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Calculation of the net greenhouse gas emissions of fertilization and irrigation strategies in a potato cropping system

By

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Abstract

In the context of modern agriculture, irrigation is a widespread technique employed to help crop growth and ensure food production. However, there are various irrigation strategies, each with its distinct set of components and machinery. These differences in irrigation methodologies significantly impact the environment, given the greenhouse gases emitted throughout the agricultural process. Our primary research objective is to comprehensively evaluate the environmental implications of these irrigation strategies along with the use of fertilizers with the aim of identifying the environmentally sustainable option.

To complete this objective, we have done an extensive potato cultivation experiments over a span of three years, in 2019, 2020, and 2021. The experiments include using of different irrigation strategies, and the main goal was to calculate and compare the net greenhouse gas emissions associated with each strategy, both in scenarios with and without the use of fertilizers.

Our research methodology started with a life cycle assessment approach, which provided an overview to all activities related to potato production, from cradle to gate. The input data for calculating greenhouse gas emissions, including material input data and type of machinery used, were provided by the Leibniz Institute of Agricultural Engineering and Bio-economy for each of the three years and the emission factors were provided mostly from KTBL and ecoinvent data base.

In our analysis, we observed that despite the fact that sprinkler irrigation had the most yield between all the strategies, drip irrigation without N fertilization consistently appeared as the most environmentally sustainable strategy, consistently yielding lower greenhouse gas emissions. On the other hand, the fertigation method, while potentially effective in nutrient management, included higher machinery utilization and therefore increased emissions, making it a less practical choice for sustainable agriculture.

The importance of these finding is to choose the most sustainable irrigation strategy that emits the least amount of greenhouse gases while being productive because the balance between yield and greenhouse gas emission use is important and judging by what we have accomplished; drip irrigation seems a reliable strategy.

1.Introduction

Potato has an important role in food production, but it also contributes as a part of activities causing climate change. The rise in greenhouse gas (GHG) emissions during the past decades makes it crucial to understand how farming impacts our environment. This Thesis focuses on three years of potato production in the fields of Marquardt, Germany. Our goal is to unravel the relationship between the cultivation of potatoes and greenhouse gas emissions. We mainly focus on two distinct methods of watering which are drip irrigation and sprinkler irrigation and explore the innovative practice of fertigation, where irrigation and fertilization intertwine. This introduction serves as the gateway to our exploration, providing not only context and insight but also an overall understanding of drip and sprinkler irrigation, the art of fertigation, the significance of potato cultivation, and the critical importance of their affect effect on climate change and the amount of greenhouse gases they produce during the process.

1.1. Greenhouse Gases: Why are they important

greenhouse gases are gases in the Earth's atmosphere that act like a blanket or a greenhouse around our planet. They trap some of the heat from the sun and keep the Earth warm, which is essential for life as we know it. (IPCC,2014)[i]

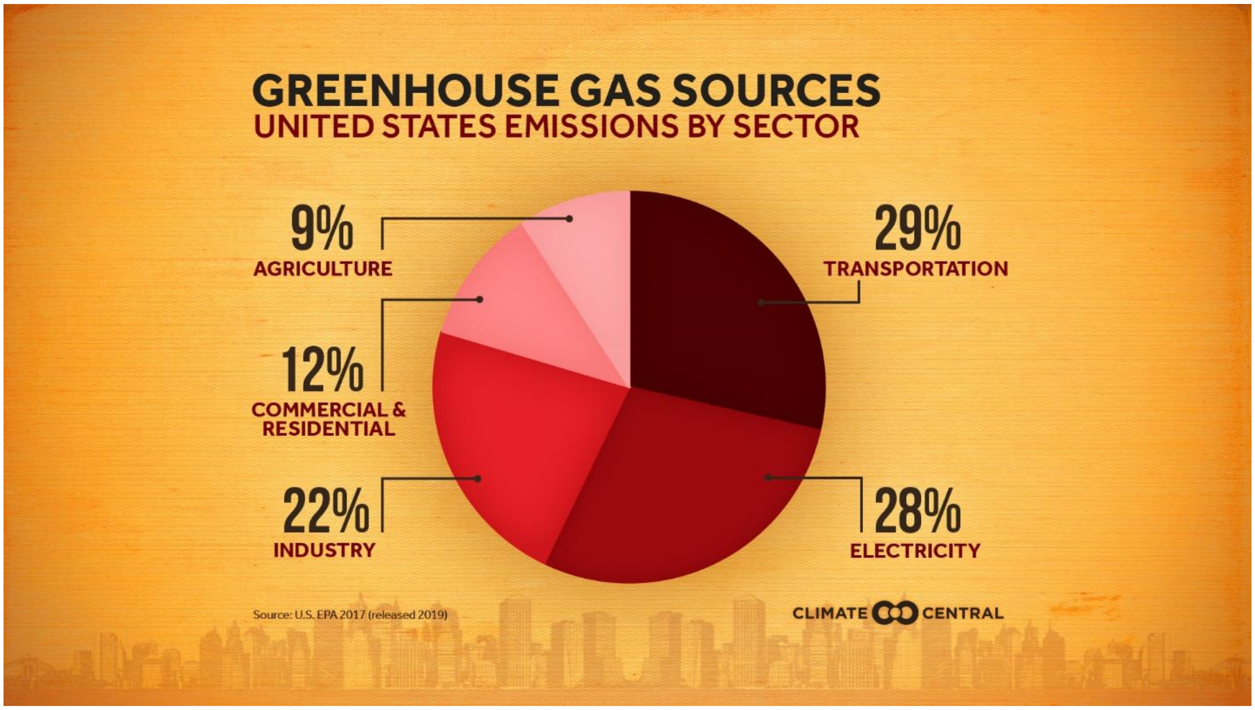


Figure 1.1: Greenhouse gases overview (Climate Central)[ii]

The most common greenhouse gases include carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) (EPA, 2001)[iii]. While these gases are important for maintaining a suitable temperature on Earth, too many of them can lead to a problem called the "greenhouse effect."

When we release excessive amounts of these gases into the atmosphere, often from activities like burning fossil fuels (coal, oil, and gas) or certain agricultural practices, they create a thicker "blanket." This can cause the Earth's temperature to rise, leading to global warming and climate change (IPCC, 2014). So, understanding how different activities, like growing potatoes, contribute to or reduce the release of these gases is crucial for protecting our environment.

1.2. Nitrous Oxide

Agriculture accounts for about 60% of Nitrous Oxide (N2O) emissions (Smith et al, 2007, IPCC, 2014)[iv]. Nitrous Oxide (N2O) has a 265-fold higher warming potential than CO2 and it is involved in destruction of stratospheric ozone layer (Ravinshakara et al, 2009)[v]. The Major factors that affect N2O emissions are: Soil Type, Soil Water Content, Soil Aeration and Oxygen Availability (Graham et al 2017)[vi].

