

**THE EFFECT OF NITRIFICATION INHIBITORS ON SOIL N₂O
EMISSIONS**

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ABSTRACT

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This thesis examines the impact of nitrification inhibitors on soil samples exposed to different temperatures, measuring the resulting nitrous oxide (N₂O) emissions. The study was conducted by a two-person team at Osnabrück University of Applied Sciences as part of the ongoing MILAGON project, which investigates greenhouse gas emissions caused by agriculture.

Nitrogen is a crucial nutrient in farming and is essential for plant growth. However, nitrogen loss is a significant issue in agriculture, leading to inefficient nutrient utilization and potential environmental harm due to its volatility. In particular, nitrous oxide emissions pose a major threat as they contribute to the greenhouse effect and climate change.

Nitrification inhibitors have previously been used successfully to stabilize nitrogen in soil, improving crop yields and enhancing nitrogen retention. However, these studies typically focused on applying inhibitors together with fertilizers during cultivation. In contrast, this study evaluates the effects of nitrification inhibitors on post-harvest soil.

In this experiment, dried cauliflower was added to the soil as plant residue, and different amounts of nitrification inhibitors were incorporated. Two inhibitors, DMPP and Piadin, were tested at three concentration levels: half the recommended amount, and twice the recommended amount. The prepared soil samples were placed in jars and stored in climate chambers at three temperatures: 5 °C, 15 °C, and 25 °C. Gas samples were collected daily over a seven-day period, except on Sundays. The gas was extracted using syringes and stored in vacuum-sealed vials before being analyzed with a gas chromatograph.

The results demonstrated that nitrification inhibitors reduced nitrous oxide emissions by 30-50%, regardless of dosage. However, environmental conditions, particularly temperature, played a more significant role in emission levels. Lower temperatures were associated with greater cumulative emissions over time.

TIIVISTELMÄ

Oulun Ammattikorkeakoulu
Maaseutuelinkeinojen tutkinto-ohjelma

Tekijä: Henry Jämsä

Opinnäytetyön otsikko: Nitrifikaation estoaineen vaikutus maaperän N₂O päästöihin

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Tämä opinnäytetyö käsittelee nitrifikaatioinhibiittoreiden vaikutusta eri lämpötiloille altistettuihin maanäytteisiin sekä näistä näytteistä vapautuvien typpioksiduulipäästöjen (N₂O) mittaamista. Tutkimus toteutettiin kaksihenkisen tutkimusryhmän toimesta Osnabrückin ammattikorkeakoulussa osana käynnissä olevaa MILAGON-projektia, joka keskittyy maatalouden aiheuttamien kasvihuonekaasupäästöjen tutkimukseen.

Typpi on keskeinen ravinne maataloudessa ja välttämätön kasvien kasvulle. Typen menetys on kuitenkin merkittävä haaste, joka johtaa ravinteiden tehottomaan hyödyntämiseen ja voi typen haihtuvuuden vuoksi aiheuttaa ympäristölle haitallisia vaikutuksia. Erityisesti typpioksiduulipäästöt ovat merkittävä ongelma, sillä ne edistävät kasvihuoneilmiötä ja siten ilmastomuutosta.

Aiemmat tutkimukset ovat osoittaneet, että nitrifikaatioinhibiittorit voivat tehokkaasti stabiloida maaperän tyyppiä, parantaa satoa sekä lisätä typen pidättymistä maassa. Näissä tutkimuksissa inhibiittorit on kuitenkin tyypillisesti levitetty yhdessä lannoitteiden kanssa viljelyn aikana. Tässä tutkimuksessa sen sijaan tarkastellaan nitrifikaatioinhibiittoreiden vaikutuksia sadonkorjuun jälkeiseen maaperään.

Kokeellisessa osassa kuivattua kukkakaalia lisättiin maaperään kasvitähteeksi, ja näytteisiin sekoitettiin eri määriä nitrifikaatioinhibiittoreita. Tutkimuksessa käytettiin kahta eri inhibiittoria, DMPP:tä ja Piadinia, ja niitä testattiin kolmella eri pitoisuudella: puolet suositellusta määrästä, suositeltu määrä ja kaksinkertainen suositeltu määrä. Valmistetut maanäytteet sijoitettiin purkkeihin, jotka säilytettiin ilmastokammioissa kolmessa eri lämpötilassa: 5 °C, 15 °C ja 25 °C. Kaasunäytteitä kerättiin päivittäin seitsemän päivän ajan, lukuun ottamatta sunnuntaita. Kaasu kerättiin ruiskulla ja säilöttiin tyhjiösuljetuissa pulloissa ennen analysointia kaasukromatografilla.

Tutkimustulokset osoittivat, että nitrifikaatioinhibiittorit vähensivät typpioksiduulipäästöjä 30–50 % annostuksesta riippumatta. Kuitenkin ympäristöolosuhteilla, erityisesti lämpötilalla, havaittiin olevan suurempi vaikutus päästötasoihin. Alemmissä lämpötiloissa kumulatiiviset päästöt olivat korkeampia ajan myötä.

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1 INTRODUCTION

Environmental concerns and climate change have become central topics across various sectors of society. In 2015, the Paris Agreement was signed by 195 countries, where the signatory nations committed to addressing climate change and mitigating global warming. Subsequently, in 2019, the Green New Deal was proposed as a European initiative aimed at reducing the cost of the green transition for businesses. These efforts are part of a broader global initiative to reduce greenhouse gas emissions and promote the sustainable use of environmental resources. One key objective of sustainability is achieving carbon neutrality, which refers to the condition where the carbon emissions of a business or industry are balanced by an equal amount of carbon absorption. (European Parliament 2023).

In the context of agriculture, reducing nitrogen loss is crucial for improving resource efficiency, both economically and environmentally. Nitrogen (N) is an essential nutrient for plant growth, and with the steady increase in cultivated land, there has been a corresponding rise in nitrous oxide (N₂O) emissions. Agriculture is significantly impacted by this challenge, and the adoption of sustainable, eco-friendly farming practices has garnered widespread attention. While nitrogen is a critical nutrient in agricultural production, it also presents an environmental risk, as it can be converted into greenhouse gases or leached into surrounding ecosystems and water bodies, leading to substantial environmental harm.

This study aims to explore methods for mitigating nitrogen leaching and atmospheric emissions by utilizing nitrification inhibitors in cultivated soils. The experiments conducted in this research seek to generate data on the emissions produced by agricultural practices and investigate potential strategies for reducing these emissions. The findings are intended to assist farmers and advisory bodies in developing new approaches to minimize fertilizer use and nitrogen loss from agricultural fields. The tests conducted as part of this research are part of the MILAGON project at Osnabrück University of Applied Sciences, which examines the effects of nitrification inhibitors post-harvest. The MILAGON

is an ongoing research project in Osnabrück University of Applied Sciences, where students can work in research projects. Two people were working on the test. The testing was done between August and November 2024.

The experiments involved varying plant residue, inhibitor quantities, and incubation temperatures. The study analyzed the impact of different levels of nitrification inhibitors and temperatures on nitrous oxide (N₂O) emissions and calculated the efficiency of these interventions.

2 ROLE OF NITROGEN IN FARMING

Nitrogen is a critical limiting nutrient for plant growth, as its availability significantly influences the development of several essential physiological factors. Nitrogen (N) is integral to the growth of plants, as it constitutes a part of the plant's cell structure and is essential for chlorophyll production. Chlorophyll, in turn, is fundamental for photosynthesis, a process in which sunlight is converted into sugars to fuel the plant's growth. Moreover, nitrogen plays a crucial role in promoting root development, which is vital for the overall health and growth of the plant. (Leghari et al. 2016, 209, 210.)

Nitrogen is extensively used in fertilizers to enhance crop yields. However, due to the environmental risks associated with excessive nitrogen application—such as leaching into surrounding ecosystems and water sources—its use is carefully regulated by local governments. Despite these concerns, nitrogen fertilization is vital for achieving high agricultural yields, as nitrogen is one of the essential elements for life. One challenge in agriculture is that nitrogen is largely inert and must be transformed by microbial activity into forms that plants can absorb and utilize.

