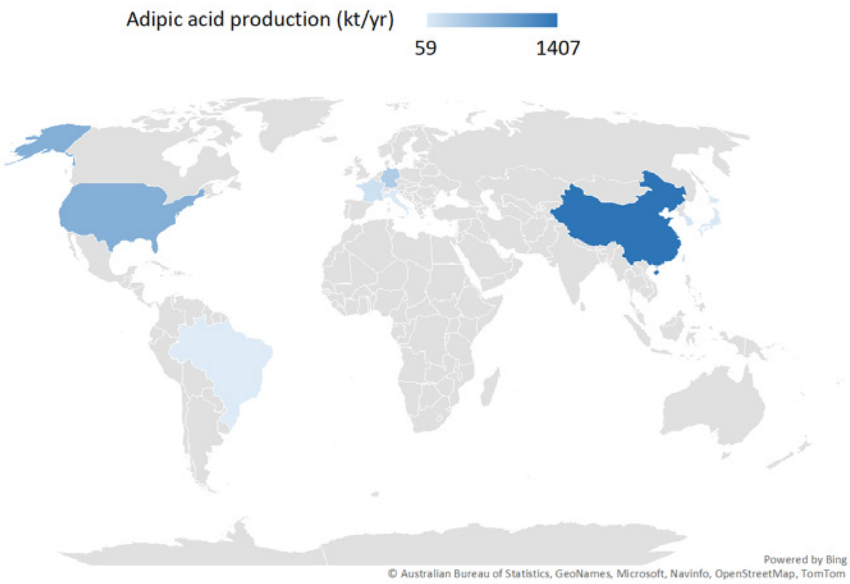


Figure 2. Concentration of adipic acid production by the country in 2021 (Source: CLIMATE STRATEGIES, 2022)

3 N_2O Emissions from Global Adipic Acid Production

3.1. Emissions by country

The adipic acid industry is an inherently N_2O emission-intensive industry. As most of the facilities in the world have been equipped with N_2O abatement technologies, the annual emissions of N_2O at most of the facilities has declined. However, there are some facilities in China that either have not installed N_2O abatement technologies or they have installed them but are not operating them to save cost (McKenna, 2020). Therefore, the share of annual N_2O emissions from Chinese adipic acid production facilities are significantly larger than other countries as shown in Figure 3.

The annual N_2O emissions from adipic acid production facilities in China is estimated to be about 134 million tons (Mt) of CO_2eq/yr for 2021 while the rest of the world is estimated to contribute just 8.5 Mt CO_2eq/yr. China accounts for 94% of global. annual N_2O emissions from adipic acid production. Estimated global N_2O emissions from adipic acid production by country (excluding China) are illustrated in Figure 4. The N_2O emissions from adipic acid production in the U.S. in 2021 is estimated to be around 7 Mt CO_2eq/yr making it the second largest N_2O emitter in the world. Thus, ensuring the N_2O abatement technologies are installed and operating in all adipic acid production plants in the China should be considered a priority in this industrial sector.

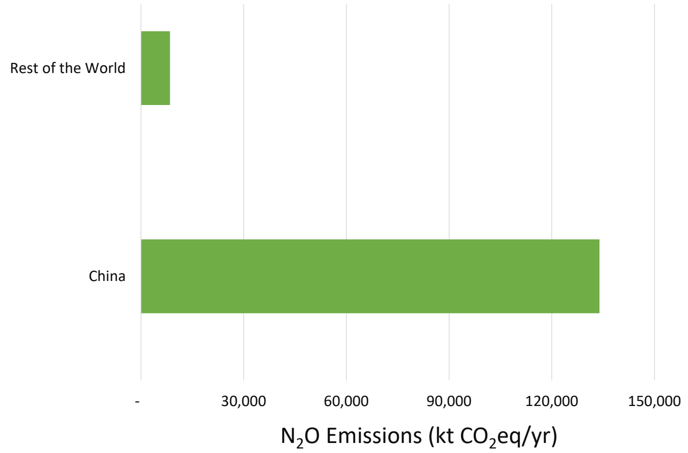


Figure 3. N_2O emissions from adipic acid production for the China and rest of the world in 2021 (Source: This study)

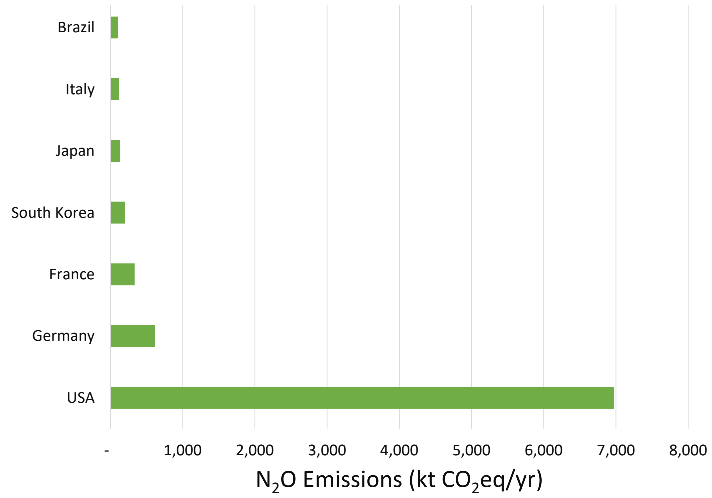


Figure 4. N_2O emissions from adipic acid production by country for Rest of the World (excluding China) in 2021 (Source: This study)

To understand the scale of future N_2O emissions from global adipic acid production, we have developed a projection model up to 2050. The model uses production forecast to project the industry's N_2O emissions under Business-as-usual, Moderate and Advanced scenarios which assume varying level of N_2O emissions abatement technology adoption through 2050. The model focuses on N_2O emissions from adipic acid production and excludes N_2O emissions from nitric acid production.

3.2. Emissions forecast up to 2050

To illustrate the future of the N_2O emissions from adipic acid production globally, we used scenario projection analysis up to 2050. Below we have provided the key assumptions and methods to develop the model for N_2O emissions in the global adipic acid industry.

Global facilities are currently abating N_2O emissions at different rates. Our key assumptions for the current abatement rates are as follow:

- **U.S. adipic acid production:** There are two adipic acid producers in the U.S. One reported to abate N_2O emissions at 97-99% rate in the last 5 years. We assumed a 98% abatement rate for this facility. The other plant's baseline abatement rate was assumed at 80%, which reflects a 5-year average (ClimeCo Corporation, 2019).

- **Chinese adipic acid production:** There are 11 producers of adipic acid in China. Several reports, in addition to expert testimony, led to the conclusion that Chinese adipic acid producers are not utilizing N_2O abatement technology (U.S. EPA, 2019, McKenna et al., 2020, Qing et al., 2020).

- **Other countries' adipic acid production:** For all others producers including Brazil, Japan, South Korea, France, Germany, and Italy we assumed abatement of 98% of N_2O emissions.

Current abatement technologies are capable of reducing N_2O emissions from adipic acid production by 98-99%. However, in practice, actual abatement rates may be closer to 90% depending on how the system is constructed based on the choice of abatement methods and where in the production process it is installed. System "downtime" when the system requires (annual) maintenance can also decrease the actual abatement rate. This gap can be addressed by installing multi-phase abatement systems, additional end-of-pipeline capacity, or a second system to bring online during the primary system's maintenance period (Climate Action Reserve, 2022, Mainhardt et al., 2001, IPCC, 2006, UNEP, 2013).

We have investigated the abatement rates of the N_2O abatement technologies for adipic acid in the available literature and the summary of our findings is provided in the next section. In our forecast model, we assumed that plants with generic single and dual abatement technology abated N_2O at 90% and 98% rate, respectively.

Production estimates were used to calculate N_2O emissions from a given adipic acid plant. The widely-used industry standard is that production of one ton of adipic acid will result in 0.3 tons of N_2O without any abatement technology installed. N_2O emissions were converted to units of CO_2 eq using a greenhouse gas equivalent of 273 units of CO_2 per unit of N_2O (IPCC, 2021).

Emissions captured by the model are only from the process emissions released from the production of adipic acid. N_2O emissions upstream from the production of nitric acid, a key input in most adipic acid production, were excluded from these estimates as additional control technologies would be needed to abate emissions from these production points. Table 1 shows the summary of the key assumptions for our analysis.

Table 1. Key assumptions for analysis (Source: This study)

Metric	Value
N_2O production rate from adipic acid (kg N_2O/kg adipic acid)	0.3
N_2O to CO_2 conversion (kg CO_2/kg N_2O)	273
Generic dual abatement technology N_2O abatement rate (%)	98%
Generic single abatement technology N_2O abatement rate (%)	90%

To develop the global N_2O emissions projection model, we have defined three pathway scenarios in two modes. The two modes and associated projection pathways are as below.

Mode 1: In this mode, we assume that although some Chinese facilities have been equipped with N_2O abatement technologies, they are not running the abatement technologies during the operation of their facilities. The three projection scenarios of this mode are as follows:

1) **Business as Usual (BAU) scenario**: Assumes the same level of N_2O abatement technology adoption rate of 2021.

2) **Moderate scenario**: Assumes facilities without N_2O abatement technology will start to implement the single abatement technology in 2022 and all facilities will have single abatement technology installed and operating by 2040. Facilities that already have single abatement technology will start to implement dual abatement technology gradually from 2030 and all those facilities will have dual abatement technology installed and operating by 2040.