1.3. Background: Where Potatoes and Farming Meet

Potatoes, as nutritious vegetables, have become a staple food in Germany and all around the world. They provide essential nutrients for millions of people. But the traditional ways of growing potatoes often require a lot of water, fertilizers and energy. While these methods help produce big potato harvests, they also harm the environment and contribute to climate change through increasing greenhouse gases.

In today's world, where climate change is happening quickly, we are now focusing more on finding sustainable ways to grow our food. This means finding the most efficient ways to grow potatoes that don't harm the environment as much.

Figure 1.2: Potato crops located in Marquardt

1.4. The Role of Irrigation in Farming

But why do we irrigate our crops in the first place? Irrigation is the process of applying water to crops artificially in places where the rain is inconsistent or there is lack of water (BYJU, 2019)[vii]. So the answer lies in making up for this lack of water in agricultural fields through irrigation technologies. Farmers need a way to ensure a consistent and reliable supply of water for their crops. That's where irrigation steps in as a reliable and controlled method of delivering water to thirsty plants. It acts as a lifeline, especially in regions where rainfall is sporadic or insufficient.

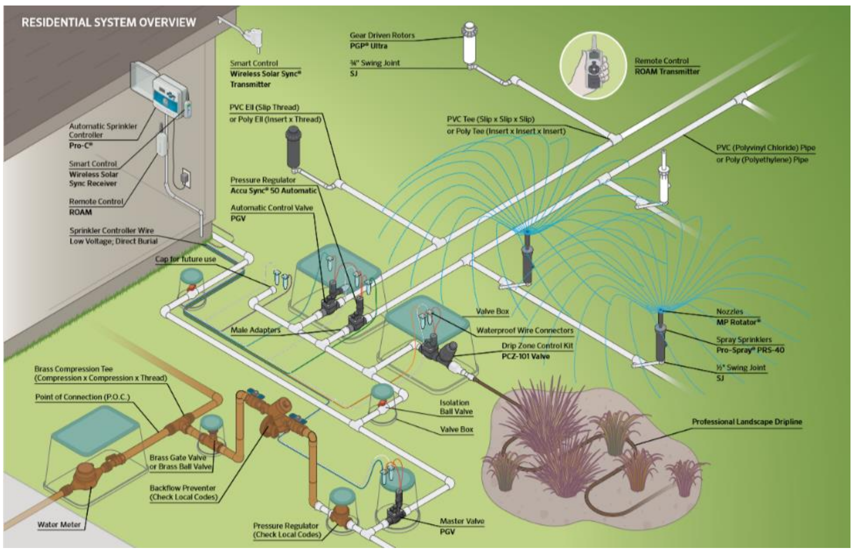


Figure 1.3: Irrigation system design[viii]

1.5. Irrigation Strategies

In Germany, approximately about 2.2% of the used agriculture area is irrigated (FAOSTAT, 2015)[ix]. The most common irrigation technology in Germany is Sprinkler irrigation which is a method of watering plants and crops by spraying water over them in the form of tiny droplets. It's like a system of pipes and nozzles that distribute water evenly across the field just as rainfall. This method is effective in providing consistent and controlled irrigation to a wide area and is commonly used in agriculture to ensure that crops receive the necessary amount of water for healthy growth. The other irrigation method that we are using in our experiment is Drip irrigation which is a method of watering plants by delivering small amounts of water directly to the roots of each plant through a network of tubes, pipes, and emitters.

In summary, sprinkler irrigation is more suitable for larger fields and a variety of crops, while drip irrigation is highly efficient and precise, making it ideal for conserving water and maintaining optimal moisture levels for specific plants or crops.

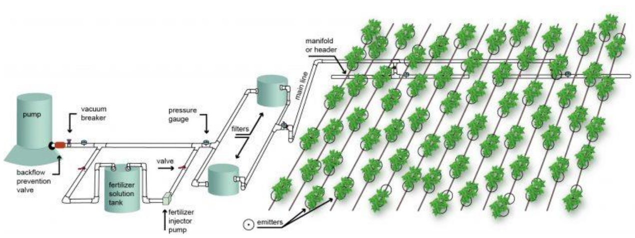


Figure 1.4: Drip irrigation system[x]

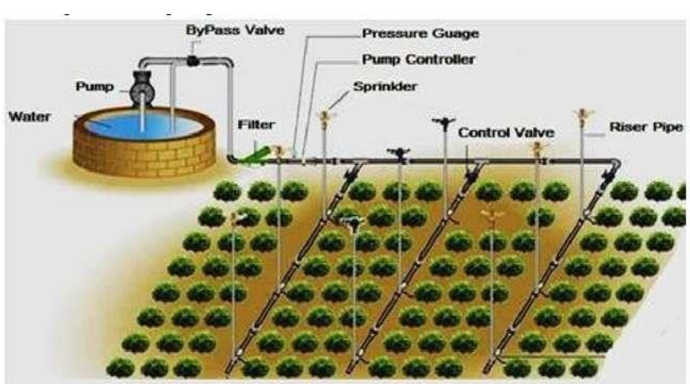


Figure 1.5: Sprinkler irrigation system (Research Gate)

1.6. Why we expect differences between irrigation strategies?

The difference between irrigation strategies in potato production can be attributed to several factors:

1. **Water Application Method**: Variations in water delivery methods, like drip and sprinkler irrigation, influences water usage efficiency. water loss is less in drip irrigating, affecting pumping and distribution-related GHG emissions. (Bauer, philipe J, et al, 2004)[xi]
2. **Fertilization Practices**: Strategies also have differences in terms of fertilizer timing, frequency, and quantity, affecting nitrous oxide (N2O) emissions due to nitrogen release in the soil. (Weier, Keith L, 2001)[xii]
3. **Machinery Usage**: The type and efficiency of machinery used vary among strategies, affecting GHG emissions through diesel consumption. (Kachouie, 2013)[xiii]
4. **Climate Variability**: Yearly climate conditions influence irrigation needs and crop growth, leading to variations in GHG emissions across different years.

These variables contribute to the divergence in GHG emissions among irrigation strategies, highlighting the need to consider them for sustainable potato production.

1.7. Fertilization

In addition to irrigation methods, we're also looking at how we give them plant food, like fertilizers. These plant nutrients are essential for good potato growth, but they can also release gases that warm the Earth. We're studying how different ways of giving these nutrients to the potatoes affect their growth and the gases that go into the air.

In general, there are three primary types of fertilizers which are: Nitrogen Fertilizers, Phosphorous Fertilizers and Potassium Fertilizers.

The fertilizers we mentioned can come in different types of forms, such as granules, powders, or liquids, and they can be applied to the soil or directly to plant leaves. The choice of fertilizer type and application method depends on the specific needs of the plants being grown and the soil conditions.