The use of nitrogen in agriculture also presents considerable environmental challenges. It is projected that by 2050, nitrogen pollution will increase by 150%, with agriculture contributing approximately 60% of this rise. (Martínez-Dalmau Javier, Berbel Julio & Ordóñez-Fernández Rafaela 2021, 1.) In Europe, for example, 8.9 million tons of fertilizer were applied in 2022 (Eurostat 2024). Despite these environmental concerns, nitrogen remains a key limiting factor in crop production. It is essential in the synthesis of amino acids, the building blocks of proteins, and is also a component of chlorophyll, which is crucial for photosynthesis and carbohydrate formation (Leghari et al. 2016, 209, 210.).

Plants primarily absorb nitrogen from the soil through their roots, with approximately 90% of plant species forming a symbiotic relationship with mycorrhizal fungi. These fungi convert nitrites into nitrates, which plants can then absorb and use for growth. Additionally, some plants, particularly legumes, have

the ability to directly absorb nitrogen from the air. (Näsholm, Kielland & Ganeteg 2008; Mokhele, Zhan, Yang & Zhang 2011.)

However, nitrogen (N) is often poorly utilized by plants, resulting in significant losses through processes such as leaching and oxidation. It is estimated that up to half of the nitrogen applied to cultivated soil through fertilization can be lost in this manner (Beeckman, Motte & Beeckman 2018,167). Therefore, improved nitrogen management practices are essential to enhance agricultural efficiency and minimize environmental impacts. In many developing countries, over-fertilization by farmers is a common practice, leading to inefficiency due to nitrogen loss through leaching and oxidation. This inefficiency not only undermines the effectiveness of fertilization but also exacerbates environmental problems, negatively affecting local ecosystems and the living standards of the population. (Martínez-Dalmau et al.2021, 2.)

The efficiency of nitrogen (N) use can be evaluated through Nutrient Use Efficiency (NUE), a metric that quantifies how effectively nitrogen is utilized by plants. NUE is calculated by comparing the nitrogen uptake efficiency (NUpE) with the nitrogen utilization efficiency (NUE). This metric provides insights into how well plants absorb available nutrients and how efficiently the applied nitrogen is used by the crops. (Congreves, K. A. Otchere, O. Ferland, D. Farzadfar, S. Williams, S. Arcand, M.M. 2021, 2, 3.; Martínez-Dalmau et al.2021, 2.)

2.1 Nitrification

Nitrification occurs in anaerobic soils, where Nitrosomonas microbes, deprived of oxygen as a food source, begin to utilize nitrogen as an alternative nutrient. This process results in the transformation of nitrogen into forms that are prone to emission or leaching. The nitrogen cycle can be categorized into five stages: ammonification, reduction of nitrite through either assimilation or dissimilation, nitrification, denitrification, methane oxidation, and nitrate-nitrite interconversion. (Stein & Klotz 2016, 95)

Nitrogen can be introduced into cultivated fields through plant residues from previous crops, from earlier cultivation within the same field, or via the application

of fertilizers. Fertilizers typically contain nitrogen (N) in the form of ammonia ($\text{NH}_3/\text{NH}_4^+$). Through the process of electrochemical interaction, ammonia ($\text{NH}_3/\text{NH}_4^+$) is converted into hydroxylamine (NH_2OH) (Stein & Klotz 2016, 95; Wrage, Velthof, van Beusichem & Oenema 2001, 1724). Subsequently, a group of bacteria reduces the oxidation process, converting nitrate into nitrite, while transforming hydroxylamine (NH_2OH) into nitrate (NO_3^-) and nitrous oxide (N_2O). This process is illustrated in figure 1.

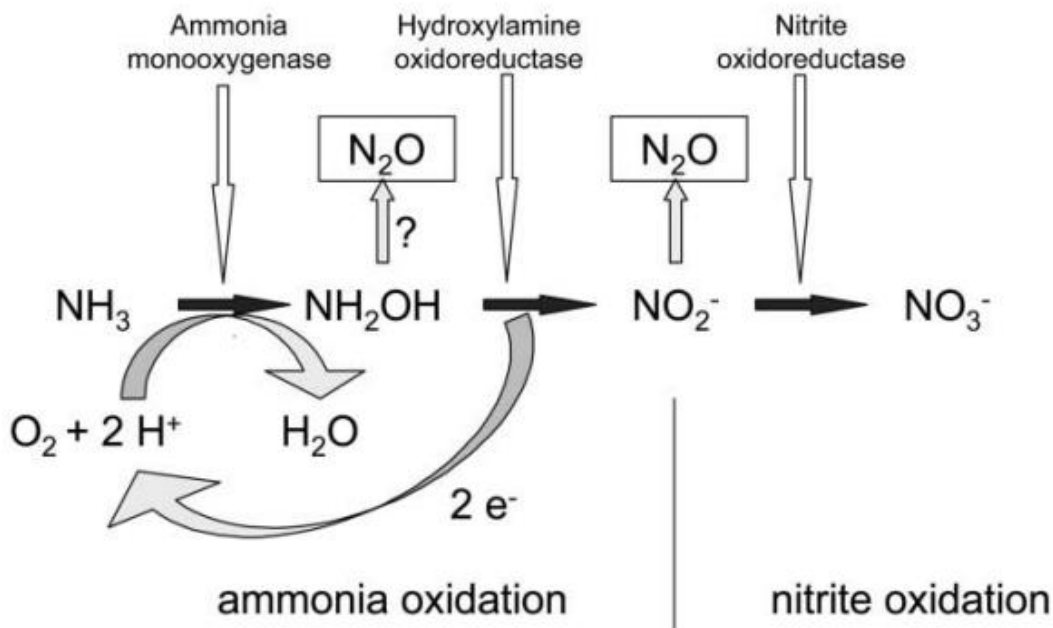


FIGURE 1. oxidation of nitrate and nitrite in the soil (Wrage, Velthof, van Beusichem & Oenema 2001.)

The microbes responsible for nitrification, known as ammonia-oxidizing microbes, are ubiquitous in the environment and can be found in both soil and freshwater sources. These microbes are typically categorized into ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA). Among the two, ammonia-oxidizing bacteria are more commonly associated with the production of nitrous oxide (N_2O) emissions, but they are also more susceptible to inhibitors. In contrast, ammonia-oxidizing archaea are more prevalent in fertilized cultivated soils than ammonia-oxidizing bacteria. However, there is currently a lack of methods to accurately differentiate which of the two nitrifying microbial groups is responsible for the majority of nitrous oxide emissions (N_2O). (Arp 2009, 2; Beeckman, Motte & Beeckman 2018, 168, 170.)

2.2 Climate effect of N₂O emission

Nitrous oxide emissions are 6% of the world's total greenhouse gas emissions. Out of all existing greenhouse gases emitted by agriculture, nitrous oxide (N₂O) is the largest by far. Global nitrous oxide (N₂O) emissions emitted by farming in the year 2020 were 2.33 billion tons, compared to CO₂ emissions that were 1.17 billion tons from land use and forestry, agriculture alone not even being its own category in the sources used. (Ritchie, Rosado & Roser 2024.)

While 6% might not seem like a large amount of total emission, the problem is that nitrous oxide (N₂O) is 273 times more potent greenhouse gas than much more common carbon dioxide (CO₂). Also, the atmospheric lifetime of the nitrous oxide (N₂O) poses a problem. Compared to carbon dioxide that stays in the atmosphere for 4 months or shorter time, nitrogen dioxide stays in the atmosphere for 109 years. (Kopittke et al. 2024, 4, 7.) Statistics show an increase in the amounts of nitrous oxide (N₂O) emission, and long atmospheric lifetimes create a risk of accumulation with time, which can contribute to climate change.

3 RESEARCH QUESTION

Nitrification can result in up to 50% nitrogen loss from soil through processes such as leaching and the conversion of nitrogen into greenhouse gases (Beeckman, Motte & Beeckman 2018, 1.). For farming to remain economically viable, cultivated fields must generate yields that provide returns on the investments made in them. This necessitates the use of fertilizers to ensure plants receive the required nutrients for growth. However, the inefficiencies in this process, particularly the aforementioned nitrogen loss, represent a loss for farmers and contribute to environmental damage by negatively impacting surrounding ecosystems and climate.

Nitrification inhibitors are already widely utilized in agriculture, often mixed with fertilizers and applied to fields slated for cultivation. These inhibitors have proven effective in retaining ammonia (NH_4^+) in the soil, thereby improving yields and nutrient use efficiency by suppressing microbial activity.