3) **Advanced scenario**: Assumes facilities without N_2O abatement technology will start to implement the single abatement technology in 2022 and all facilities will have single abatement technology installed and operating by 2030. Facilities that already have single abatement technology will start to implement dual abatement technology gradually from 2030 and all those facilities will have dual abatement technology installed and operating by 2040.

Mode 2: In this mode, we assume that 50% of Chinese facilities are equipped with N_2O abatement technologies and are running the abatement technologies in 2021 with the other half either have not installed an abatement technology or not operating them. The three projection scenarios of this mode are as same as the above scenarios.

Table 2 provides the adoption rate of N_2O abatement technologies for different scenarios of this study.

Table 2. The adoption rate of N_2O abatement technologies for different scenarios of this study

Year	The adoption rate of single abatement technology for the Moderate scenario	The adoption rate of dual abatement technology for the Moderate scenario	The adoption rate of single abatement technology for Advanced scenario	The adoption rate of dual abatement technology for Advanced scenario
2021	0%	0%	0%	0%
2025	17%	0%	38%	0%
2030	44%	0%	100%	0%
2035	72%	50%	100%	50%
2040	100%	100%	100%	100%

We forecasted the total N_2O emissions of the global adipic acid industry up to 2050 under different scenarios by applying varying adoption rates for abatement technologies. The results of our analysis are shown in Figure 5. In the BAU scenario, total N_2O emissions of the global adipic acid industry will increase by about 92% between 2021 and 2050 while adipic acid production is assumed to increase by 53% during the same period due to the significant growth of adipic acid production in China (about 98% production growth between 2021 and 2050) with fewer implemented/running abatement technologies and small growth of adipic acid production in rest of the world (about 7% growth during 2021-2050) (Industrious Labs, 2022). However, in the Moderate scenario, due to the moderate adoption of the abatement technologies, the annual N_2O emissions will decrease by 42% and 94% in 2035 and 2050 compared to 2021 levels. The total annual N_2O emissions of the global adipic acid industry will drop from 142 Mt CO_2eq/yr in 2021 to 82 Mt CO_2eq/yr in 2035 and 8.1 Mt CO_2eq/yr in 2050 under the Moderate scenario.

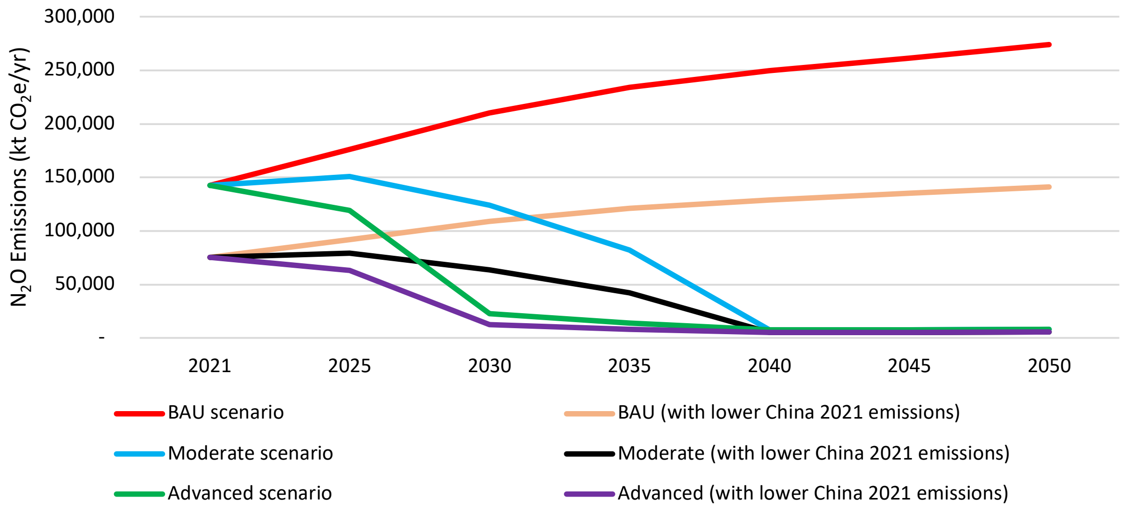


Figure 5. Global N_2O emissions from adipic acid production up to 2050 (Mt CO_2eq/yr) (Source: This study)

Our analysis clearly shows that higher deployment of the single and dual abatement technologies will result in significant abatement rates for the global adipic acid industry under the Advanced scenario. By application of the single and dual abatement technologies globally, the annual N_2O emissions will decrease by 90% and 94% up to 2035 and 2050, respectively under the Advanced scenario. The total annual N_2O emissions of the global adipic acid industry in this scenario will drop from 142 Mt CO_2eq/yr in 2022 to 14 Mt CO_2eq/yr in 2035 and 8.1 Mt CO_2eq/yr in 2050 under the Advanced scenario.

By assuming that 50% of the Chinese facilities have and operate N_2O abatement technologies in 2021, all emissions levels in the model will be dropped significantly since they have a lower starting point in 2021 as shown in Figure 5. According to the results of our analysis, in the second mode of analysis and under the BAU scenario, total N_2O emissions of the global adipic acid industry will increase by about 87% between 2021 and 2050. However, under the Moderate scenario, due to the moderate adoption of the abatement technologies in the second mode of analysis, the annual N_2O emissions will decrease by 44% and 93% up to 2035 and 2050. In the second mode of analysis, by application of the single and dual abatement technologies globally, the annual N_2O emissions will decrease by 89% and 93% up to 2035 and 2050, respectively under the Advanced scenario. The total annual N_2O emissions of the global adipic acid industry will drop from 142 Mt CO_2eq/yr in 2022 to 8.3 Mt CO_2eq/yr in 2035 and 5.5 Mt CO_2eq/yr in 2050.

4 N_2O Emissions Control Technologies for Adipic Acid Plants

The majority of adipic acid producers have implemented and operating N_2O abatement technologies except in China and, as a result, N_2O emissions have decreased substantially in the past decades except in China. In industry there are several different methods to restrict the pollutant emissions of N_2O listed below including; catalytic decomposition of N_2O to N_2 and O_2, thermal destruction - N_2O decomposition in a boiler; conversion of N_2O into recoverable NO; recycle to nitric acid and recycle to feedstock for adipic acid.

Of these processes, catalytic abatement is considered the simplest removal method for N_2O. Catalysts such as noble metals Pt and Au, pure or mixed oxides spinel, perovskite – types, or hydrotalcite on varied supports are used. Unfortunately, there are some problems linked to the strong exothermicity of the reaction such as sintering of the catalyst or their supports, high investment costs for the special heat-resistant materials for reactor bodies, and the potential to generate regulated NO_x with increasing reactor temperature.

Thermal abatement occurs either by oxidizing or reducing the N_2O. In the first case, N_2O is oxidized into NO and NO_2 and absorbed in water to recover nitric acid, to be recycled in the process upstream. In the reducing case, an excess of methane is fed to the gas mixture. The excess of methane produces an unburnt share (CO and H_2), which is a driving force for the reduction of nitrogen oxides to nitrogen.

Adipic acid facilities commonly direct the reaction-coproduced N_2O gas to a reductive furnace in a thermal destruction process at high temperatures to reduce nitric oxide (NO_x) emissions. Thermal destruction is the combustion of off-gases (including N_2O) in the presence of CH_4. The combustion process converts N_2O to nitrogen, resulting primarily in emissions of NO and some residual N_2O. The heat generated from this process can also be used to produce process steam used for heating applications in the facility (U.S. EPA, 2019).

Recycling technologies either convert N_2O to nitric acid or use N_2O as an input in another industrial process. These technologies have abatement efficiencies ranging from 90-99% when running at full capacity (e.g., single thermal reduction units can operate at a 90% destruction factor; modern catalytic technologies can achieve a destruction factor in the upper 90%). The installation of multiple abatement controls (either multi-phase systems or second auxiliary systems) helps ensure abatement efficiency of close to 98% including periods of system maintenance (Industrious Labs, 2022).

Table 3 provides information related to the abatement rates of the N_2O abatement technologies for the adipic acid plants from different sources.

Table 3. Abatement rates of the N_2O abatement technologies for the adipic acid industry

Catalytic decomposition	Thermal destruction	Twin technologies (catalytic plus thermal)	Recycle to nitric acid	Recycle to feedstock for adipic acid	Reference
99%	90%	98%	NA	NA	(Industrious Labs, 2022)
95%	95%	99%	NA	NA	(Winiwarter et al., 2018)
92.5%	98.5%	NA	98.5%	94%	(IPCC, 2006)
99%	99%	NA	NA	NA	(Schneider et al., 2010)
95%	94%-96%	NA	98%	NA	(EU BREF, 2003)

In our analysis, we have investigated the impact of catalytic decomposition, thermal destruction, and twin technologies. The recycling technologies mentioned in Table 3 are out of the scope of the analysis. In our modeling we have assigned the generic single abatement technology (catalytic or thermal) a 90% abatement rate and the generic dual abatement technology a 98% abatement rate.

5 Adipic Acid Value Chain – Intermediary and Consumer Products

Figure 6 illustrates the share of adipic acid consumed for downstream intermediary industries (Merchant Research & Consulting, 2022). Adipic acid intermediaries include nylon 6,6, polyurethane, adipate ester, and other products. Nylon 6,6 is the most significant adipic acid intermediary with a share of over 83% (over 2,500 kt/yr) and polyurethane is the second largest user with a share of over 8% (over 230 kt/yr) of total global adipic acid consumed.