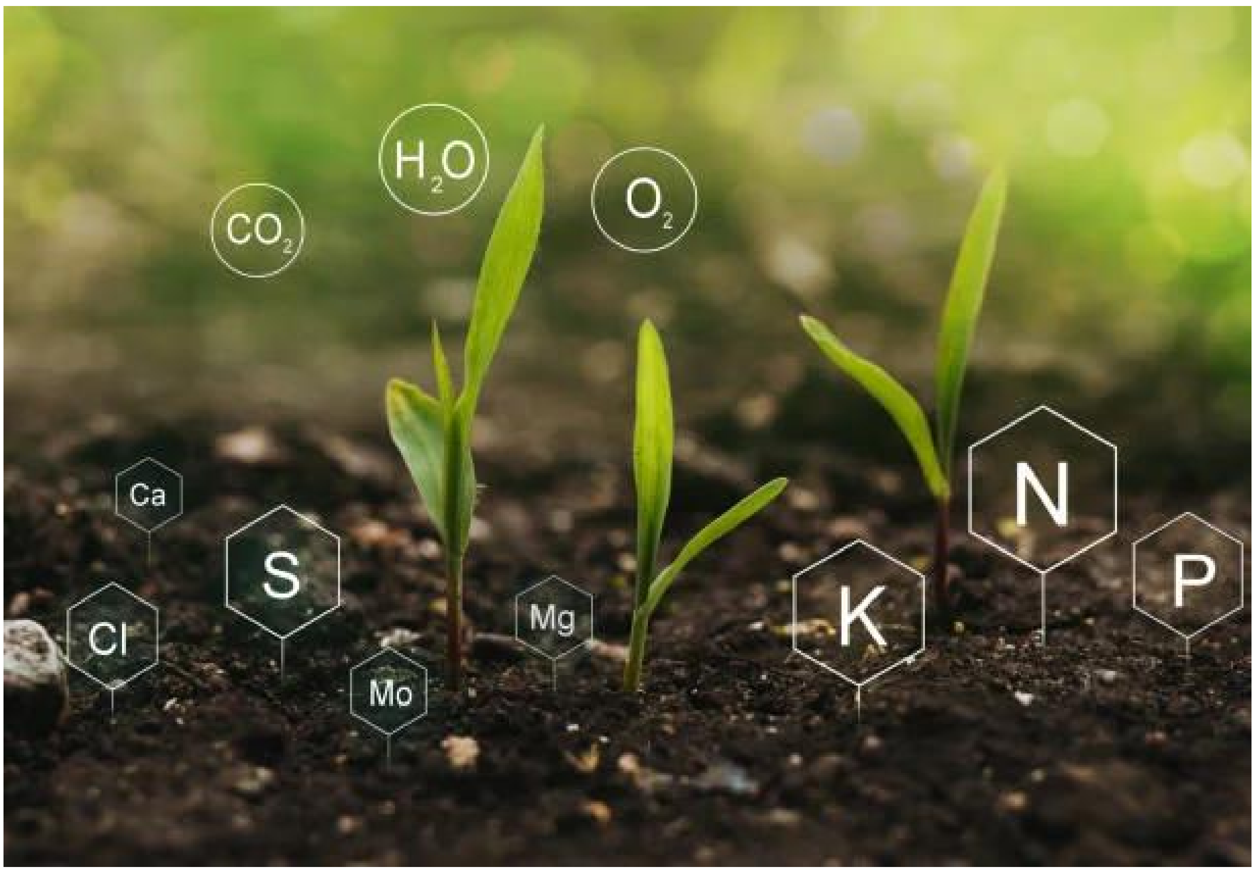


Figure 1.6: Fertilization[xiv]

1.8. Fertigation: Cultivating Nutrients

Fertigation is a farming practice that combines irrigation and fertilization, allowing running nutrients into the plants through an irrigation system. By doing so, farmers can enhance their nutrient management strategies to meet the specific needs of their crops, improving overall plant health and yield.

Fertigation not only maximizes the efficiency of water and nutrient usage but also reduces the risk of nutrient runoff, making it a sustainable and environmentally friendly approach to modern agriculture.

Fertigation stands as of hope for more efficient nutrient management, potentially reducing both fertilizer waste and the accompanying GHG emissions. However, it's essential to proceed with caution and precision in this practice. The injection process requires energy, and doing something wrong in managing this could result in unintended environmental harm.

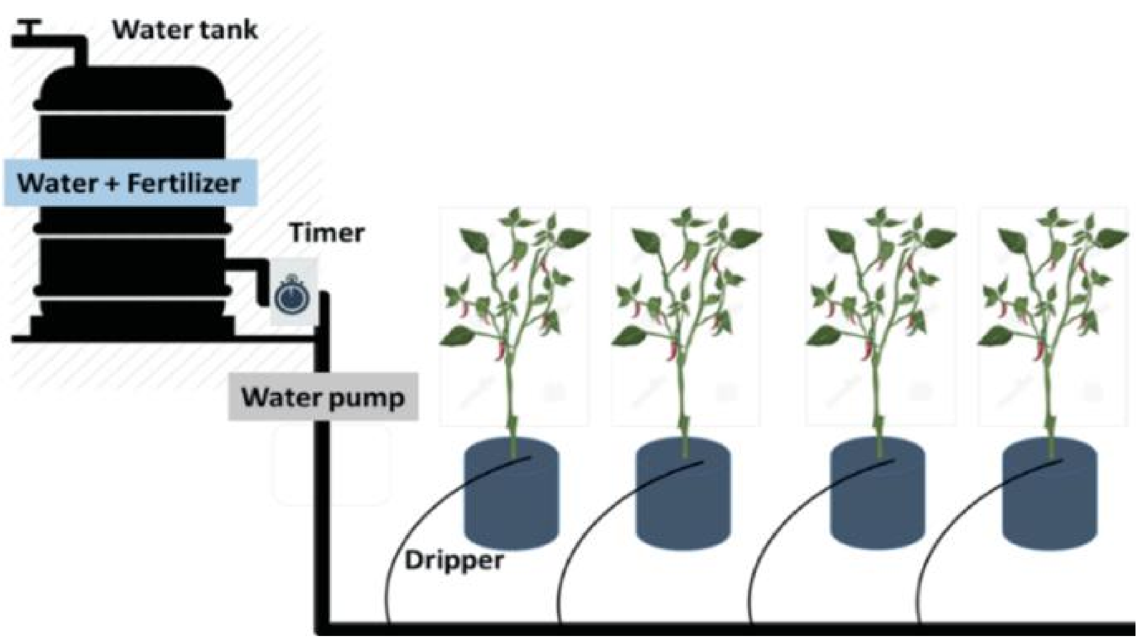


Figure 1.7: Fertigation system[xv]

1.9. Potato Cultivation: A Lifecycle Perspective

We most enlarge our perspective to cover the entire lifecycle of potatoes from cradle to gate. From planting the potato seeds to harvesting them, lies a complex process. We refer to this as the "life cycle" of potatoes, analyzing various stages such as soil preparation, planting, watering, harvesting, transportation. At each step of this journey, GHG emissions may take part. To make informed decisions about sustainable potato production, we need a general understanding of how these emissions accumulate throughout the potato's lifecycle.