The effects of nitrification inhibitors on nitrous oxide emissions from the soil have been the subject of previous studies, which have explored variations in herbicides, nitrogen sources, and nitrification inhibitors. A study conducted at the University of Nebraska-Lincoln, titled “Nitrogen Source Regulates Soil Nitrification and Nitrogen Losses More Than Nitrification Inhibitor and Herbicide: A Laboratory Evaluation” by William Neels et al, concluded that the nitrogen source has a greater impact on reducing nitrification than the inhibitor itself. The study also found that aqueous ammonia reduced ammonia (NH_3) volatility in the soil. The findings suggest that selecting the right combination of fertilizers and nitrification inhibitors could stabilize nitrogen in the soil, leading to reduced leaching and nitrous oxide emissions. (William Neels et al. 2024, 1.)

The focus of this thesis is to investigate the effect of nitrification inhibitors on nitrogen dioxide (N_2O) emissions from soil and explore methods to reduce these emissions. Soil samples were put in jars and subjected to different treatments, varying in inhibitor dose and incubation temperature. Gas samples were collected from the jars and analyzed using gas chromatography to measure the

concentration in parts per million (ppm). From this data, the amount of emissions in kilograms was calculated. This analysis allows for the determination of how many kilograms of gas different samples emitted, thereby enabling conclusions regarding the effectiveness of the nitrification inhibitors in reducing emissions.

4 MATERIAL AND METHODS

The soil used in this experiment was sourced from previously cultivated farmland. Various amounts of crop residue and a nitrification inhibitor were incorporated into the soil samples. The process of weighing the plant residue is illustrated in figure 2. Water was then added to each sample, constituting 60% of the soil's total water-holding capacity. The nitrification inhibitor used in this study was DMPP (3,4-dimethylpyrazole phosphate), a widely used nitrogen stabilizer that is commonly added to fertilizers to minimize nitrogen loss.

One of the samples served as a control, receiving no nitrification inhibitor or plant residue. The second sample was mixed with cauliflower residue to simulate field conditions, where plant material is left in the soil after harvest and is incorporated during tilling.

For the first two repetitions, no nitrification inhibitor was added to the samples. In the remaining repetitions, three different concentrations of the nitrification inhibitor were applied: half of the recommended dose, the recommended dose, and double the recommended dose.



Figure 2. Measuring the residue

The experiment was designed with five variations, each repeated three times, resulting in a total of fifteen repetitions. A visualization of the test setup can be seen in table 2. The test was conducted at three different temperatures, resulting in a total of forty-five repetitions. The samples were placed in climate chambers set to temperatures of 5°C, 15°C, and 25°C. Each sample was contained in airtight jars to facilitate the collection of accumulated gases. In total, 270 vials were prepared for sampling, as shown in figure 3. The samples were stored in labeled vials, each sealed with a vacuum to ensure proper storage and subsequent analysis.



FIGURE 3. Vials with vacuum inside them

TABLE 1. Visualization of the test layout. The orange circles represent sample jars

	No residue No inhibitor	Residue <u>no</u> inhibitor	Residue <u>0,5</u> dose	Residue <u>1,0</u> dose	Residue <u>2,0</u> dose
5 °C					
15 °C					
25 °C					

Samples were collected over a seven-day period, excluding Sundays. On each collection day, the jars were removed from the climate chambers, and syringes were used to extract the accumulated gas. After each sampling, the jars were opened for 10 minutes to allow any residual gas to escape, before being resealed and returned to the climate chambers. Once all samples were collected, they were stored in vials for later analysis using a gas chromatograph. The model of the gas chromatograph used was the Trace 1300 from Thermo Scientific. The chromatograph columns employed were of the TG-Bond Q type, made from divinyl benzene. The primary column was 30 meters in length, while two smaller columns were each 15 meters long. All columns had a diameter of 0.53 mm. This configuration enabled precise analysis of nitrous oxide (N₂O) content in the samples. The gas chromatograph is shown in figure 4.

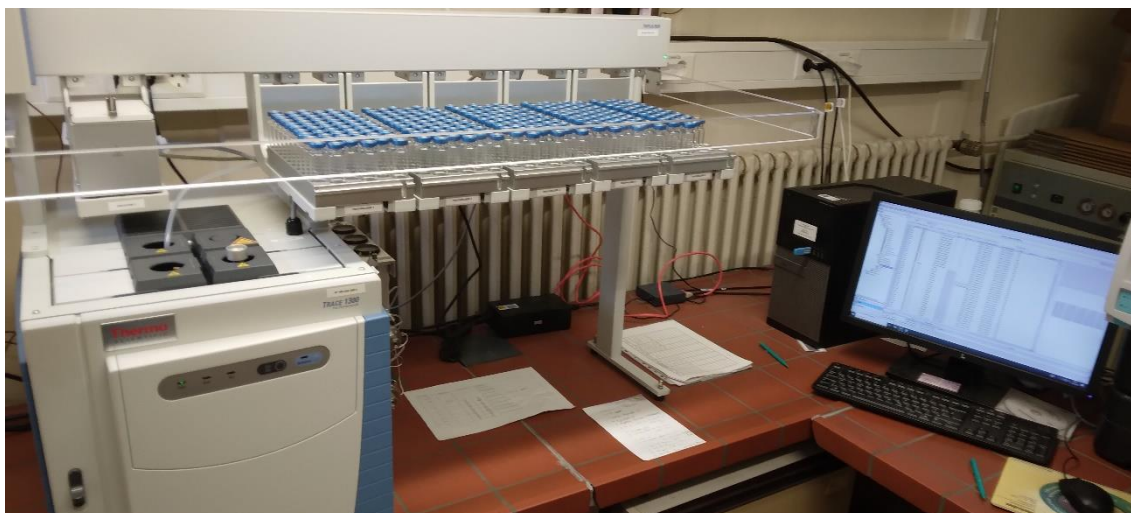


FIGURE 4. Gas chromatograph used to analyze the gas samples

The test was repeated using a different nitrification inhibitor, Piadin (3,4-dimethylpyrazole phosphate), to facilitate a comparison of results. Aside from the change in the inhibitor, the testing method remained identical to the previous procedure.

DMPP (3,4-dimethylpyrazole phosphate) is a nitrification inhibitor that targets the microbes responsible for converting nitrite into nitrate in the soil. Specifically, it reduces the activity of Nitrosomonas bacteria, which play a crucial role in the nitrification process. By inhibiting the activity of these bacteria, DMPP helps

reduce the conversion of ammonium to nitrate, thereby limiting the formation of nitrous oxide (N₂O) emissions.

1.1 DMPP

DMPP (3,4-dimethylpyrazole phosphate) is a nitrification inhibitor used in agriculture to reduce nitrogen (N) leaching and gasification from the soil. It works by decreasing the population of ammonia-oxidizing bacteria in the soil, which ensures that more nitrogen remains available for plant uptake, rather than being lost to the environment. (Adrián et al. 2022, 1.)

1.2 Piadin

Piadin is a mixture of 3-Methylpyrazole and 1H-1,2,4-Triazole, and it is commonly used as a nitrification inhibitor mixed with fertilizers. Its primary function is to reduce the loss of nitrogen (N) through leaching or gasification by inhibiting the activity of ammonia-oxidizing bacteria table. (Piadin).

5 RESULTS

1.3 Results with DMPP

The control group, as the figure 5 shows, had no residue or inhibitor, and exhibited the following emission patterns: 0,41 kg per hectare on the first day, 0,53 kg on the second day, 0,24 kg on the third day, 0,13 kg on the fourth day, 0,09 kg on the fifth day, and 0,03 kg on the seventh day.