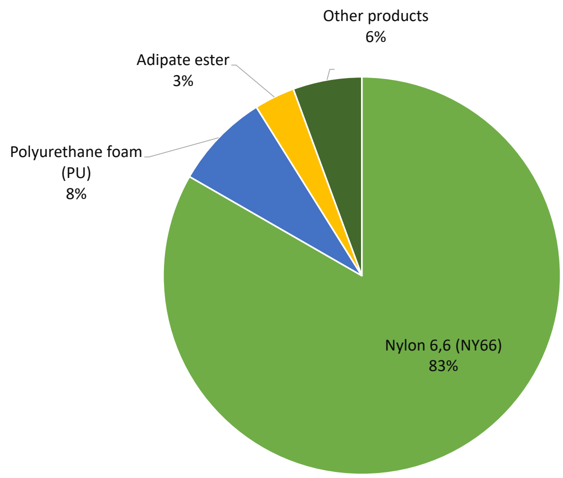


Figure 6. Share of adipic acid consumed in downstream intermediary industries globally in 2021

The adipic acid market is anticipated to have substantial growth in the future with the rising demand for adipic acid in the global market (Tealfeed, 2021). Figure 7 demonstrates the adipic acid value chain with the intermediary and consumer products. The automotive industry is the most important consumer segment for both nylon 6,6 and polyurethane. The global production levels of adipic acid, nylon 6,6, and polyurethane foam in 2021 are provided in Table 4.

Table 4. Production of adipic acid, nylon 6,6, and polyurethane foam globally in 2021

Product	Produced amount in 2021 (kt/yr)	Reference
Adipic acid	3,068	(Industrious Labs, 2022)
Nylon 6,6 (NY66)	1,340	(Chemanalyst, 2022)
Polyurethane foam (PU)	24,720	(Statista, 2022)

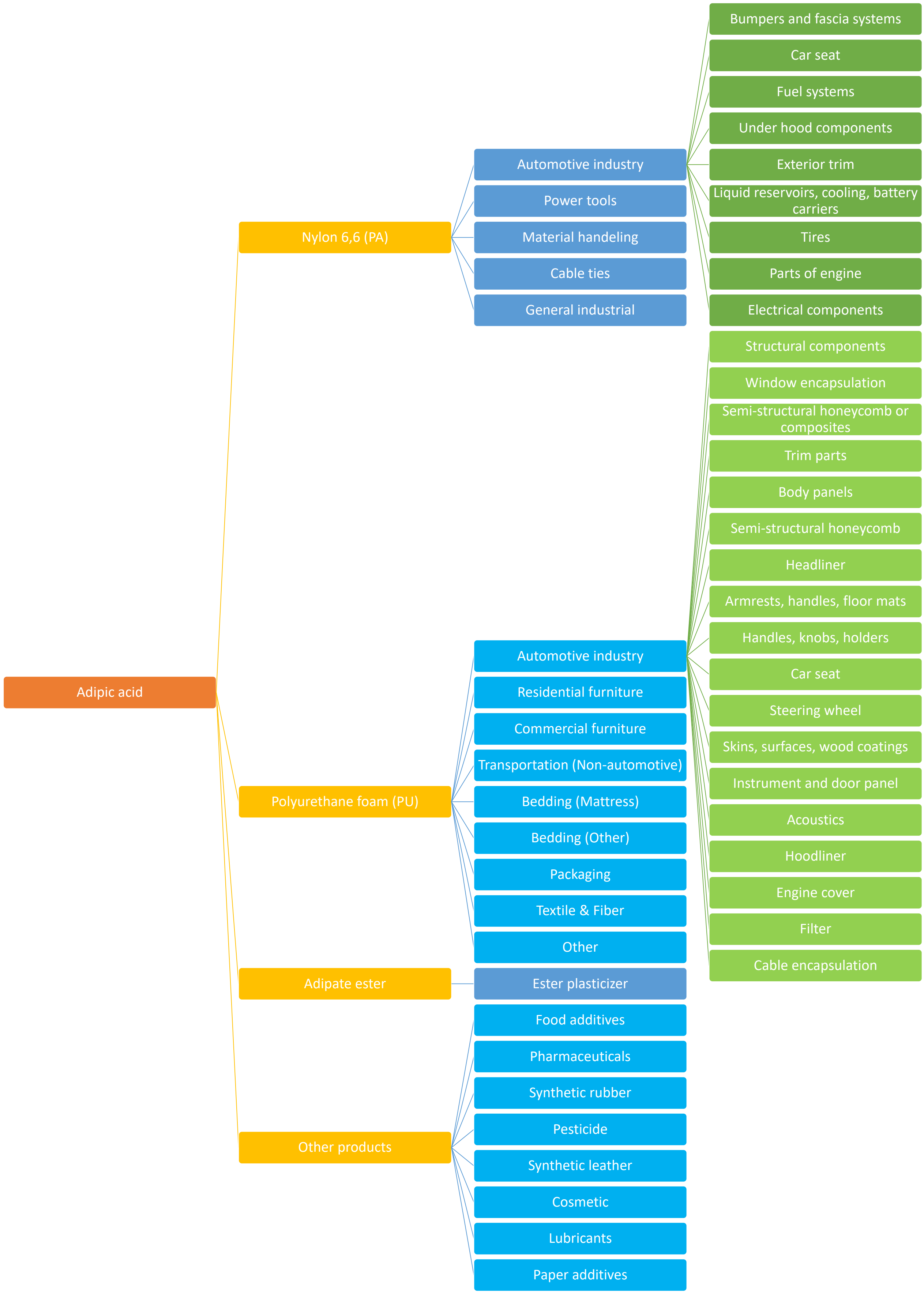


Figure 7. Adipic acid value chain with the intermediary and consumer products (Source: Compiled from various sources by this study)

The share of nylon 6,6 consumed in downstream industries is provided in Figure 8 (Chemanalyst, 2022). Automotive industries consume about 65% of global nylon 6,6. About

25% of nylon 6,6 is consumed in power tools, material handling, and general industries and about 10% is consumed for the production of cable ties.

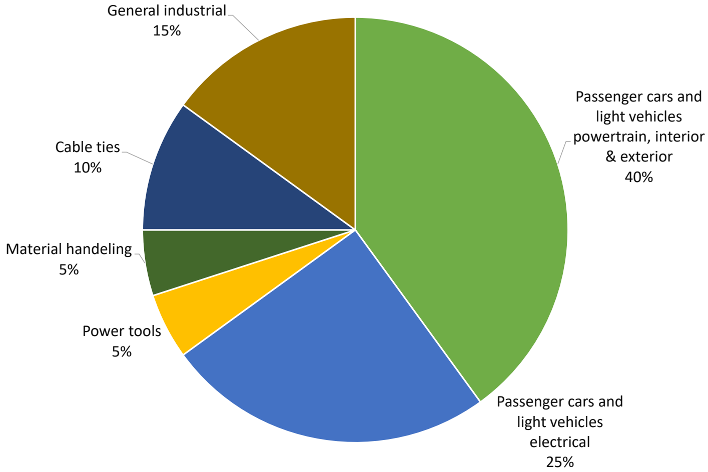


Figure 8. Share of nylon 6,6 consumed in downstream industries globally in 2021

The share of polyurethane consumed in downstream industries is provided in Figure 9 (American Chemistry Council, 2016). The bedding mattress segment consumes about 40% of the global polyurethane. About 51% of the polyurethane is consumed in furniture, non-automotive transportation, packaging, textile and fiber, and other industries and about 9% of polyurethane is consumed by passenger cars and light vehicles.

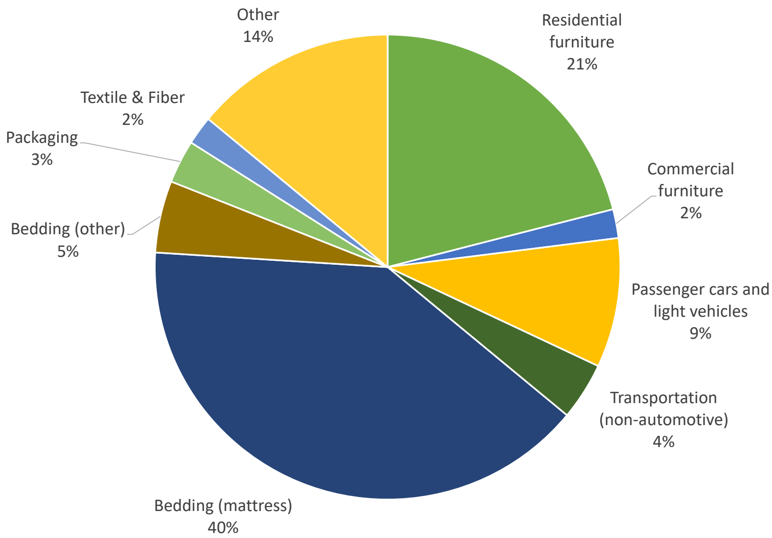


Figure 9. Share of polyurethane consumed in downstream industries globally in 2021

After mapping the adipic acid value chain, we calculated the amount of embodied N_2O emissions for each intermediary and consumer product. Chapter 6 and chapter 7 below shows the results of this analysis.

6 Embodied N_2O Emissions in Nylon 6,6, Polyurethane, and Their Value Chain

Nylon is one of the most popular and widely used engineering thermoplastic materials due to its cost-effective and excellent mechanical properties. Adipic acid and hexamethylene diamine are combined to create repeat units of 6 carbon atoms, thus the name nylon 6,6. Nylon 6,6 is also known for dimensional stability, higher melting point, and compact molecular structure. With a less open structure, the nylon 6,6 fiber has good dye wash fastness, Ultraviolet (UV) light-fastness, and excellent performance in high-speed spinning processes (Maximize market research, 2020).