1.10. The Significance of Our Endeavor

Our research extends its importance so far beyond the boundaries of potato fields. It's about finding ways to maintain a safe environment while ensuring a steady supply of potatoes. The results we uncover have the potential to guide farmers toward making environmentally conscious choices, inform policymakers in crafting sustainable agricultural practices, and secure a future where we continue to enjoy utilization of potatoes while being environmental friendly.

1.11. Objectives

The primary goal of this research project is to calculate the net greenhouse gas (GHG) emissions for irrigation strategies, with and without fertilization, in the context of potato cultivation. This assessment takes into account the entire life cycle of potato production, from cradle to gate, and is conducted over a three-year period starting from 2019 to 2021.

Assumptions

1. **Comprehensive Life Cycle Assessment:** The study includes a comprehensive life cycle assessment, which includes the assessment of GHG emissions at each stage of potato production. The focus is on assessing the net emissions throughout the entire life cycle of the potato, considering all relevant production processes and activities like machinery usage.
2. **Different Irrigation Strategies:** The research considers a total of eight different irrigation strategies, as detailed in the accompanying table. These strategies encompass different approaches to water management and nutrient application during potato cultivation.
3. **Emission Factors for Material Usage:** for the calculation of GHG emissions for each production stage relies on the utilization of material inputs. For machinery-related emissions, the study considers diesel consumption and employs relevant emission factors to estimate GHG emissions accurately.
4. **Stable GHG Emissions in Key Stages:** It should be noted that certain stages of the potato production process, including soil preparation, seed provisioning, fertilization, and harvesting, exhibit relatively consistent GHG emissions across the three-year period (2019-2021). The research takes this consistency into account when assessing the environmental implications of the irrigation strategies.

By addressing these objectives and considering the associated assumptions, this research aims to provide a comprehensive evaluation of the environmental impact of different irrigation strategies within potato production. The results are intended to inform environmentally sustainable practices and contribute to informed decision-making within the agricultural sector.

Variant	Irrigation	N Fertilization
ZI-ZN	No irrigation	No N fertilization
ZI-N	No Irrigation	N Fertilization (Optimal 150 Kg N/ ha)
SI-ZN	Sprinkler Irrigation	No N Fertilization
SI- N	Sprinkler Irrigation	N Fertilization (Optimal 150 Kg N/ ha)
DI-ZN	Drip irrigation	No N Fertilization
DI-N	Drip Irrigation	N Fertilization (Optimal 150 Kg N/ ha)
F	Fertigation	N Fertilization (Optimal 147 Kg N/ ha)
F-ZC	Fertigation with no crops	N Fertilization (Optimal 147 Kg N/ ha)

Table 1.1: irrigation strategies

2. Methodology

Research Design

Research Approach: This research adopts a mixed-methods approach, which means combining both quantitative and qualitative methods to thoroughly study greenhouse gas emissions for potato production activities in a potato field in Marquardt, Germany over a three-year period (2019, 2020, and 2021). This approach is chosen to provide a holistic understanding of the factors contributing to greenhouse gas emissions throughout the potato production process during this period of time.

Figure 2.1: Photo of Marquadrt

For calculating net greenhouse gas emissions accurately in this period quantitative data is crucial. It involves the measurement of gases emitted starting from the pre-chain activities to harvesting the potatoes. Also measurement of greenhouse gas emitted from the soil using gas chambers placed in 24 distinct plots of the potato field. There are 4 containers on each chamber, which we will open them one by one in the time interval of 20 minutes. These gas samples are then transported to the lab for analysis, and data analysis is conducted using Excel to calculate the flux greenhouse gas emissions for each step in the potato production process. In order to better understand and analyze the N2O fluxes, we have also calculated the yield related N2O for each irrigation strategy which we will talk more in the chapter of result and discussion.

Figure 2.2: Gas chambers located in Marquardt

On the other hand, qualitative data is important for understanding the significant factors influencing greenhouse gas emissions. It includes observations and interviews with field workers, scientists, and other stakeholders involved in potato cultivation in Marquardt. This qualitative information helps to interpret the quantitative data and provides insights into the practices and decisions affecting greenhouse gas emissions during the three-year research period.

Research Strategy: The research strategy employed in this study is a combination of field observations, data collection, and laboratory analysis. It encompasses the following key components:

- **Gas Chamber Placement and Sampling:** In the potato field located in Marquardt, Germany, gas chambers are strategically placed in 24 different sections. Within each section, four plots are selected for hourly gas sampling. This systematic approach allows for a comprehensive assessment of greenhouse gas emissions at different locations within the field.
- **Data Collection:** The amount of material used for each step Gas samples collected from the chambers are transported to the laboratory for analysis. The data collection process includes recording the type and quantity of gases produced by the soil.
- **Energy Consumption Measurement:** To determine the energy consumption associated with each step in the potato production process, detailed measurements are taken. For instance, in the initial step of soil preparation, the energy consumption of machinery such as tractors or trucks is assessed. This involves recording data related to fuel consumption, operation duration, and equipment specifications.
- **Emission Factor Calculation:** Once energy consumption data is gathered, emission factors specific to the equipment used in each production step are determined. These emission factors are essential in quantifying the greenhouse gas emissions resulting from energy usage. They are calculated by considering factors such as fuel type, engine efficiency, and emission standards.

- **Net Greenhouse Gas Calculation:** The net greenhouse gas emissions for each production step are calculated by multiplying the energy consumption by the corresponding emission factor. This calculation yields the amount of greenhouse gases emitted during a specific stage of potato cultivation.

The mixed-methods research approach we've adopted here enables us to conduct a thorough examination of greenhouse gas emissions. It combines quantitative measurements with qualitative observations, taking into account how these emissions vary over the course of our three-year study. This approach is designed to ensure that our research not only gathers concrete data but also considers the broader contextual factors that play a role in shaping greenhouse gas emissions within the Marquardt region's potato cultivation practices during this specific time period. In the following sections, we will provide more detailed information about how we collect and analyze our data, as well as address the ethical considerations that guide our research process.

Data Collection: Soil Preparation Phase

The first step in our Data collection phase is the soil preparation phase, where we carefully prepare the ground for successful potato cultivation. This phase includes a sequence of substeps, each serving a specific purpose in creating an optimal environment for potato growth.

Step 1: Cultivating

- **Substep 1.1: Initial Soil Breakup**: This is the starting point of our soil preparation. During this phase, we use specialized equipment such as plows or cultivators to break up and loosen the soil. The goal is to make the soil more manageable and receptive to further treatment. For this step, we are considering using a New Holland T6.180 Tractor[xvi] which consumes about 25 liters per hectare of diesel. In order to calculate the amount of Greenhouse gases produced by this step, we need to find the Emission factor for diesel consumption which based on Ecoinvent Data base[xvii] is around 2.68 KgCO2e/ha.