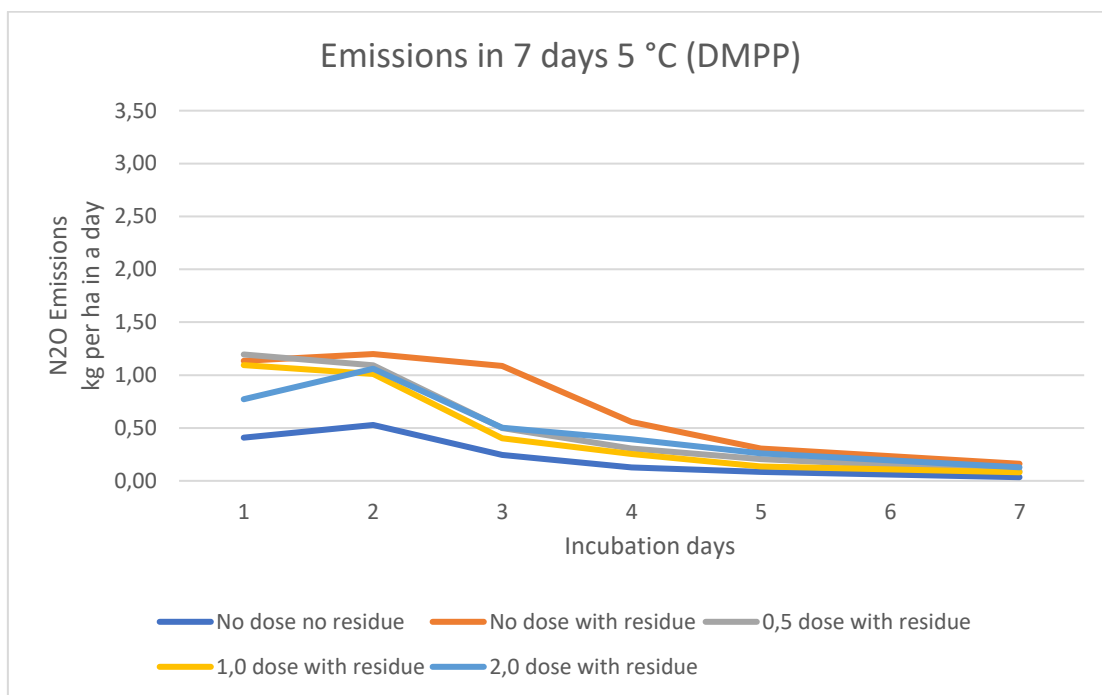


FIGURE 5. Emissions in 7 days 5 °C

Following the figure and the sample, it's seen that with plant residue mixed into the soil, emissions were 1,1 kg per hectare on the first day, 1,2 kg on the second day, 1,0 kg on the third day, 0,5 kg on the fourth day, 0,3 kg on the fifth day, and 0,1 kg on the seventh day.

For the sample with half of the recommended amount of residue, emissions were 1,1 kg per hectare on the first day, decreasing to 1,0 kg on the second day, 0,5 kg on the third day, 0,3 kg on the fourth day, 0,2 kg on the fifth day, and 0,09 kg on the seventh day.

The figure 6 illustrates the total emissions over the 7-day incubation period in 5 °C. The control group, with no dose or residue, emitted 1,43 kg per hectare. Samples that were not inhibited but contained residue emitted 4,45 kg per hectare over the course of the week. In samples where half of the recommended inhibitor dose was used, emissions were reduced to 3,39 kg per hectare. Samples treated with the full recommended amount of inhibitor emitted 2,98 kg per hectare. The sample with twice the recommended dose of inhibitor emitted 3,12 kg per hectare.

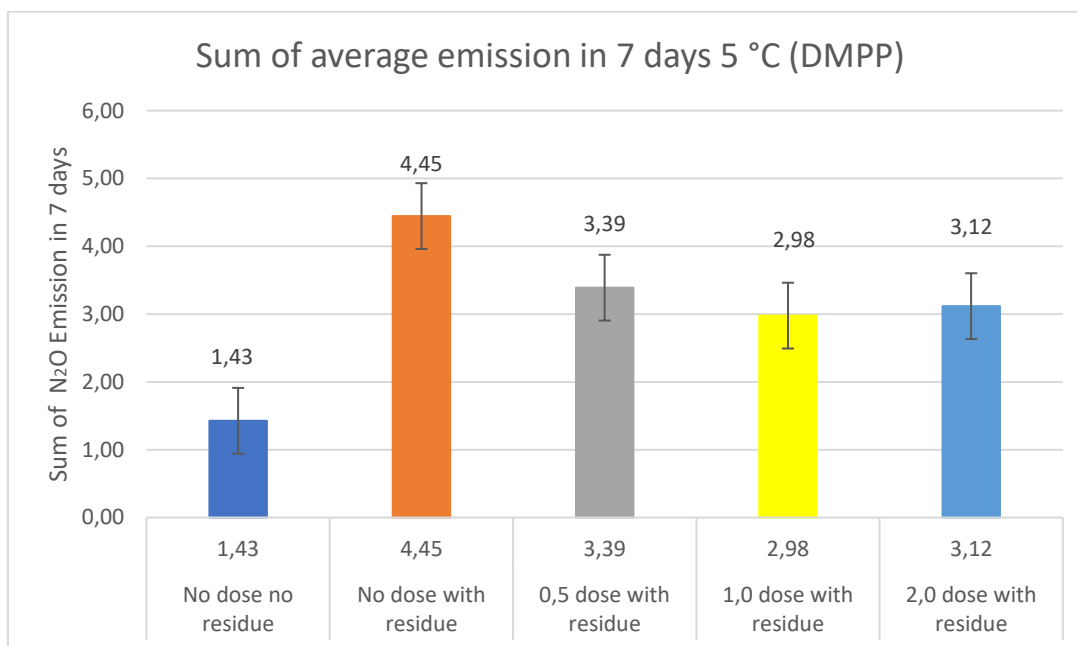


FIGURE 6. Total of accumulated emissions in 5 °C

At 15°C, the uninhibited sample with no residue initially emitted 1,25 kg per hectare on the first day, which decreased to 0,23 kg on the second day. Emissions continued to decline, reaching 0,03 kg on the third day, and remained at this low level until the fifth day, where emissions further reduced to 0,01 kg on the seventh day. As the figure 7 shows.

In the sample with plant residue, emissions were 2,96 kg per hectare on the first day. On the second day, emissions decreased to 0,37 kg, and on the third day, emissions further reduced to 0,04 kg per hectare. The decline continued at a rate of 0,01 kg per day in the following days, with emissions reaching 0,03 kg per day on the fourth day, 0,02 kg on the fifth day, and 0,01 kg per day on the seventh day.

The inhibited samples followed a similar trend, and thus, the results for all inhibited samples are explained together, using the data from the sample with the recommended amount of inhibitor. On the first day, these samples emitted 1,46 kg of nitrous oxide (N₂O), which decreased to 0,17 kg on the second day, and further dropped to 0,03 kg by the third day. Emissions did not decrease on the third day and continued at a rate of 0,03 kg per hectare per day. On the fifth day, emissions were reduced to 0,02 kg, and on the seventh day, emissions further decreased to 0,01 kg per hectare per day.

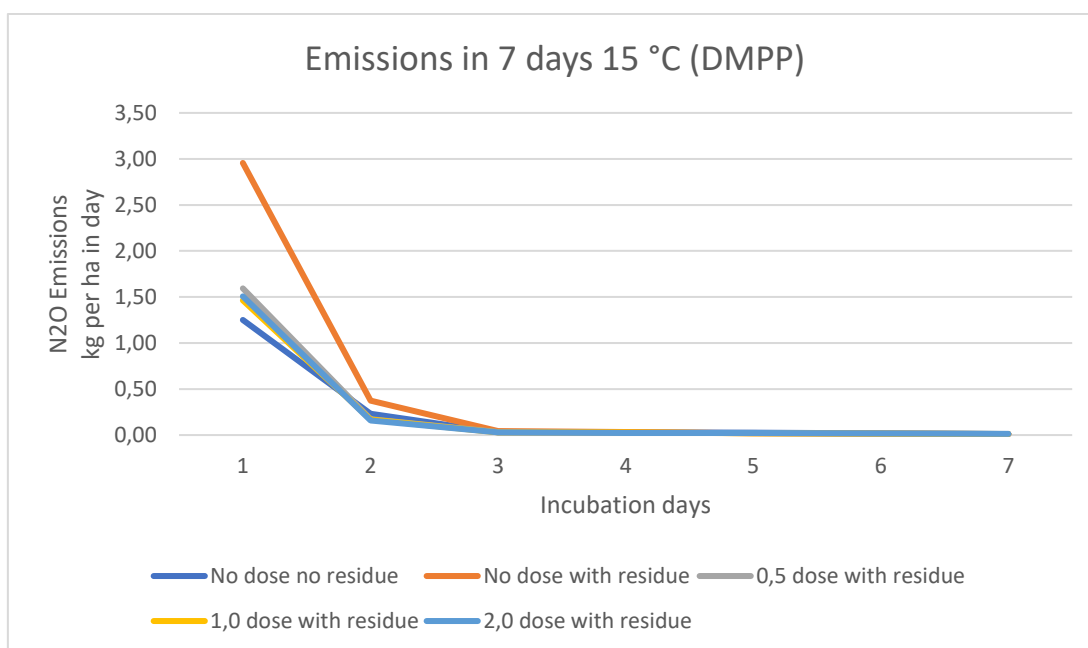


FIGURE 7. Emissions in 7 days 15 °C

The figure 8 shows that the sample with just the soil emitted 1,58 kg of nitrous oxide (N₂O) over the seven-day period, while the sample with plant residue emitted 3,43 kg. The inhibited samples exhibited lower emissions, with the sample containing half of the recommended amount of inhibitor emitting 1,85 kg. The sample with the recommended amount of inhibitor emitted 1,73 kg. Finally, the sample with double the recommended amount of inhibitor emitted 1,75 kg.