Automotive applications dominate the global market for nylon 6,6. Increasing demand for automobiles because of global population growth, infrastructure improvements and rising consumer disposable income is anticipated to boost nylon 6,6 market growth over the next few decades. A shift towards fuel-efficient and eco-friendly automobiles has encouraged the application of nylon 6,6 in automobiles which also boost its market growth. An increase in the production of electronic and electrical products is also likely to influence the demand of the nylon 6,6 market (Maximize market research, 2020). Its demand in the engineering plastics industry has maintained a relatively high growth rate in recent years driven in part by strong economic growth in the U.S. and China. (Chemanalyst, 2022).

Polyurethanes are widely used polymers to manufacture a variety of products in almost all industries, such as electronics, automotive, footwear, furniture, construction, packaging, etc. The polyurethane market is segmented into rigid foam, flexible foam, coating, elastomers, adhesives, and sealants as well as other product types. Polyurethane in elastomers, foams, and coatings offers excellent abrasion resistance. Over three-quarters of the global consumption of polyurethane products is in the form of foams, with flexible and rigid types being roughly equal in market size. Rigid polyurethane foams are being widely used as insulation materials because of the combination of cost-effectiveness and low heat transfer properties. Flexible foams are behind upholstery fabrics in commercial and domestic furniture. Polyurethane is also used for moldings which include door frames, columns, balusters, window headers, pediments, medallions, and rosettes good low-temperature capability, wide molecular structural variability, low cost, and high abrasion resistance are all supporting market growth for polyurethanes.

Below, we first present the embodied N_2O emissions in nylon 6,6 and polyurethane which are the two main downstream intermediaries of adipic acid value chain. After that, we present the embodied N_2O emissions in selected consumer products which are using nylon 6,6 and/or polyurethane as one of their raw materials.

The embodied N_2O emissions of nylon 6,6 and polyurethane production make up the majority of the embodied N_2O emissions in adipic acid value chain due to their high share of adipic acid consumption. The global embodied N_2O emissions due to adipic acid consumption in nylon 6,6 and polyurethane were about 112 and 10.5 Mt CO_2eq/yr in 2021, respectively (Figure 10).

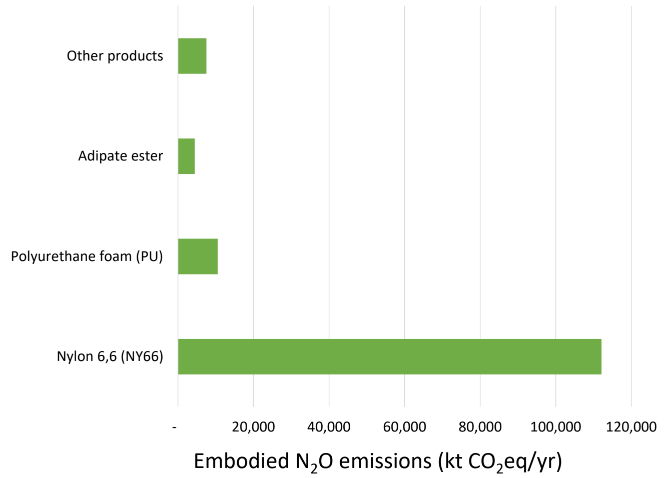


Figure 10. Global embodied N_2O emissions in adipic acid intermediaries in 2021 (kt CO_2eq/yr) (Source: This study)

In the previous section, we highlighted that passenger cars and light vehicles as well as cable ties are the significant consumers of nylon 6,6. Also, we highlighted that passenger cars and light vehicles as well as bedding mattresses are two of the most significant consumers of polyurethane. In this section, we will the embodied N_2O emissions in these consumer sections.

Figure 11 illustrates the embodied N_2O emissions in nylon 6,6 downstream products. Passenger cars and light vehicles are by far the most important consumer sector with the largest embodied N_2O emissions from nylon 6,6 consumption with about 73 Mt CO_2eq/yr (combined for powertrain, interior & exterior, and electricals). Therefore, this nylon 6,6 consumer sector will be investigated further for embodied N_2O emissions (see below). Also, our results show that the cable ties industry will be a good case for further investigations, as the annual embodied N_2O emissions in this sector were more than 11 Mt CO_2eq/yr in 2021.

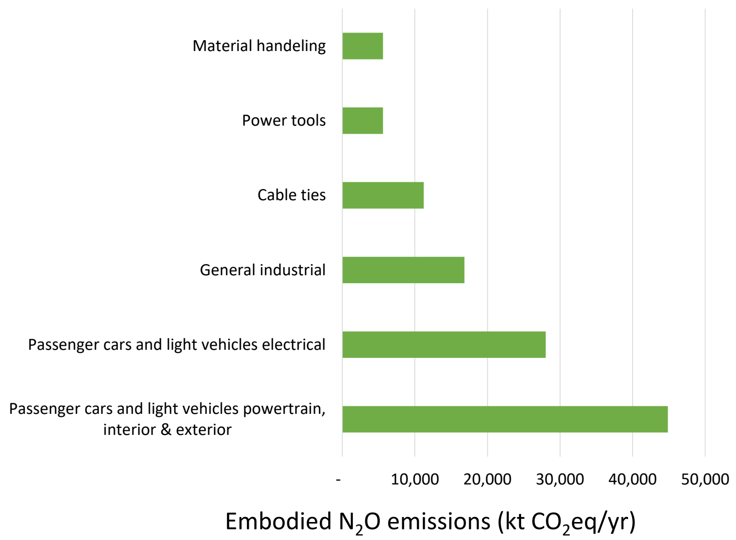


Figure 11. Embodied N_2O emissions by nylon 6,6 related industries due to adipic acid consumption in 2021 (Source: This study)

Figure 12 shows the embodied N_2O emissions in polyurethane downstream products. The bedding mattress is the most important consumer of polyurethane with the highest embodied N_2O emissions from polyurethane consumption with about 4.2 Mt CO_2eq/yr in 2021. Therefore, this polyurethane consumer sector will be investigated further for embodied N_2O emissions (see below). Also, our investigation showed that car seats that are used in the passenger cars and light vehicles sector use both nylon 6,6 and polyurethane. This is considered in our estimation of embodied N_2O emissions in this product.

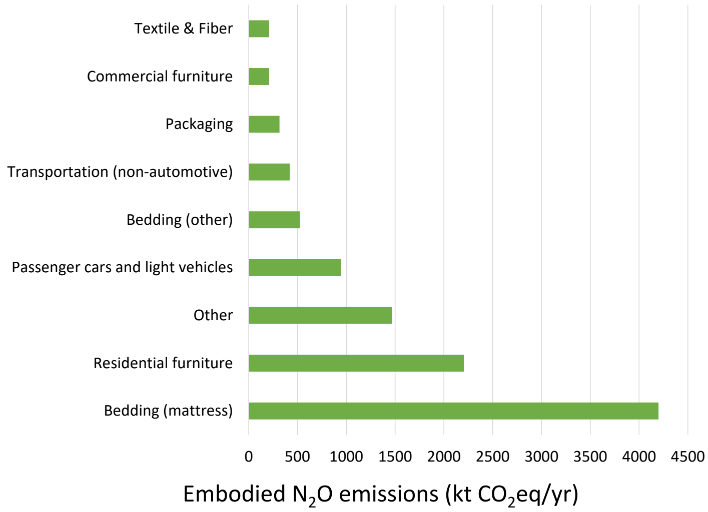


Figure 12. Embodied N_2O emissions by polyurethane-related industries due to adipic acid consumption in 2021 (Source: This study)

The following consumer products which use nylon 6,6 and/or polyurethane have been selected for further analysis on embodied N_2O emissions and cost impacts: nylon 6,6 (NY66) and polyurethane (PU) for passenger cars and light vehicles industry and their seats, tires and airbags, nylon 6,6 for cable ties, and polyurethane for bedding mattress.

Figure 13 shows the embodied N_2O emissions for the selected consumer products in adipic acid value chain. In addition, we estimated the total embodied N_2O emissions in passenger cars and light vehicles globally which is around 74 Mt CO_2eq/yr in 2021. The automotive sector has the strongest leverage to incentivize the installation of the N_2O abatement technologies in its upstream thereby reduce its GHG emissions footprint. For the passenger cars and the light vehicles industry, about 99% of the source of these embodied N_2O emissions belong to nylon 6,6 and the remaining is sourced by polyurethane. Out of this 74 Mt CO_2eq/yr, the share of tires, airbags, and car seats are 15, 4.6, and 4.3 Mt CO_2eq/yr, respectively (Figure 13).