Figure 2.3: Cultivator[xviii]

Step 2: Plowing with Packers

- **Substep 2.1: Deep Soil Turning**: Moving on to the second substep, we employ equipment fitted with packers. These machines dig deep into the soil, turning it over and forming raised ridges. These ridges provide the ideal conditions for planting potatoes due to their loose and elevated structure. For this step, we are using a New Holland 6050 Tractor which consumes about 10 liters per hectare of diesel.

Figure 2.4: Ploughing [xix]

Step 3: Harrowing with Rotary Harrows

- **Substep 3.1: Soil Refinement**: The third sub step involves the use of rotary harrows, which play a crucial role in further refining the soil. Rotary harrows are equipped with rotating blades that break down any remaining large soil clumps into smaller, finer particles. This specific process ensures that the soil achieves a uniform and fine texture, ready for planting. For this purpose, we use a 102Kw, 3m tractor which according to KTBL data base[xx] consumes 13.35 liters per hectare of diesel.

Figure 2.5: Harrowing with rotary harrows[xxi]

Step 4: Making the Soil Fine

- **Substep 4.1: Achieving Fine Soil Texture**: Substep four focuses on achieving an even finer soil texture. This is essential for promoting healthy root development in potato plants. Fine soil crumbles provide an excellent medium for roots to establish themselves. For this purpose, we use a rotary tiller which consumes 15 liters per hectare of diesel.

Step 5: Hilling Up with a Rotary Tiller

- **Substep 5.1: Creating Soil Ridges**: In the final substep, we utilize a rotary tiller to create raised rows or hills in the soil. These raised areas serve multiple important functions. They enhance drainage, reduce the risk of waterlogging, and offer additional space for potato plants to thrive. This step marks the completion of the soil preparation process, rendering the field perfectly primed for potato planting. Also for this step we use a rotary tiller but in this purpose the consumption of fuel according to KTBL data base is 16 liters per hectare of diesel.

Figure 2.6: Rotary Tiller[xxii]

Each of these substeps contributes significantly to prepare the soil. This comprehensive approach ensures that the soil is suitably conditioned to support healthy potato growth during all the phases of our research.

Here, I have added a table specifically for the calculation of Greenhouse gases emitted in Soil Preparation activities, using the amount of diesel consumption and diesel emission factor for each activity.

Activity	Amount l/ha	Emission Factor	Total GHG KCO2e/ha	Source
Cultivating	25	2.68 KgCO2e/l	67	The new Holland website
Tillage: Plowing With packers	10	2.68 KgCO2e/l	26.8	Ecoinvent Data V3.4
Tillage: Harrowing with rotary harrows	13.35	2.68 KgCO2e/l	35.778	KTBL Data base
Cultivating fine	15	2.68 KgCO2e/l	40.2	KTBL Data base
Hilling up with a rotary tiller	16	2.68KgCO2e/l	42.88	KTBL Data base

Table 2.1: emissions from soil preparation

Data Collection: Seed Potato Production Phase

The "Seed Potato Production" phase includes preparing and choosing the seed potatoes that will be used for planting. This phase is divided into substeps, each of which plays an important role in ensuring the quality of the seeds and, therefore, the overall potato crop.

Step 1: Seed Selection

In the potato production process, seed potato selection is a crucial step, where we put a lot of effort to choose the most suitable seed potato. During this phase, specific materials are established to identify the most suitable seed potatoes. These criteria include a range of factors, such as the size, shape, and overall health of the potatoes. Our purpose here is to select seed potatoes that meet quality standards, ensuring they are free from diseases and have the attributes necessary for robust growth. Seed potatoes are not only chosen based on their physical characteristics but also based on their source which need to be considered. It's necessary to get seeds from reliable sources to minimize the risk of disease transmission and ensure the overall success of the potato crop. This careful selection process sets the foundation for a healthy and productive potato cultivation journey, aligning with the broader goal of sustainable and efficient agricultural practices.

Step 2: Sorting and Grading

Sorting and Grading Seed Potatoes is a critical step in preparing potatoes for planting. Imagine you have a big batch of potatoes, and you want to make sure you plant only the best ones. This process involves carefully looking at each potato and deciding if it's fit for planting based on a few factors.

First, we consider the **size** of the potato. Potatoes come in various sizes, and this matters because it determines how far apart they need to be planted in the field. Some potatoes are larger, and we might need to cut them into smaller pieces to plant them effectively. Others are just the right size to plant as a whole potato.

Next, we check the **shape** of the potatoes. Ideally, we want potatoes that are nice and round, without any strange bumps or deformities. This ensures that they'll grow uniformly and produce healthy crops.

Lastly, we examine the potatoes for any signs of **disease or defects**. We want our seed potatoes to be healthy, free from any issues that could affect their growth or spread to other plants.

Now, here's where the machinery comes in. To do this sorting and grading quickly and accurately, we use specialized machines called **Case IH Puma 165** and **Amazon E 600**. These machines help us sort the potatoes much faster than doing it by hand. They have mechanisms that can measure the size, shape, and even check for defects.

By using these machines, we make sure that only the best and healthiest potatoes make it to the planting stage. This ensures that the crop will grow consistently, with fewer problems like diseases or uneven growth.

So, in a nutshell, sorting and grading seed potatoes is like picking out the cream of the crop to start your potato field, and the machinery makes this process much more efficient.

At the bottom, the table for the amount of greenhouse gases produced by seed selection and preparation is attached:

Activity	Amount	Emission Factor	Total GHG Kgco2e/ha	Source
Seed potato Production	500 Kg	0.367 Kgco2e/kg	163.5	Ecoinvent data base v3.4
Sorting and grading seed potatoes	15l/ha + 5l/ha	2.68 Kgco2e/l	53.6	KTBL Data base

Table 2.2: Emission from Seed potato production and sorting

Data Collection**:** Use of Fertilizers

Now, let's dive into the use of fertilization, a crucial phase in our potato farming endeavor. Here, we are trying to find the balance between supplying essential nutrients for potato growth and being friendly to the environment. We are dealing with four main nutrients: nitrogen, potassium, magnesium, and phosphorus using Patentkali as the main fertilizer. We will use different irrigation strategies with or without fertilization to see how much of a difference it will make.

1. **Nitrogen Fertilization**: Imagine nitrogen as the energy boost for potato plants. We're trying different ways of giving them nitrogen. We're testing drip irrigation with and without nitrogen, and also not watering them but still giving them nitrogen. These experiments help us figure out how to grow the most potatoes while not releasing too many greenhouse gases. The entire nitrogen used in our project during 1 year is about 744 Kg N/ha which is divided between different strategies.