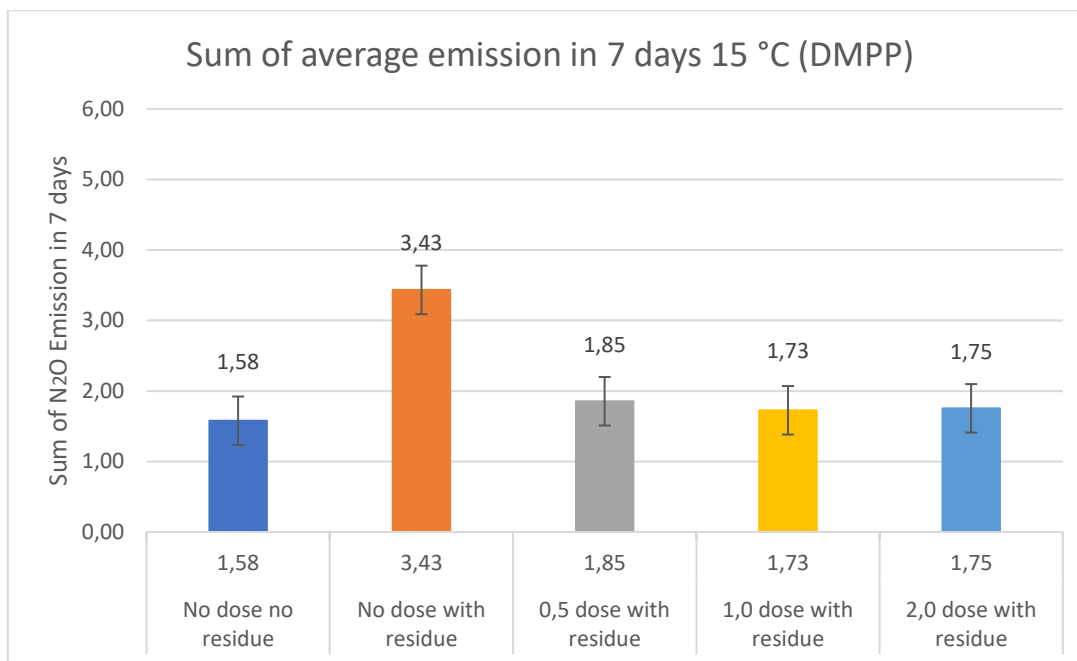


FIGURE 8. Total of accumulated emissions in 15 °C

The sample with no residue or inhibitor emitted 1,55 kg of nitrous oxide (N₂O) on the first day. On the second day, emissions decreased to 0,05 kg and further dropped to 0,03 kg on the third day. As the figure 9 shows.

The sample with only plant residue emitted 3,26 kg of nitrous oxide on the first day. Emissions decreased to 0,07 kg on the second day, and further reduced to 0,04 kg on the third day. On the fourth and fifth days, emissions remained at 0,03 kg, and on the seventh day, emissions decreased to 0,02 kg.

The inhibited samples showed slight variation in emissions, but due to the small differences, the sample with the recommended amount of inhibitor is used for analysis. On the first day, the sample emitted 1,85 kg of nitrous oxide. Emissions decreased to 0,07 kg on the second day, and further dropped to 0,04 kg on the third day. On the fourth day, emissions were reduced to 0,02 kg, followed by a slight increase to 0,03 kg on the fifth day, and then decreased again to 0,02 kg on the seventh day.

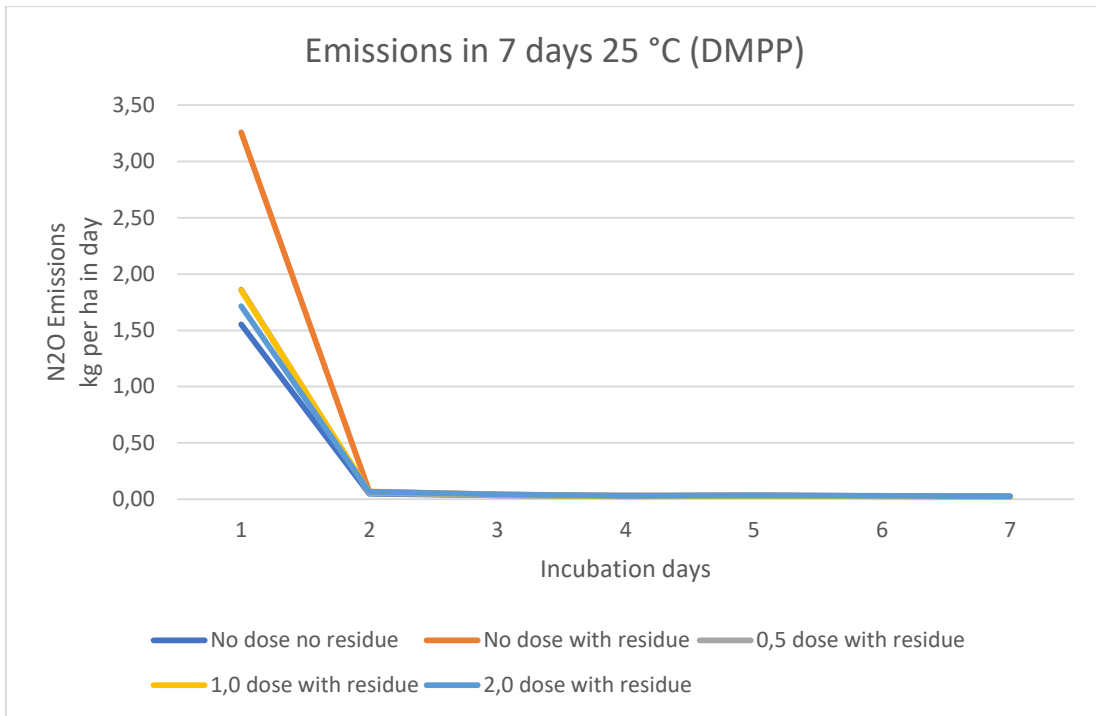


FIGURE 9. Emissions in 7 days 25 °C

The figure 10 shows the results done with the DMPP in the temperature of 25 °C. The control sample, which contained neither plant residue nor inhibitor, emitted 1,72 kg of nitrous oxide (N₂O) over the seven-day period. The sample containing only plant residue emitted 3,46 kg of nitrous oxide. Inhibited samples emitted 2,04 kg with half of the recommended dose of inhibitor and the same amount with the full recommended dose. The sample treated with twice the recommended amount of inhibitor emitted 1,91 kg of nitrous oxide.