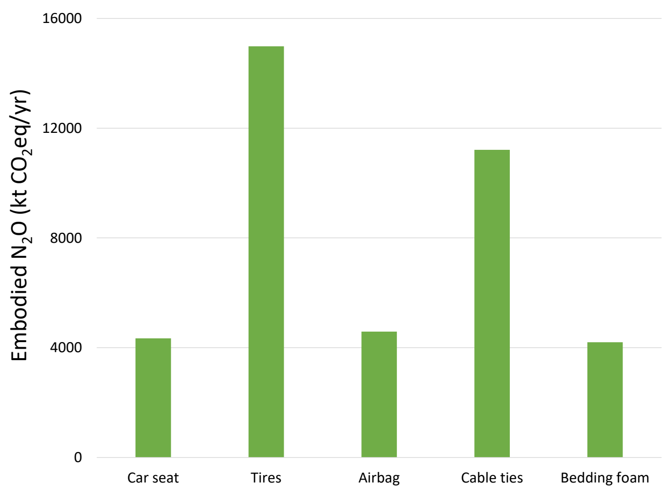


Figure 13. Embodied N_2O emissions for the selected consumer products in 2021 (Source: This study)

In the production of car seats, both nylon 6,6 and polyurethane are consumed. About 78% of the source of the embodied N_2O emissions is related to nylon 6,6 and about 22% is sourced by polyurethane in car seats production. The cable ties, produced by nylon 6,6, had 11.2 Mt CO_2eq/yr of embodied N_2O emissions in 2021. The bedding mattress industry, with 4.2 Mt CO_2eq/yr embodied N_2O emissions, is another important consumer product with a source of polyurethane.

The embodied N_2O emissions intensities for these products are shown in Figure 14. Our analysis estimates that a passenger car or light vehicle has an average embodied N_2O emissions of 976 kg CO_2eq/vehicle, just shy of 1 tonne CO_2eq per vehicle[2]. The embodied N_2O emissions intensity for an airbag, car seat, and tire is estimated to be 28.7, 14.3, and 9.4 kg CO_2eq/product, respectively. Embodied N_2O emissions intensity for cable tie and bedding mattresses are estimated to be 0.2 and 6.2 kg CO_2eq/product, respectively.

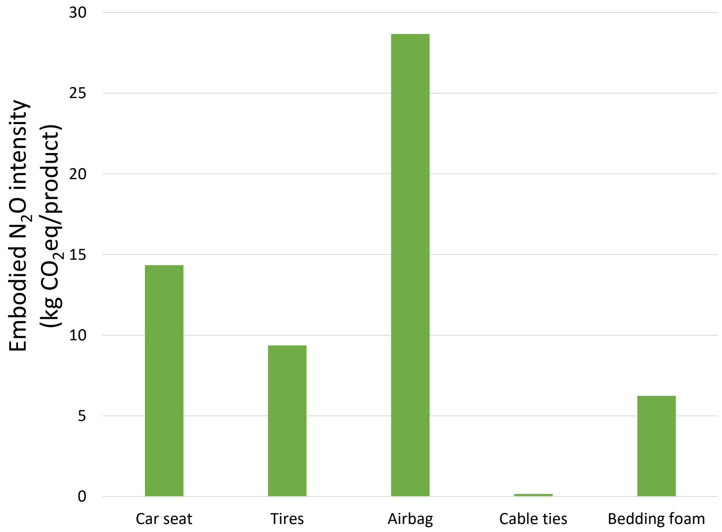


Figure 14. Embodied N_2O emissions intensity for the selected consumer products in 2021 (Source: This study)

2 For comparison the embodied CO_2 emissions associated with steel used in a passenger car is around 0.9 and 1.8 tonne CO_2 per car if manufactured using steel produced in the U.S. and China, respectively. Around 900 kg of steel used in a passenger car (worldsteel, 2022). The average CO_2 emissions intensity of the steel industry in the U.S. and China are 1.0 and 2.0 tonne CO_2 per tonne crude steel (Hasanbeigi, 2022).

7 N_2O Abatement Cost Impact on Adipic Acid Intermediaries and Final Consumers

To evaluate the cost impact of applying N_2O emissions abatement technologies in adipic acid plants on intermediaries and final consumer products, we have determined the marginal abatement costs per unit of reduced N_2O emissions ($/ton CO_2eq) for each product. According to some sources (China Dialogue, 2020, Inside Climate News, 2020), Chinese adipic acid facilities are the main producers that have not implemented or run N_2O emissions abatement technologies. However, a large plant in U.S. (Ascend plant) is operating only minimal levels of N_2O emissions control well below the performance of European, Japanese, or South Korean plants.

We have investigated the cost impact of adipic acid on selected intermediaries and final consumer products with the application of N_2O emissions abatement technologies in Chinese facilities. Table 5 shows the marginal abatement cost assumptions used in this analysis for N_2O emissions abatement technologies installed in adipic acid plants from various sources. Applying a single N_2O abatement technology (catalytic decomposition or thermal destruction) for the adipic acid facility, may result around 95% abatement. Application of twin abatement technology could increase the abatement rate to around 99% (Winiwarter et al., 2018). Since the capital cost of the twin abatement technology is substantially higher than the single abatement technology while it provides only around 5% higher abatement rate, it results in a substantially higher marginal cost of N_2O emissions abatement ($/ton CO_2eq) for the twin abatement technology.

Table 5. The marginal cost of N_2O emissions abatement technologies for adipic acid plants

Catalytic decomposition ($/ton CO_2eq)	Thermal destruction ($/ton CO_2eq)	Twin technologies (Catalytic plus Thermal) ($/ton CO_2eq)	Reference
0.2	0.2	4	(Winiwarter et al., 2018)
0.07 - 0.22	0.146	NA	(IEA, 2000)
0.18 - 0.4	0.1 - 0.18	2.59 - 4	(Schneider et al., 2010)
0.15	NA	NA	(IIASA, 2005)

Table 5 shows that the maximum marginal cost for a single abatement technology is 0.4 $/ton CO_2eq. We also assumed that an additional 25% (0.1 $/ton CO_2eq) will be added to this cost due to operational costs. Thus, we assumed that abatement of one ton of CO_2eq of N_2O emissions will cost $0.5 per ton CO_2eq to the adipic acid facility. The capital cost for installation of a single abatement technology in a typical adipic acid production facility with the capacity of 100 kt/yr will be around $3.9 million.

Using the production and embodied N_2O emissions data provided in the previous sections, we calculated the N_2O abatement cost impact on adipic acid selected intermediaries and final products. Figures 15 and 16 illustrate the N_2O abatement cost impact on adipic acid intermediaries' industries if the cost of N_2O emissions abatement were to increase the price of adipic acid. Due to the higher share of nylon 6,6 from adipic acid consumed globally compared to polyurethane, the associated annual abatement cost for nylon 6,6 industry will be the larger share and is estimated to be around $46 million per year for the entire global industry (M$/yr).

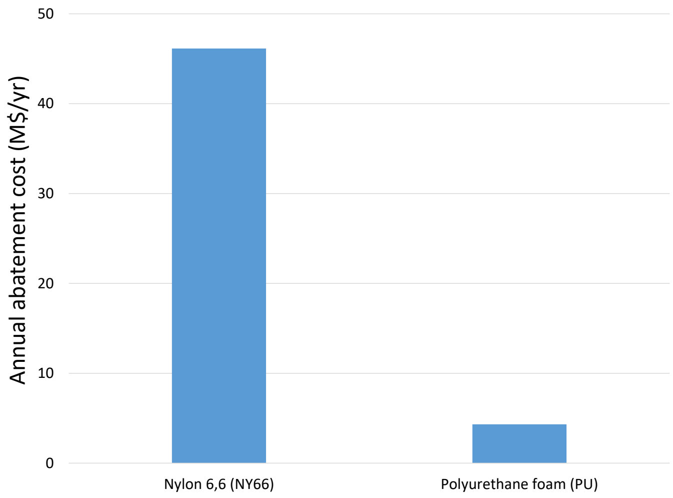


Figure 15. N_2O abatement cost impact on adipic acid intermediaries (Source: This study)

As per the incremental cost per unit of product, due to the high production quantity of polyurethane and a relatively lower ratio of adipic acid consumption for this intermediary, the abatement cost per unit of product is estimated to be $0.17 per tonne of polyurethane produced, while the cost is much higher for nylon 6,6 at $34 per tonne of nylon 6,6 produced (Figure 16). However, these prices should be considered in context of nylon 6,6 commodity prices, which have recently been in the $3000 to $5000 per tonne range, which translates into N_2O abatement resulting in an approximately 1% change in commodity pricing if the entire cost is reflected in nylon 6,6 wholesale prices.

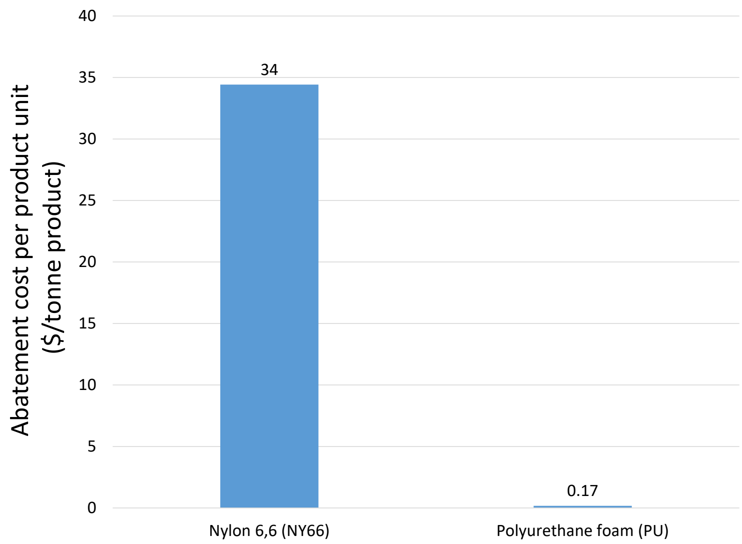


Figure 16. N_2O specific abatement intensity impact on adipic acid intermediaries (Source: This study)

Figures 17 and 18 show the N_2O abatement cost impact on final products if the cost of N_2O emissions abatement were to increase the price of adipic acid and associated intermediary products (i.e. nylon 6,6 and polyurethane). The global passenger cars and light vehicles industry in total is estimated to require an abatement cost of around 30 M$/yr and is the most affected sector. Out of this amount, the share of tires, car seats, and airbag manufacturers will be 6.2, 1.8, and 1.9 M$/yr in total annual abatement costs, respectively. The cable ties industry is estimated to require 4.6 M$/yr in total abatement cost and the bedding mattress industry is estimated to require 1.7 M$/yr in incremental (Figure 17).