2. **Potassium Fertilization**: Potassium is essential for potato tuber development and overall plant health. We use "Patentkali," a fertilizer which includes both potassium and magnesium, to provide the necessary potassium levels. Proper application is crucial to

ensure adequate potassium for growth without excessive emissions. About 30 percent of our fertilizer Patentkali is Potassium. In the entire year of our project, we have used about 301.266 Kg K/ha.

3. **Magnesium Fertilization**: Magnesium plays an important role in chlorophyll production. Our choice of "Patentkali" for potassium fertilization also provides magnesium. During the year of our project we used 100.422 Kg Mg/ha which includes 10 percent of the Patentkali.

Balancing the application of these nutrients is vital to promoting healthy potato growth while minimizing environmental impacts. Proper management and precise application techniques help us achieve this balance, contributing to sustainable potato cultivation practices.

In our ongoing research, we have calculated the amount of greenhouse gas emissions each of these fertilization processes produce. In the table below you can see the result:

Activity	**Amount**	**Emission Factor**	**Total GHG KgCO2e/ha**	**Source**
Nitrogen N	744 Kg N/ha	3.52 KgCO2e/Kg N	2618.88	KTBL Data base
Potassium K	301.266 Kg K/ha	0.42 KgCO2e/ Kg K	126.53	KTBL Data Base
Magnesium Mg	100.422 Kg Mg/ha	1.06 KgCO2e/Kg Mg	106.44	Winnipeg.ca [xxiii]

Table 2.3: Emissions from fertilization

Data Collection: Irrigation Strategies

In this section, we look into the data collection process for the different irrigation strategies employed in our study. The goal here is to measure and understand the greenhouse gas emissions associated to each strategy during the three years of operation. These strategies include:

1. **Drip Irrigation with N Fertilization**
2. **Drip Irrigation without N Fertilization**
3. **Sprinkler Irrigation with N Fertilization**
4. **Sprinkler Irrigation Without N Fertilization**
5. **No Irrigation, No Fertilization**
6. **No Irrigation with N Fertilization**
7. **Fertigation**
8. **Fertigation with No Crop**

Our comprehensive data collection process takes into account several key factors:

1. Water Consumption Monitoring:

We've closely observed and recorded how much water we've used for irrigation during the three consecutive years of 2019,2020,2021 for drip and sprinkler irrigation. This information is crucial because it will help us understand how much energy is consumed by each strategy while taking into account their water consumption. In the table below, we have attached the available data for water consumption for each strategy during each year (For no irrigation strategies, the amount is obviously zero).

Strategies	Amount (2019)	Amount (2020)	Amount (2021)
Drip with N	97.28 l/m2	37.29 l/m2	69.14 l/m2
Drip without N	97.28 l/m2	37.29 l/m2	69.14 l/m2
Sprinkler with N	185 l/m2	120 l/m2	93 l/m2
Sprinkler without N	185 l/m2	120 l/m2	93 l/m2
Fertigation	100.78 l/m2	55.95 l/m2	90.91 l/m2
Fertigation with 0 crop	100.78 l/m2	55.95 l/m2	90.91 l/m2

Table 2.4: total amount of irrigated water during 2019, 2020 and 2021

2. Setting Up Devices, Tubes, and Pumps:

Before we could start irrigating, we had to set up all the equipment, like hoses, pipes, and pumps, to make sure water could flow to our potato plants and of course, this setup process produces emissions. These emissions are like the environmental cost of getting everything ready.

3. Machinery and Diesel Consumption:

Now, let's talk about the machines we used to pump water onto our potato field. These machines need fuel, just like cars need gasoline. We tracked how much fuel, called diesel, each machine used. Diesel consumption tells us how much pollution these machines create. By having the amount of diesel consumption and their emission factor which is 2.68 KgCO2e/liter.

4.Total amount of potato produced by each strategy

At the end of each year, each of these strategies produce different amount of potatoes. For a better comparison between these strategies we also need to take into account how much is the yield for each one of them in order to calculate the total amount of greenhouse gas emitted by them based on kg of potato. Based on the information provided by the ATB institution, in the table below we have attached the yield for each strategy in all the three consecutive years:

Strategies	Ton of potato (2019)	Ton of potato (2020)	Ton of potato (2021)
Drip with N	55.52	34.32	32.15
Drip without N	41.2	24.79	15.25
Sprinkler with N	71.41	43.34	44.64
Sprinkler without N	42.84	24.69	17.15
Fertigation	53.24	32.35	30.6
Fertigation with 0 crop	0	0	0
No irrigation No N	28.44	28.47	26.46
No Irrigation with N	17.32	22.07	12.07

Table 2.5: Total amount of potato produced

1.12. Fertilizer Emissions:

Lastly, we considered the fertilizers we used for our potatoes. As we explained before Fertilizers are like vitamins for plants, but they can also release gases that warm the Earth. We looked at the types of fertilizers and how they were applied. This helps us calculate the emissions from fertilizers, specially Nitrogen. In the table below, the total amount of N fertilizer used for each strategy in an entire year is calculated and for all the years, these amounts are the same.

Strategy	N Fertilizer
Drip Irrigation	150 Kg N/ha
Sprinkler Irrigation	150 Kg N/ha
No Irrigation with N fertilization	150 Kg N/ha
Fertigation	147 Kg N/ha
Fertigation with no crops	147 Kg N/ha

Table 2.6: total amount of N fertilizer for each strategy

By collecting data on all these aspects, we can now add up the emissions from each part and figure out the total greenhouse gas emissions for each irrigation strategy during the three years. In this way, we get a complete picture of how each strategy impacts the environment and helps us make better choices for sustainable potato farming. The tables below show the results of emissions for each strategy including the emissions for operation and set up devices and the emissions for fuel consumption (diesel) over the years.

Strategies	Total GHG for Machinery Diesel consumption KgCO2e/ha	Total GHG for Setting up the machinery KgCO2e/ha	Total GHG for use of N fertilizers KgCO2e/ha	Source
Drip with N fertilization	**437.37**	**2.144**	**528**	**KTBL data base**
Drip without N fertilization	**437.37**	**2.144**	**0**	**KTBL data base**
Sprinkler with N fertilization	**495.5**	**3.752**	**528**	**www.lwk-niedersachsen.de**[xxiv] **and KTBL data**
Sprinkler without N fertilization	**495.5**	**3.752**	**0**	**www.lwk-niedersachsen.de and KTBL data**
No irrigation No fertilization	**0**	**0**	**0**	**-**
No irrigation with fertilization	**0**	**0**	**528**	**KTBL data base**
Fertigation	**437.37**	**2.144**	**517.44**	**KTBL data base**
Fertigation with no Crop	**0**	**0**	**517.44**	**KTBL data base**

Table 2.7: Total emissions for all the strategies (2019)