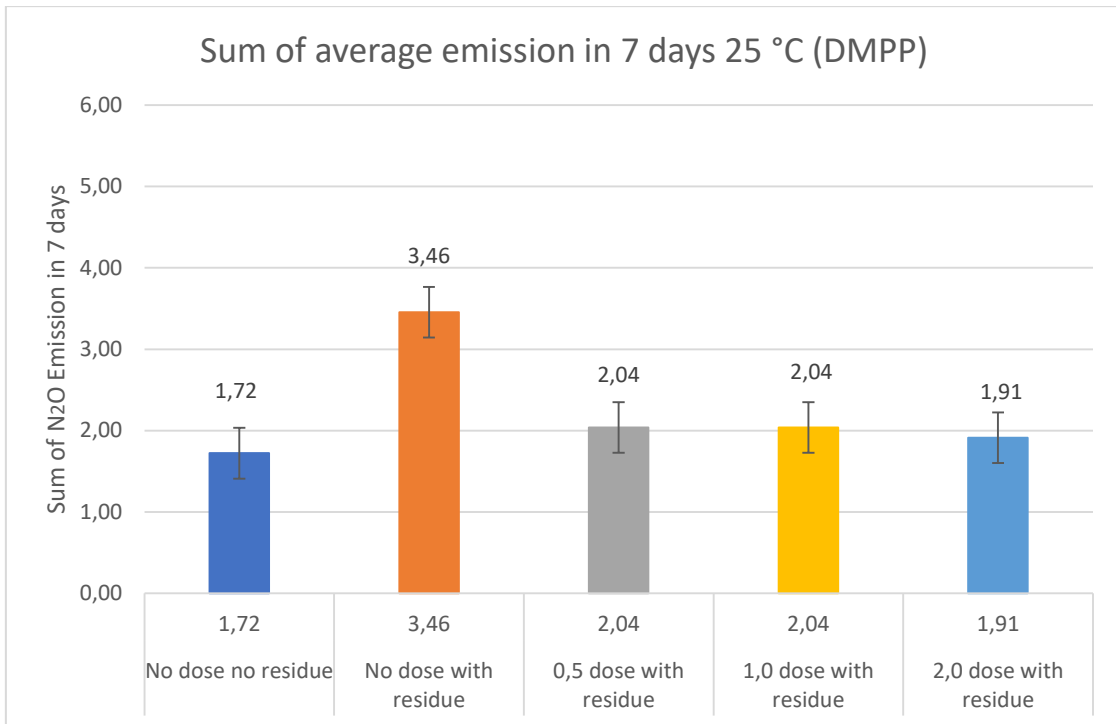


FIGURE 10. Total of accumulated emissions in 25 °C

1.4 Results with Piadin

The figure 11 shows the results of test with Piadin, and 5 °C incubation temperature. The sample with no plant residue or inhibitor emitted 0,06 kg on the first day, 0,12 kg on the second day, 0,08 kg on the third day, 0,03 kg on the fourth day, and 0 kg on the fifth day. On the seventh day, emissions were 0,01 kg.

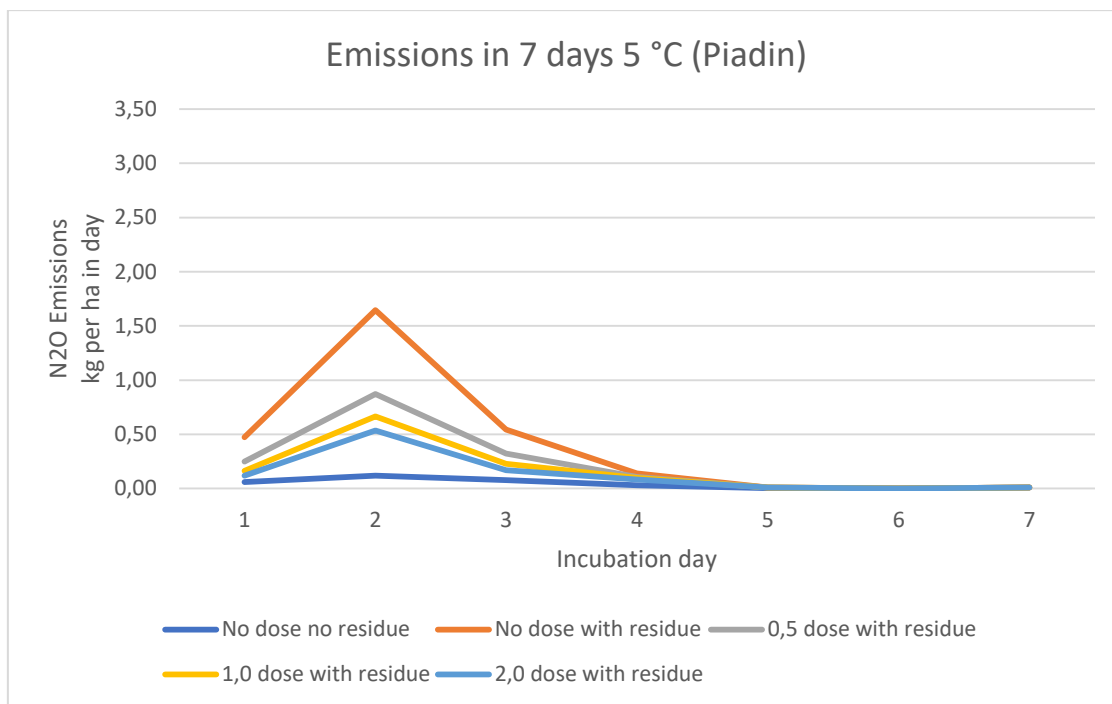


FIGURE 11. Emissions in 7 days 5 °C

The sample with only plant residue emitted 0,47 kg of nitrous oxide (N₂O) on the first day, which increased to 1,65 kg on the second day. Emissions then decreased to 0,54 kg on the third day, 0,14 kg on the fourth day, and 0,01 kg on the fifth day. On the seventh day, emissions remained at 0,01 kg.

The sample with half of the recommended amount of inhibitor emitted 0,25 kg of nitrous oxide on the first day. On the second day, emissions increased to 0,87 kg, before decreasing to 0,32 kg on the third day. Emissions further reduced to 0,11 kg on the fourth day, and to 0,01 kg on the fifth day.

The sample with the recommended amount of inhibitor emitted 0,16 kg of nitrous oxide on the first day, which increased to 0,67 kg on the second day. On the third day, emissions decreased to 0,23 kg, and further dropped to 0,10 kg on the fourth day. By the fifth day, emissions had reached their lowest point of 0,01 kg, with no further change observed by the seventh day.

The sample with double the recommended amount of inhibitor emitted 0,12 kg of nitrous oxide on the first day, which increased to 0,54 kg on the second day. On the third day, emissions decreased to 0,17 kg, and continued to decrease to 0,08

kg on the fourth day. Emissions were at 0,01 kg on the fifth day and remained at this level through the seventh day.

The figure 12 shows total average emissions over the seven-day period, done in 5 °C temperature. The figure 12 shows that the sample with no residue or inhibitor emitted 0,30 kg of nitrous oxide. The sample containing plant residue emitted 2,82 kg of nitrous oxide. Inhibited samples exhibited the following emissions: 1,57 kg for the sample with half of the recommended amount of inhibitor, 1,18 kg for the sample with the recommended amount of inhibitor, and 0,93 kg for the sample with double the recommended amount of inhibitor.

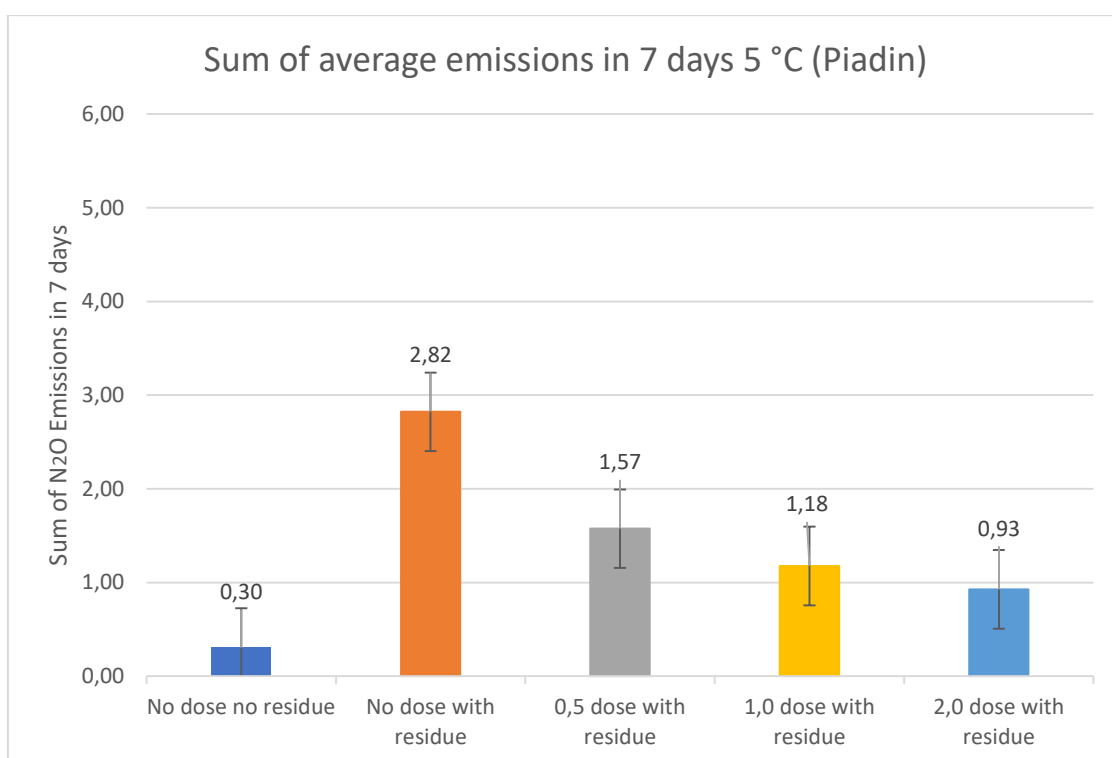


FIGURE 12. Total of accumulated emissions in 5 °C

When looking at the figure 13 and the results of 15 °C incubation temperature, the sample with no inhibitor and no plant residue emitted 0,15 kg of nitrous oxide (N₂O) on the first day. On the second day, emissions decreased to 0,02 kg, and remained at 0 kg on the third and fourth days. On the fifth and seventh days, emissions were 0,01 kg.