The global market size for nylon 6,6 in 2021 was around 5.25 billion $/yr (Maximize market research, 2022). The share of automotive industry from the global nylon 6,6 market in 2021 was about 3.7 billion $/yr. Therefore, the impact of required investment in N_2O abatement technologies in adipic acid plants on automotive industry (30 M$/yr) is less than 1% of the cost to purchase nylon 6,6 by the global automotive industry.

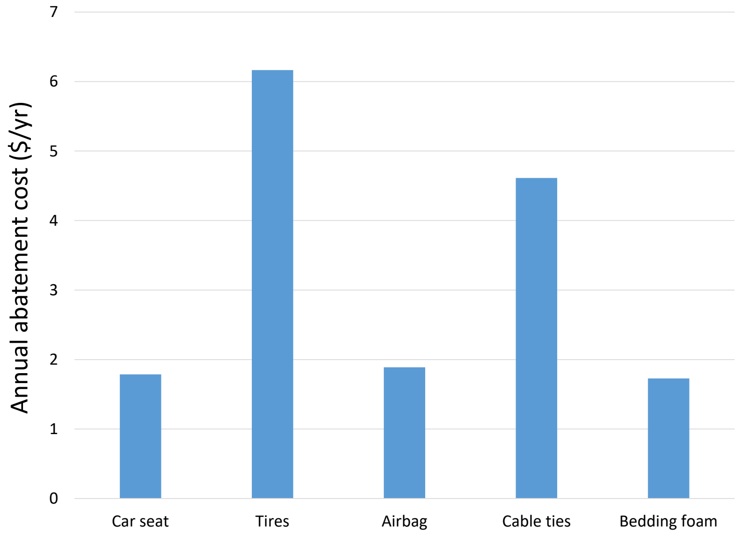


Figure 17. N_2O abatement cost impact on the selected consumer products (Source: This study)

As per the abatement cost per unit of product, the average abatement cost for a passenger car or light vehicle is just $0.4 per vehicle. The abatement cost for airbags, car seats, and tires is estimated to be $0.012, $0.006, and $0.004 per product, respectively. The abatement cost for cable ties and bedding mattresses are estimated to be $0.00007 and $0.0026 per product, respectively. We conclude that the cumulative total abatement cost for all the nylon 6,6 components in a light duty vehicle would be less than $0.4 per vehicle.

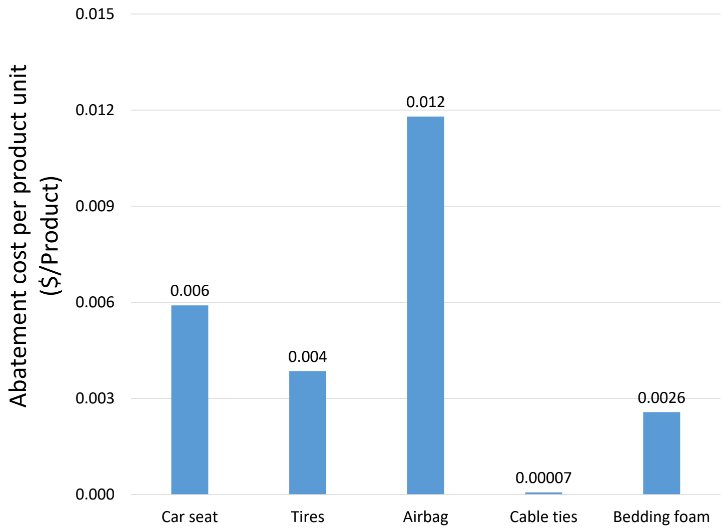


Figure 18. N_2O abatement cost impact on the selected final products (Source: This study)

8 Conclusions and Recommendations

Adipic acid is primarily used in the production of nylon 6,6 and polyurethanes. There are estimated to be 39 operational facilities globally producing adipic acid while almost two third of the global adipic acid production takes place in China and U.S. Adipic acid production is one of the largest sources of nitrous oxide (N_2O) emissions. The impact of 1 kg of N_2O on warming the atmosphere is almost 273 times that of 1 kg of carbon dioxide (CO_2). Therefore, N_2O is one of the so-called super pollutants.

This study investigated the N_2O emissions in the global adipic acid industry value chain. We analyzed N_2O emissions in the global adipic acid industry by country and made a forecast up to 2050. Then, we discussed the fully commercialized N_2O emissions control technologies that adipic acid production plants can implement to reduce their N_2O emissions to near zero. We investigated the N_2O emissions in the adipic acid value chain and the embodied N_2O emissions in intermediary products (e.g. Nylon 6,6, and polyurethane) and final consumer products in downstream of adipic acid value chain. We then quantified the N_2O abatement cost impact on adipic acid intermediary products and final consumer products.

We forecasted the total N_2O emissions of the global adipic acid industry up to 2050 under different scenarios by applying varying adoption rates for abatement technologies. Our analysis clearly showed that the higher deployment of the single and dual abatement technologies will result in significant abatement rates for the global adipic acid industry under the advanced scenario. Below is the summary of the results:

- In the **business-as-usual (BAU) scenario**, total N_2O emissions of the global adipic acid industry are projected to increase by about 92% between 2022 and 2050 while adipic acid production is assumed to increase by 53% during the same period.

- In the **Moderate scenario**, due to the moderate adoption of the abatement technologies, the annual N_2O emissions are projected to decrease by 42% and 94% up to 2035 and 2050 compared to 2022 levels.

- In the **Advanced scenario** application of the single and dual abatement technologies globally resulted in the projected annual N_2O emissions decreasing by 90% and 94% up to 2035 and 2050 compared to 2022 levels.

Nylon 6,6 is by far the most significant adipic acid intermediary with a share of over 83% (over 2,500 kt/yr) and polyurethane is the second largest with a share of 8% (over 230 kt/yr). Automotive industries consume about 65% of the produced nylon 6,6 and the bedding mattress segment consumes about 40% of the produced polyurethane.

A summary of the embodied N_2O emissions of the adipic acid intermediaries and selected consumer products in our analysis is summarized below:

- Global embodied N_2O emissions from adipic acid consumption for nylon 6,6 was about 112 Mt CO_2 eq in 2021.
- Global embodied N_2O emissions from adipic acid consumption for polyurethane was about 10.5 Mt CO_2 eq in 2021.

- The passenger cars and light vehicles industry is estimated to account for 74 Mt CO_2eq/yr and may benefit from the most from the installation of the N_2O abatement technologies in its upstream. The share of tires, car seats and airbags are 15, 4.6, and 4.3 Mt CO_2eq/yr, respectively.
- The cable ties industry is estimated to account for 11.2 Mt CO_2eq/yr of embodied N_2O emissions and is another important consumer product sourced from nylon 6,6.
- The bedding mattress industry is estimated to account for 4.2 Mt CO_2eq/yr of embodied N_2O emissions.

Our analyses indicate that adipic acid emissions reductions are highly cost effective, with high-level controls available at less than $0.50 per ton of CO_2eq abated, and ultra-high levels of control at less than $5 per ton of CO_2eq abated. Our analysis for the incremental cost of N_2O abatement from adipic acid industry showed that the average incremental cost for the passenger car or light vehicle is estimated to be $0.4 per vehicle. The incremental cost for airbags, car seats and tires are estimated to be $0.012, $0.006, and $0.004 estimated to be $0.00007 and $0.0026 per unit of product, respectively.

Conducting an awareness campaign through the key players and manufacturers of the automotive industry can support the installation and operation of the N_2O emissions abatement technologies in their supply chain in the adipic acid facilities. Consumers of adipic acid can play a key role in encouraging the use of these abatement technologies and in turn, lower the embodied emissions of the consumer products they produce.

References

Ameri sleep, 2022. How much does a memory foam mattress weigh. Available at: https://www.amerisleep.com.au/how-much-does-a-memory-foam-mattress-weigh#:~:text=Weights%20of%20these%20mattress%20types,of%20material%20in%20the%20bed

American Chemistry Council, 2016. End-Use Market Survey on the Polyurethanes Industry in the United States, Canada and Mexico.