Strategies	Total GHG for Machinery Diesel consumption KgCO2e/ha	Total GHG for Setting up the machinery KgCO2e/ha	Total GHG for use of N fertilizers KgCO2e/ha	Source
Drip with N fertilization	**231.552**	**2.144**	**528**	**KTBL data base**
Drip without N fertilization	**231.552**	**2.144**	**0**	**KTBL data base**
Sprinkler with N fertilization	**321.6**	**3.752**	**528**	**www.lwk-niedersachsen.de and KTBL data**
Sprinkler without N fertilization	**321.6**	**3.752**	**0**	**www.lwk-niedersachsen.de and KTBL data**
No irrigation No fertilization	**0**	**0**	**0**	**-**
No irrigation with fertilization	**0**	**0**	**528**	**KTBL data base**
Fertigation	**411.648**	**2.144**	**517.44**	**KTBL data base**
Fertigation with no Crop	**0**	**0**	**517.44**	**KTBL data base**

Table 2.8: Total emissions for all the strategies (2020)

Strategies	Total GHG for Machinery Diesel consumption KgCO2e/ha	Total GHG for Setting up the machinery KgCO2e/ha	Total GHG for use of N fertilizers KgCO2e/ha	Source
Drip with N fertilization	**257.28**	**2.144**	**528**	**KTBL data base**
Drip without N fertilization	**257.28**	**2.144**	**0**	**KTBL data base**
Sprinkler with N fertilization	**249.24**	**3.752**	**528**	**www.lwk-niedersachsen.de and KTBL data**
Sprinkler without N fertilization	**249.24**	**3.752**	**0**	**www.lwk-niedersachsen.de and KTBL data**
No irrigation No fertilization	**0**	**0**	**0**	**-**
No irrigation with fertilization	**0**	**0**	**528**	**KTBL data base**
Fertigation	**437.37**	**2.144**	**517.44**	**KTBL data base**
Fertigation with no Crop	**0**	**0**	**517.44**	**KTBL data base**

Table 2.9: Total emissions for all the strategies (2021)

Data Collection: Crop Protection

Each year, we need to protect our crops from harmful insects, diseases and weeds. For this reason, we have a step called crop protection which includes applying herbicide, pesticide and fungicide usage. Each of this steps separately emits a certain amount of greenhouse gas. From the material we use to the machinery used for its application. The amount of greenhouse gases for each year is different since different material and machinery were needed depending on the year and seasonal condition.

1. Pest and Disease Monitoring: We monitored our potato plants to look for pests like insects and diseases. By noting when and where these issues occur, we can make better decisions on how to protect our crops.

2. Pesticide and Herbicide Application: When we found out there are pests or weeds threatening our potato plants, we used pesticides and herbicides to remove them. These applications also have an environmental impact. So, we tracked how much of these chemicals we used and when.

3. Fungicide Usage: Fungicides are special chemicals that help protect our potatoes from fungal diseases. We also monitored how much fungicide we applied and when to safeguard our potato crops.

At tables below, we calculated the total amount of greenhouse gases emitted by this step for each year.

Crop protection	**Amount**	**Emission Factor Kg Co2e/ Kg ai**	**Total GHG emitted KgCO2e/ha**	**Source**
Mixed weed infestation control (Herbicide)	5 Kg/ha	5.41	27.05	Research gate website[xxv]
Phytophthora control (Fungicide) (Used Twice)	4 Kg/ha	3/9	15.6	MDPI[xxvi]
Colorado potato beetle control (Insecticide)	0.3 Kg/ha	5.1	1.53	MDPI
Machinery used for applying Pesticide	10+10+5+5 l/ha	2.68 Kgco2e/l	80.4	KTBL data

Table 2.10: Crop protection emissions for the year 2019

Crop protection	**Amount**	**Emission Factor Kg Co2e/ Kg ai**	**Total GHG emitted KgCO2e/ha**	**Source**
Phytophthora control (Fungicide) (Used six times)	1.2 kg/ha	3/9	4.68	MDPI
Colorado potato beetle control (Insecticide) (Used Three times)	0.05 l/ha 0.05 l/ha 0.075 l/ha	5.1	0.892	MDPI
Machinery used for applying Pesticide	45 l/ha	2.68 Kgco2e/l	120.6	KTBL data

Table 2.11: Crop protection emissions for the year 2020

Crop protection	**Amount**	**Emission Factor Kg Co2e/ Kg ai**	**Total GHG emitted KgCO2e/ha**	**Source**
Dicotyledons UK (used two times)	3.4 l/ha	0.13	0.442	Agribenchmark[xxvii]
Fungal Disease (Fungicide) (Used seven times)	9.05	3/9	35.295	MDPI
Colorado potato beetle control (Insecticide) (used three times)	0.175 l/ha	5.1	0.8925	MDPI
Machinery used for applying Pesticide	50 l/ha	2.68 Kgco2e/l	134	KTBL data

Table 2.12: Crop protection emissions for the year 2021

Data Collection: Harvesting

In our research, we employed mechanical harvesting, specifically the use of lifting bunkers, consistently over three years. This method efficiently extracts potatoes from the soil and simplifies the data collection process. We tracked factors such as machinery type, fuel consumption, potential environmental impacts like soil compaction, and the storage conditions for the harvested potatoes. This comprehensive data gathering approach helps us assess the environmental aspects of the harvesting phase while ensuring the potatoes' quality and safety during storage.

Harvesting	**Amount**	**Emission Factor**	**Total GHG in KgCO2e/ha**	**Source**
Mechanical Harvesting	47.15 l/ha	2.68 kgco2e/l	126.362	KTBL data set

Table 2.13: Emission from harvesting for the year 2019,2020,2021

3. Results and Discussion

In this section, we present an overview of the greenhouse gas (GHG) emissions from potato production during the years of 2019, 2020, and 2021. We considered all the steps, such as soil preparation, selecting and preparing seeds, fertilization, and harvesting, while also looking at different irrigation methods. We've organized the results and data in a table for a better point of view and to understand how each strategy impacts the environment.'

Total GHG Emissions for Common Stages

Several crucial steps, such as soil preparation, providing seeds, applying fertilizers, and harvesting, stayed the same across these three years. These steps are similar, which is why we added up the GHG emissions for them together. You can see the total GHG emissions for these shared steps in Table below:

Steps	**Total GHG in Kg CO2e/ ha**
Soil Preparation	212.658
Seed Selection and Preparation	217.1
Fertilization (No N)	232.97
Harvesting	126.362

Table 3.1: Total GHG Emissions for Common Steps in Potato Production (Soil Preparation, Seed Selection and Preparation, Fertilization, and Harvesting) for 2019, 2020, and 2021

These stages had quite stable emissions over these years, but there were slight changes. These changes were because of differences in machine efficiency and energy use, along with small alterations in how we protect the crops but since they were negligible, we did not mention them.