The sample with only plant residue emitted 0,60 kg of nitrous oxide on the first day. On the second day, emissions decreased to 0,05 kg, and during the

remainder of the trial, emissions fluctuated between 0,01 kg and 0 kg, with 0,01 kg of emissions on the third, fifth, and seventh days.

The sample with the recommended amount of inhibitor was used as a representative sample due to similar emissions and a consistent pattern. On the first day, the sample emitted 0,45 kg of nitrous oxide. On the second day, emissions dropped to 0,03 kg and further reduced to 0,01 kg. No further change in emissions occurred after the third day.

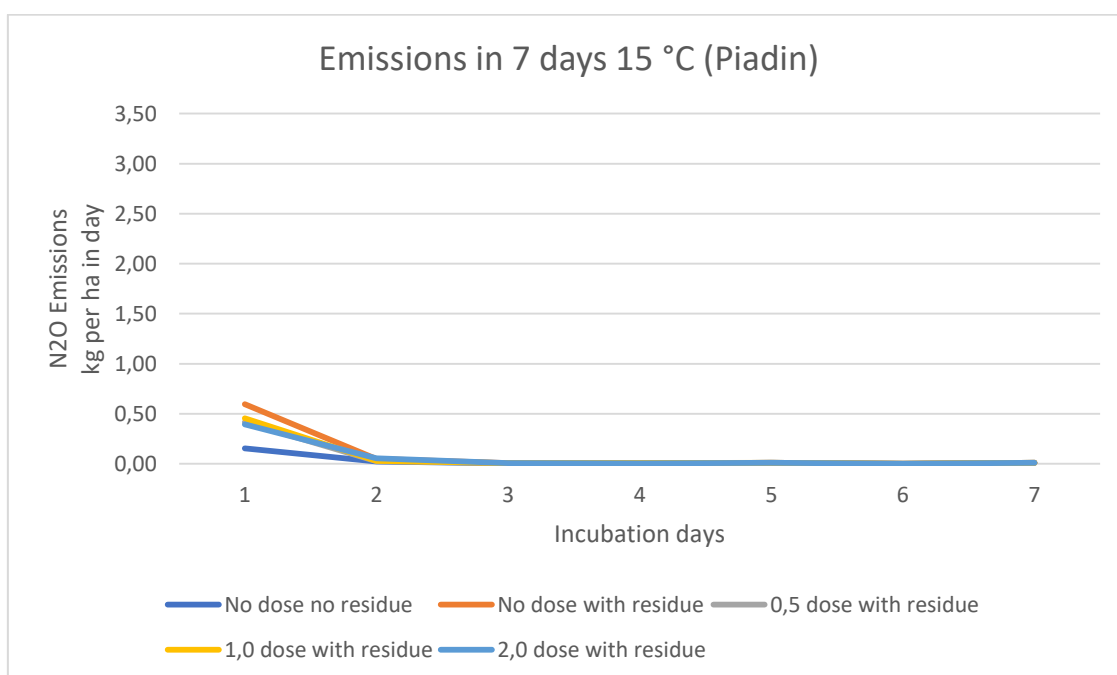


FIGURE 13. Emissions in 7 days 15 °C

The figure 14 shows that sample with no residue or inhibitor emitted a total of 0,21 kg of nitrous oxide (N₂O) during the testing period. The sample with only plant residue emitted 0,68 kg of nitrous oxide over the seven days. The sample with half of the recommended dose of inhibitor emitted 0,47 kg, the sample with the recommended amount of inhibitor emitted 0,51 kg, and the sample with double the recommended dose emitted 0,48 kg of nitrous oxide.

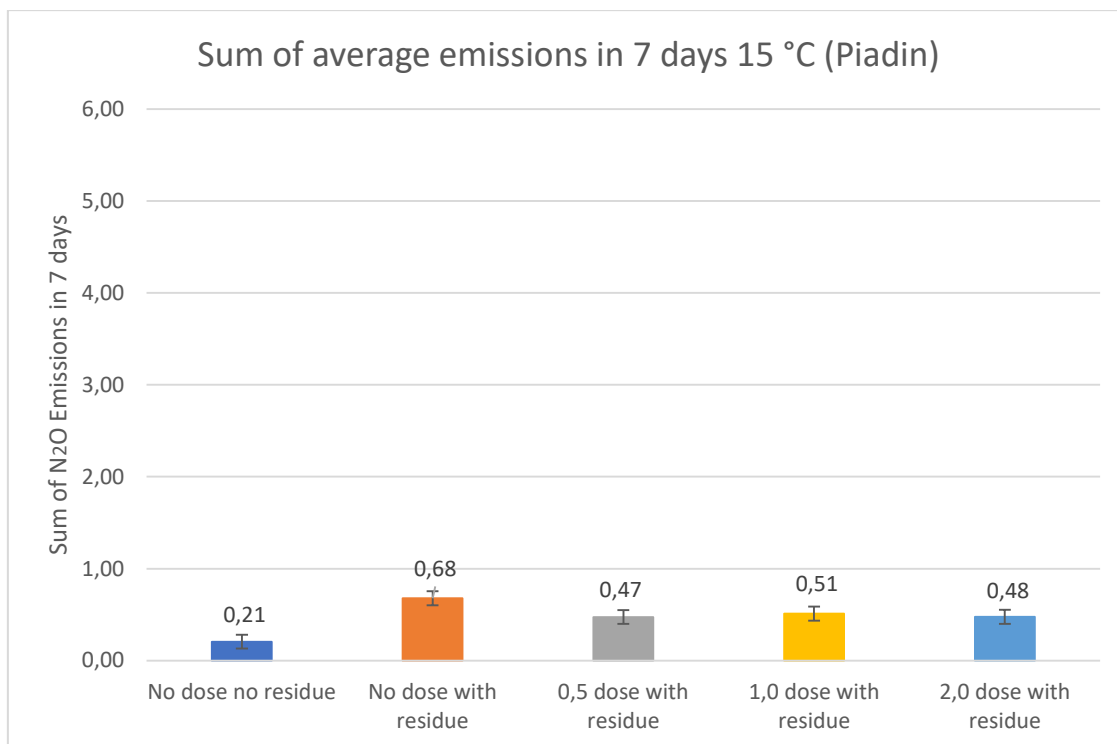


FIGURE 14. Emissions in 15 °C

When looking at the figure 15, it shows that the sample with no plant residue or inhibitor emitted 0,21 kg of nitrous oxide (N₂O) on the first day. On the second day, emissions decreased to 0,01 kg, and by the third day, emissions had dropped to 0 kg. The emissions remained at 0 kg until the fifth day, when they increased to 0,01 kg, and remained at this level on the seventh day.

The sample with residue but no inhibitor emitted 0,32 kg of nitrous oxide on the first day. On the second day, emissions decreased to 0,01 kg, and remained at this level on the third day. By the fourth day, emissions had dropped to 0 kg, and on the fifth and seventh days, emissions increased back to 0,01 kg.

The representative sample for the inhibited group is the one with the recommended amount of inhibitor. On the first day, emissions were 0,41 kg, and by the second day, they decreased to 0,01 kg. On the third day, emissions decreased to 0 kg and did not change until the fifth day, when emissions increased to 0,01 kg.