American Chemistry Council, 2022. Automotive industry groups. Available at: https://www.americanchemistry.com/industry-groups/diisocyanates-dii/dii-applications/automotive

American Chemistry Council, Economics & Statistics Department, 2019. Plastics and Polymer Composites in Light Vehicles. Available at: https://www.automotiveplastics.com/wp-content/uploads/Plastics-and-Polymer-Composites-in-Light-Vehicles-2019-REV-Sm.pdf

Ausbeds, 2022. Queen size mattress. Available at: https://www.ausbeds.com.au/mattress-size/queen-size-mattress/

BASF, 2019. Polyurethanes for automotive enthusiasts. Available at: https://plastics-rubber.basf.com/global/en/performance_polymers.html

Cable ties online, 2022. How many cable ties are sold each year. Available at: https://www.cableties-online.co.uk/blog/how-many-cable-ties-are-sold-each-year#:~:text=From%20its'%20initial%20production%20in,cable%20ties%20are%20the%20same

Capece, N. Università di Bologna. 2018. Catalysts study of adipic acid synthesis from 1,6-hexanediol .Available at: https://amslaurea.unibo.it/16711/1/Capece_Noemi_tesi.pdf

Chemanalyst, 2022. Nylon 6,6 Market Analysis. Available at: https://www.chemanalyst.com/industry-report/polyamide-66-market-682

Climate Action Reserve, 2022. Adipic Acid Production Protocol Version 1.0. Available at: https://www.climateactionreserve.org/wp-content/uploads/2021/07/Adipic-Acid-Production-Protocol-V1.0_Package_072721.pdf

ClimeCo Corporation, 2019.Adipic Acid Production Issue Paper. Available at: https://www.climateactionreserve.org/wp-content/uploads/2019/10/Proposed-Adipic-Acid-Production-Issue-Paper_Public_FINAL.pdf

Data bridge market research, 2021. Global adipic acid market report. Available at: https://www.databridgemarketresearch.com/reports/global-adipic-acid-market#:~:text=Global%20Adipic%20Acid%20Market%20was,forecast%20period%20of%202022%2D2029

DuPont, 2000. Materials Selection for Airbag Fabrics. Available at: https://docplayer.net/62866731-Materials-selection-for-airbag-fabrics.html

Eastex Products, Inc., 2020. Nylon products. Available at: https://www.eastexproducts.com/products/420d-nylon

ERC Evolution Ltd., 2021. News posted by ERCE on 26/08/2021, updated 03/10/2022Based on IPCC Sixth Assessment Report (AR6) Global Warming Potentials. Available at: https://www.ercevolution.energy/ipcc-sixth-assessment-report/

European Aluminium Association, 2022. The aluminum automotive manual, Applications – Car body – Interior and other applications. Available at: https://european-aluminium.eu/blog/aluminium-automotive-manual/

European IPPC Bureau, 2003. BAT reference documents. Available at: https://eippcb.jrc.ec.europa.eu/reference

Fact.Mr, 2021. Polyurethane Market Outlook (2022-2032). Available at: https://www.factmr.com/report/polyurethane-market

Fortune business inside, 2022. Mattress market. Available at: https://www.fortunebusinessinsights.com/mattress-market-102108

Goldstein research, 2022. Global tire recycling industry market trends analysis. Available at: https://www.goldsteinresearch.com/report/global-tire-recycling-industry-market-trends-analysis

Hasanbeigi, A., 2022. Steel Climate Impact - An International Benchmarking of Energy and CO_2 Intensities. Global Efficiency Intelligence, LLC.

Industrious Labs. 2022. N2O Emissions from Global Adipic Acid Production.

Intergovernmental Panel on Climate Change (IPCC), 2021. Adipic acid and nitric acid production. Available at: https://www.ipcc-nggip.iges.or.jp/public/gp/bgp/3_2_Adipic_Acid_Nitric_Acid_Production.pdf

International energy agency (IEA), 2000. Abatement of other greenhouse gases - Nitrous oxide, Report number PH3/29. Available at: https://ieaghg.org/docs/General_Docs/Reports/PH3-29%20nitrous%20oxide.pdf

International Institute for Applied Systems Analysis (IIASA), 2005. The GAINS Model for Greenhouse Gases - Version 1.0: Nitrous Oxide (N2O). IIASA Interim Report IR-05-55..

IPCC, 2006. Guidelines for National Greenhouse Gas Inventories, Volume 3: Industrial Processes and Product Use. Available at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol3.html

Maximize market research, 2021. Nylon 66 Market – Global Industry Analysis and Forecast (2021-2027) by Grade, Application, and Region.

McKenna, P., Pike, L. and Northrop, K. China Dialogue. 2020. Eleven Chinese chemical plants may have stopped controlling 'super-pollutant'. Available at: https://chinadialogue.net/en/pollution/chinese-chemical-plants-super-pollutant-nitrous-oxide/

McKenna, P., Pike, L. and Northrop, K. Inside Climate News. 2020. 'Super-Pollutant' Emitted by 11 Chinese Chemical Plants Could Equal a Climate Catastrophe.. Available at: https://insideclimatenews.org/news/06082020/china-n2o-super-pollutant-nylon-emissions-climate-change/

Merchant Research & Consulting ltd., 2022. Adipic Acid World Market Outlook and Forecast up to 2031. Available at: https://mcgroup.co.uk/researches/adipic-acid-adpa

Pehlken, A. 2004. The Processing of Scrap Tyres with Focus on the Comminution Technology. Aufbereitungs-Technik/Mineral Processing 45 (5), pp. 37-46. Available at: https://www.researchgate.net/publication/282856985_The_Processing_of_Scrap_Tyres_with_Focus_on_the_Comminution_Technology

Procurement resource, 2022. PA66 (Nylon 66) Price Trend. Available at: https://www.procurementresource.com/resource-center/pa66-nylon-66-price-trends

Qing, T., et al. 2020. Scenario Analysis on Abating Industrial Process Greenhouse Gas Emissions from Adipic Acid Production in China. Petroleum Science 17. pp. 1171–79. Available at: https://link.springer.com/article/10.1007/s12182-020-00450-0#additional-information

Reed, S., Hutchison, M., 2000. Green Chemistry in the Organic Teaching Laboratory: An Environmentally Benign Synthesis of Adipic Acid, Journal of Chemical Education, vol. 77, Issue 12. pp. 1627–1629. Available at: https://pubs.acs.org/doi/10.1021/ed077p1627

Schneider, L., Lazarus, M. Kollmuss, A. Stockholm Environment Institute. 2010. Industrial N_2O Projects Under the CDM: Adipic Acid - A Case of Carbon Leakage?. Available at: https://www.sei.org/publications/industrial-n2o-projects-cdm-adipic-acid-case-carbon-leakage/

Statista, 2022. Global polyurethane market size forecast. Available at: https://www.statista.com/statistics/720341/global-polyurethane-market-size-forecast/

Statista, 2022. Worldwide motor vehicle production by type,. Available at: https://www.statista.com/statistics/1097293/worldwide-motor-vehicle-production-by-type/

Statista, 2022. Worldwide motor vehicle production by type. Available at: https://www.statista.com/statistics/1097293/worldwide-motor-vehicle-production-by-type/

Survival Tech Shop, 2022. Average Tire Weight (With 10 Examples). Available at: https://www.survivaltechshop.com/tire-weight/

Tealfeed, 2021. Global adipic acid market report. Available at: https://tealfeed.com/track-suits-market-global-upcoming-demand-growth-qzap0

Techly, 2022. Cable tie nylon patch. Available at: https://www.techly.com/cable-tie-nylon-patch-280x4-8-mm-100-pcs-black.html

TextileSchool, 2022. Airbag woven fabrics for automobiles. Available at: https://www.textile-school.com/7601/air-bag-woven-fabrics-for-automobiles/

United Nations Environment Program (UNEP), 2013. Drawing Down N2O To Protect Climate and the Ozone Layer.

United States Environmental Protection Agency (U.S. EPA), 2019. Office of Atmospheric Programs (6207A). Washington. DC 20005. EPA-430-R-19-010. Global Non-CO2 Greenhouse Gas Emissions Projections & Mitigation 2015-2050.

Winiwarter, W., Hoglund-Isaksson, L., Klimont, Z., Schopp W. and Amann, M., 2018. Technical opportunities to reduce global anthropogenic emissions of nitrous oxide, Environmental research letters 13. Available at: https://doi.org/10.1088/1748-9326/aa9ec9

worldsteel. 2022. Steel in automotive. https://worldsteel.org/steel-topics/steel-markets/automotive/

Ye, Y., et al. 2017. The development of polyurethane, Materials Science: Materials Review. pp. 1–8. Available at: https://ojs.whioce.com/index.php/msmr/article/view/507

Appendices

Appendix 1. Description of the adipic acid production process

Currently, adipic acid is obtained by a two-step oxidation process. In the first step, the oxidation of cyclohexane in a mixture of cyclohexanone/cyclohexanol (One/Ol, KA Oil) is performed by air and in the second step, the oxidation of KA Oil to adipic acid with HNO_3 occurs. (Figure 19).

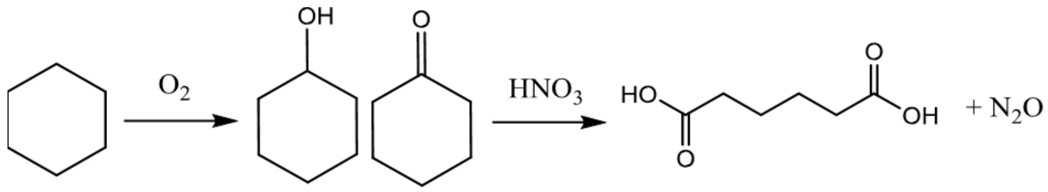


Figure 19. The conventional process for the manufacture of adipic acid from KA Oil (Reed et al., 2000)

Cyclohexane derives from either the hydrogenation of benzene or from naphtha fraction but is only utilized in a small quantity. The oxidation of cyclohexane to KA Oil was first industrialized by DuPont in the early 1940s. The reaction conditions utilize temperatures between 150 °C and 180 °C and pressures between 10-20 atm. The reaction is catalyzed by Co or Mn organic salts in the liquid phase. Products of this oxidation are KA Oil, with a selectivity of 75-80 %, as the primary product and carboxylic acids (mainly succinic and glutaric acid) as by-products (Capece, 2018).

The reaction is carried out in a series of three reactors (Figure 20). Cyclohexane is fed in the first reactor and air is distributed to the three reactors, allowing better control of the reaction and improving safety. In the first reactor, cyclohexane is oxidized to cyclohexyl hydroperoxide which is the rate-limiting step of the process. The decomposition of hydroperoxide is carried out in the second reactor, where catalyst quantities and reaction conditions are optimized. During the process the products are washed with water and a caustic solution, to reduce acid impurities (Capece, 2018).

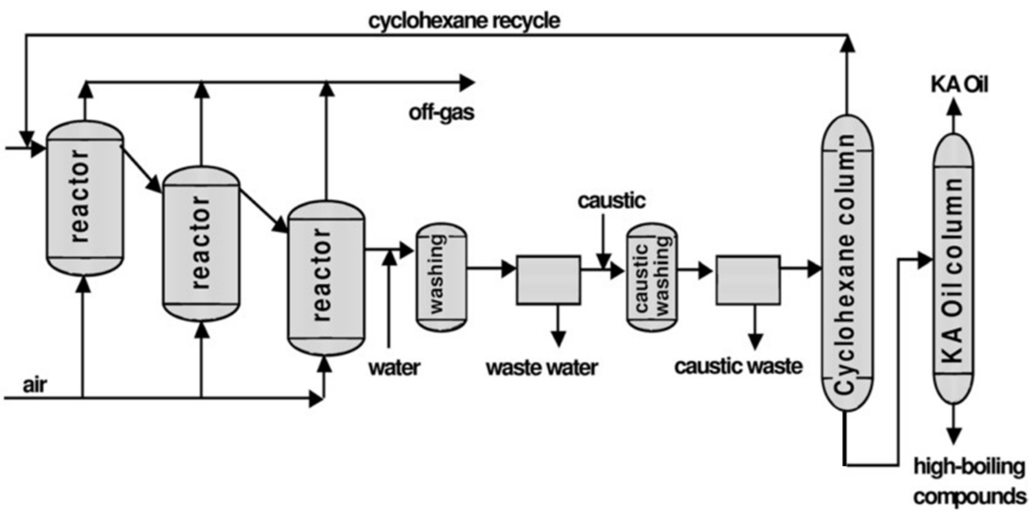


Figure 20. Simplified flow diagram of the process for the oxidation of cyclohexane with air

The current process adopted a variation characterized by the use of substantial quantities of anhydrous meta-boric acid in a process known as Bashkirov Oxidation. No other catalyst is necessary for this process. Boric acid reacts with cyclohexanol to give a borate ester that stabilizes the product and reduces its tendency to be oxidized further to form either cyclohexanone or degradation products. Results show a conversion of 10% (or even 15%) and selectivity of 90%. The borate ester formed is easily hydrolyzed by hot water to boric acid and cyclohexanol. Alternately in this process, there are two other variations currently employed: hydrogenation of phenol to KA Oil and hydration of cyclohexene to cyclohexanol (Capece, 2018).

The hydrogenation of phenol, this process is safer than that based on cyclohexane oxidation, leading to reduced investment costs. Moreover, by increasing the amount of ketone it is possible to use less nitric acid in the next oxidation step.

For the oxidation option, cyclohexane is obtained from benzene by partial hydrogenation. Due to the difficulty to stop the hydrogenation of benzene to cyclohexene it is necessary to work with a catalyst consisting of Pt or Ru powder, coated with a layer of an aqueous solution of zinc sulfate. The reaction is carried out in a bi-phasic system composed of benzene and water solution (Capece, 2018).

Since cyclohexene is less soluble in the aqueous phase it migrates preferentially to the organic phase, avoiding further hydrogenation. Cyclohexane is obtained with 80% selectivity and is further hydrated on a ZMS-5 catalyst to produce cyclohexanol. Less hydrogen is consumed in this process and fewer by-products are formed compared to the above-mentioned methods, but more nitric acid must be used in the subsequent oxidation step. The second step in the synthesis of adipic acid from cyclohexane is the further oxidation of KA Oil with 65% nitric acid in a molar ratio of HNO_3/KA Oil of at least 7/1 in presence of Cu and ammonium metavanadate catalyst (Capece, 2018).

The reaction mechanism has been known since 1963 and is discussed in detail by van Asselt and van Krevelen. In the first step nitric acid oxides, are cyclohexanol to cyclohexanone, and the latter is further nitrosated to 2-nitroso cyclohexanone by nitrous acid. Many reactions occur during this step; however, the main pathway is the formation of 2-nitro-2-nitroso cyclohexanone, which is hydrolyzed to 6-nitro-6-hydroximinohexanoic acid. The final step is the oxidative hydrolysis of the latter product to adipic acid (Capece, 2018).

The reaction is carried out in two in-series reactors: the first operates at 60-80 °C and the second one at 90-100 °C under a pressure of 1-4 atm (Figure 21). KA Oil conversion is 95% and by-products are glutaric acid (selectivity 3%) and succinic acid (selectivity 2%) (Capece, 2018).

Due to the exothermicity of the reaction, to avoid run-away, the KA Oil mixture is added in small amounts to the solution of the nitric acid and the catalyst in the first reactor. In the second reactor the products are stripped by air to separate nitrogen oxides (NO_x) and nitrous oxide (N_2O). Nitrogen compounds and others gas streams deriving from the first two reactors are adsorbed in water. The last step allows converting of nitrogen oxides into nitric acid to recycle the reagent for the oxidation of KA Oil, nitrous oxide is treated to reduce the emissions (Capece, 2018).

The aqueous phase, carrying the main products, is passed through a crystallizer. The first crystallization permits the separation of the adipic acid from the solution, and then the recrystallization is done again to purify the product. After the separation of adipic acid, the solution is concentrated to obtain nitric acid with a concentration of about 60%. One part of this liquid is recycled while the other is purged and the catalyst is recovered (Capece, 2018).

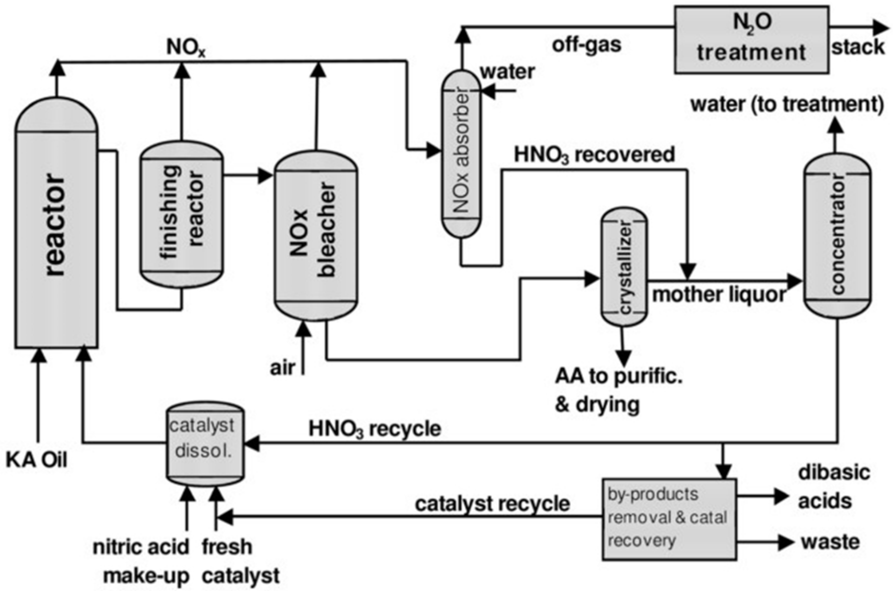


Figure 21. Simplified flow diagram of oxidation of KA Oil to adipic acid

The last step of the oxidation process could be also carried out under an air atmosphere using Cu-Mn acetate. In this case, reaction mixtures rich in cyclohexanone are used. Oxidation is conducted in acetic acid solution at about 80-85°C and 6 bar over Cu and Mn acetate catalysts. This process has the advantage that no HNO_3 is used avoiding corrosive and environmental problems. Rohm & Hass in the U.S. produced several thousand tons of adipic acid yearly via this method but the project was abandoned due to poor product quality (Capece, 2018).

This industrial process has many disadvantages that include; low overall product yield (4-11%), corrosion of reactors and pipes due to nitric acid, high-energy consumption, and emissions of greenhouse gas N_2O (0.3 kg N_2O/kg adipic acid)

Appendix 2. List of Acronyms

atm	Atmosphere
Au	Aurum
BAU	Business as Usual
CH_4	Methane
Co	Cobalt
CO	Carbon monoxide
CO_2	Carbon dioxide
Cu	Cupper
eq	equivalent
EU	European Union
GHG	Greenhouse gas
Gt	Giga tons
H_2	Hydrogen
HNO_3	Nitric acid
KA	Ketone-alcohol
kg	Kilogram
kt	Kilo tons
M$	Million dollars
Mn	Manganese
Mt	Million tons
N_2	Nitrogen
N_2O	Nitrous oxide
NA	Not available
NO	Nitrogen monoxide
NOx	Nitrogen oxides
NY66	Nylon 6,6
O_2	Oxygen
OH	Hydroxide
Pt	Platinum
PU	Polyurethane
Ru	Ruthenium
U.S.	United States
UV	Ultraviolet
yr	Year