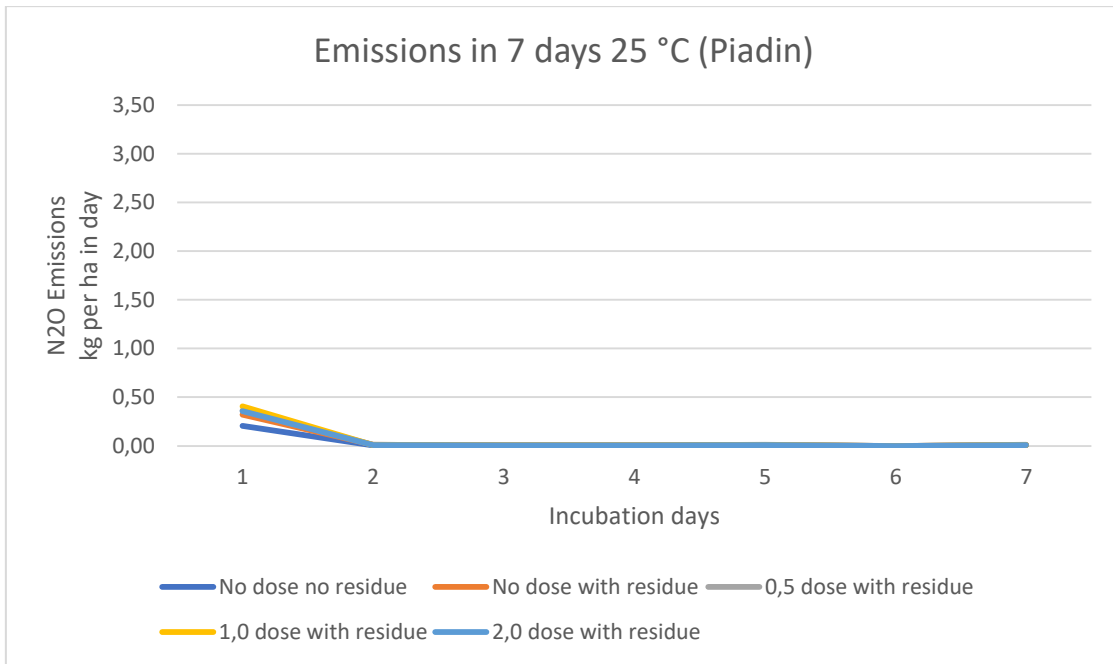


FIGURE 15. Emissions in 7 days 25 °C

The figure 16 shows sample with no plant residue or inhibitor emitted a total of 0,24 kg of nitrous oxide (N₂O) over the seven-day period. The sample with only plant residue emitted 0,67 kg of nitrous oxide. The sample with half of the recommended amount of inhibitor emitted 0,40 kg, while the sample with the recommended amount of inhibitor emitted 0,44 kg of nitrous oxide. The sample with double the recommended amount of inhibitor emitted a total of 0,39 kg of nitrous oxide.

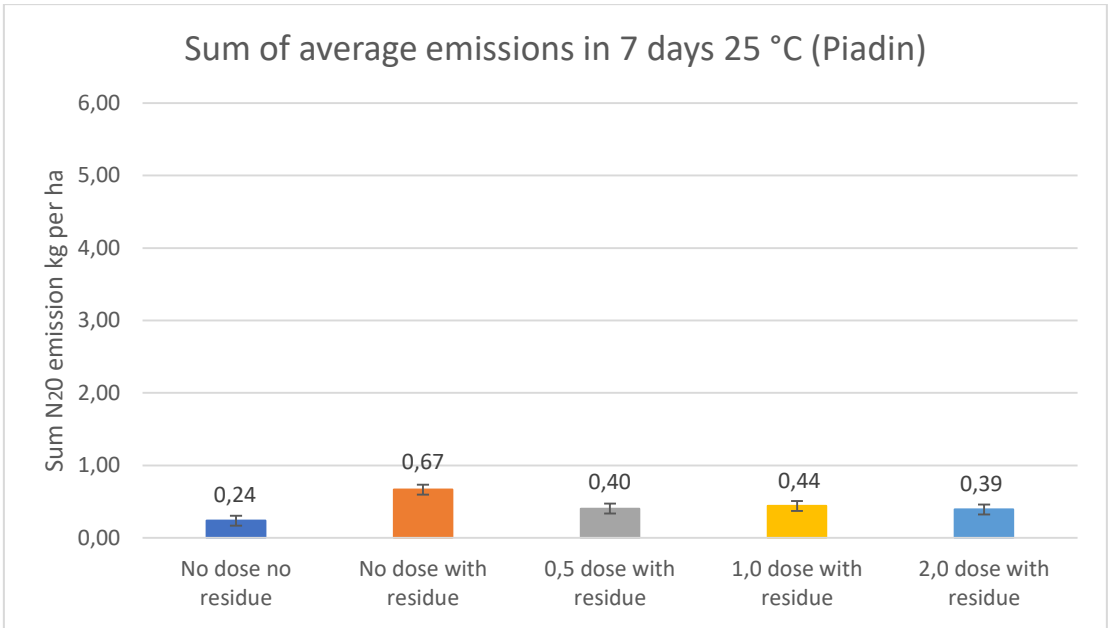


FIGURE 16. Total of accumulated emissions in 25 °C

6 CONCLUSIONS

The tests demonstrated that both Piadin and DMPP were effective in reducing nitrous oxide (N₂O) emissions from the soil samples. The samples with inhibitors consistently exhibited lower emissions starting from the first day. While the rate of emission reduction was similar to uninhibited samples, the inhibitors' lower starting emissions resulted in a significant overall reduction. The inhibitors were successful in halving the emissions from the soil samples.

The reduction of emissions average on 40-50% with DMPP, usually having a major decrease on the second day, and on-going reduction on the following days, usually amounting 30-50%. Piadin managed to inhibit the emissions better in warm climates, having over usually a 90% decrease in emissions on the second day. In a few samples the emissions were reduced to zero, and then they increased by ten grams, which most likely is the remaining buildup of small amount of emissions.

It can be seen in figures showing the overall emissions, in both tests conducted with Piadin and DMPP that the average reduction of total emissions within the seven days were 40-50%, with Piadin having usually overall lower inhibition of emissions, ranging around 40%, or sometimes under. Nevertheless, Piadin acted faster in all temperatures, making it more efficient in decreasing the total amount of emissions.

The results in the inhibited samples revealed that the effectiveness of the inhibitors in reducing N₂O emissions was more strongly influenced by the temperature of the incubation than by the amount of inhibitor used. While the inhibitors successfully reduced N₂O emissions in all trials, lower temperatures slowed down both chemical reactions and microbial activity. This did not result in overall lower emissions; rather, the inhibitor and microbes transformed the embedded nitrogen at a slower rate, leading to a larger cumulative amount of N₂O emissions over time. The variant without residue or inhibitor exhibited the lowest emissions, likely due to reduced microbial activity from the lack of plant residue as a food source.

In contrast, in variants with warmer simulated climates (15°C and 25°C), the inhibited patterns of emission were comparable to those of the sample with no residue or inhibitor. The amount of inhibitor applied, whether at doses of half of the recommended amount, recommended amount or double the recommended amount, had little effect on emissions. Larger differences in emissions were observed in the 5°C variant, likely due to the cooler temperature slowing down chemical reactions. Overall, the results suggest that temperature has a more significant impact on emissions than the amount of inhibitors applied.

7 DISCUSSION

All in all, the project did well, even though it had some delays. Some chemicals used in the project might have been chosen beforehand, so they would have been acquired in more timely manner, and thus made plan proceed more smoothly. It could cause delays in further projects that are not in the laboratory environment, but outside in the field. Also due to the number of different projects within the Osnabrück University of Applied Sciences there was shortage of space and time, but that is unavoidable due to university needing to accommodate multiple projects.

Findings are interesting, but results seem to indicate that chemical reduction of nitrogen dioxide (N_2O) is possible, quite consistently we see emissions being halved from what they would be uninhibited. It would be interesting to see if similar results could be achieved with crop rotation where nitrogen fixing plants were used, for example legume plants, for nonchemical methods of reduction of emissions. This way it could be seen if emissions and cultivation of vegetable protein at the same time could be achieved, both being goals of Finnish government currently.

When comparing the two inhibitors, DMPP and Piadin, we see that Piadin was much more efficient in reducing the emissions of the samples in all temperatures. However, in graphs something surfaces that can give some doubt about the results. Trials done with Piadin have significantly lower amounts of emissions in batches with no inhibitor. In DMPP trials samples with residue and no inhibitor, the median sum of emissions was 3,46 kg per ha. With Piadin we see median of 0,68 kg per ha emissions in the sample with plant residue and no inhibitor. This could be because there was some problem in the components of the sample, or preparing the second batch of samples for the testing.

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