Total GHG Emissions for Crop Protection

The steps we took to protect the crops from diseases and pests (Herbicide: Insecticide, Fungicide) had different impacts each year due to the weather. Table 14 summarizes the total GHG emissions for crop protection activities in 2019, 2020, and 2021:

Step	2019 (KgCO2e/ha)	2020 (KgCO2e/ha)	2021 (KgCO2e/ha)
Crop Protection	124.58	126.17	197.429

Table 3.2: Total GHG Emissions for Crop Protection in Potato Production for 2019, 2020, and 2021

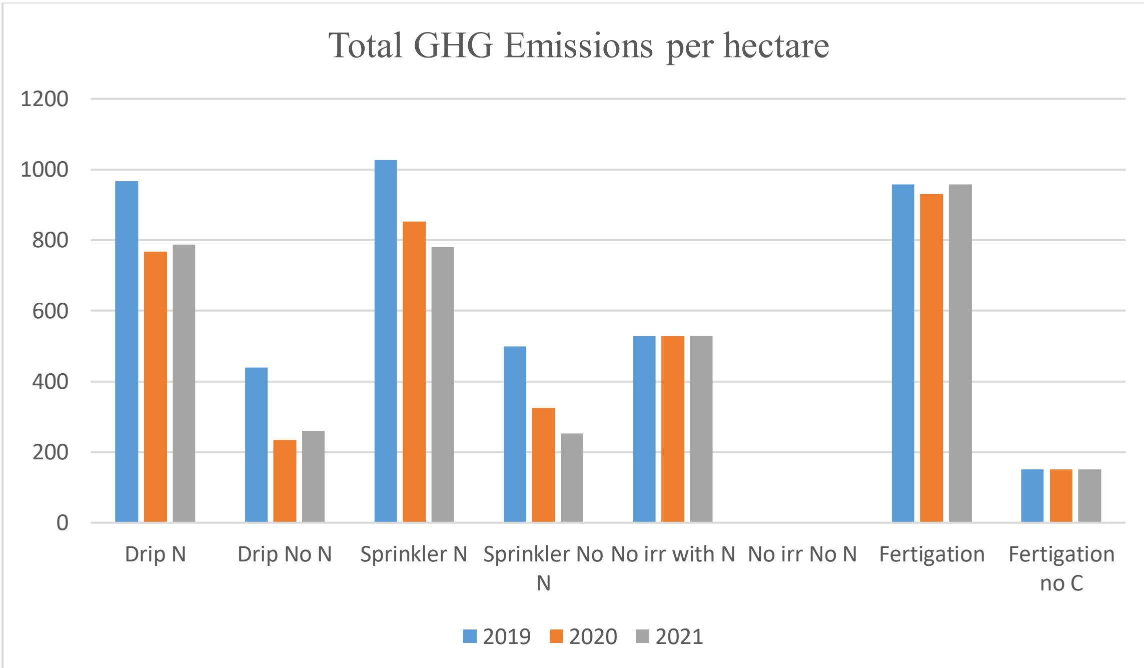
These results show that changes in GHG emissions for crop protection relate to weather conditions affecting disease and pest pressure. 2021 had more emissions due to less favorable weather conditions, like more pests.

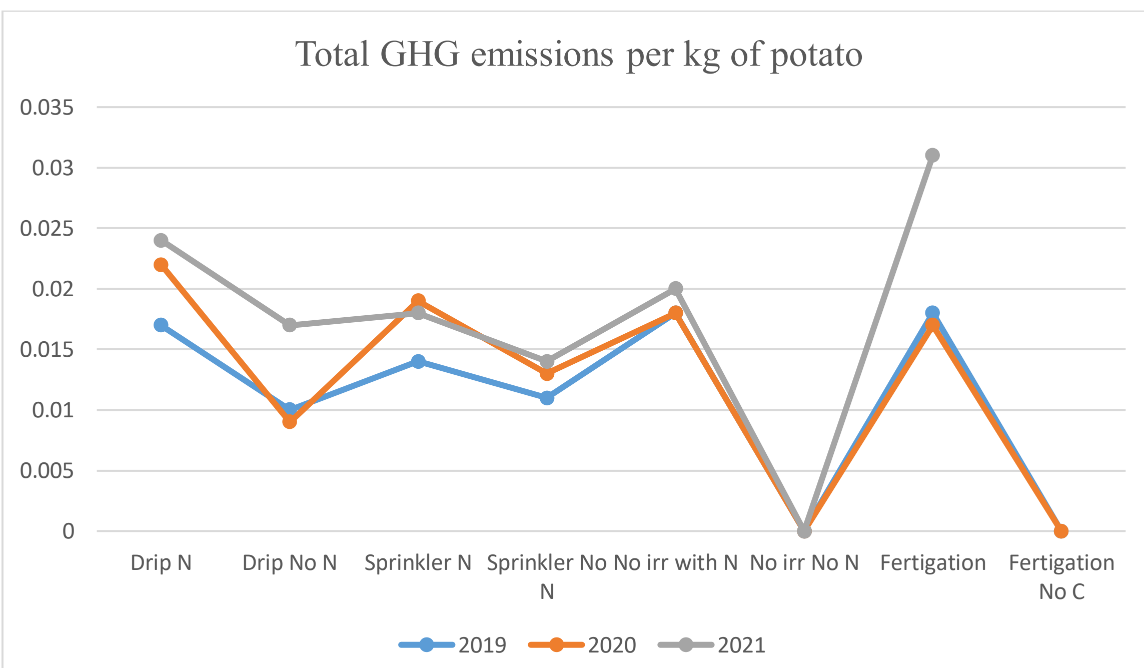
Total GHG Emissions for Irrigation Methods

The irrigation stage is very sensitive to the weather. This stage had different impacts on GHG emissions each year because of changing climate conditions. We used various irrigation strategies, including Drip Irrigation with N fertilization, Drip Irrigation without N fertilization, Sprinkler Irrigation with N fertilization, Sprinkler Irrigation without N fertilization, No irrigation and No fertilization, Fertigation, and Fertigation with no crop. Table 15 summarizes the total GHG emissions for these irrigation strategies in 2019, 2020, and 2021:

Strategy	2019 (KgCO2e/ha)	2020 (KgCO2e/ha)	2021 (KgCO2e/ha)
Drip irrigation with N Fertilization	967.514	767.696	787.424
Drip Irrigation Without Fertilization	439.514	233.696	259.424
Sprinkler irrigation with N Fertilization	1027.252	852.752	780.992
Sprinkler irrigation Without Fertilization	499.252	324.752	252.992
No Irrigation with N Fertilization	528	528	528
No irrigation and No fertilization	0	0	0
Fertigation	956.954	930.792	957.567
Fertigation without Crops	150.52	150.52	150.52

Table 3.3: Total GHG Emissions for Different Irrigation Strategies (per hectare) in Potato Production for 2019, 2020, and 2021

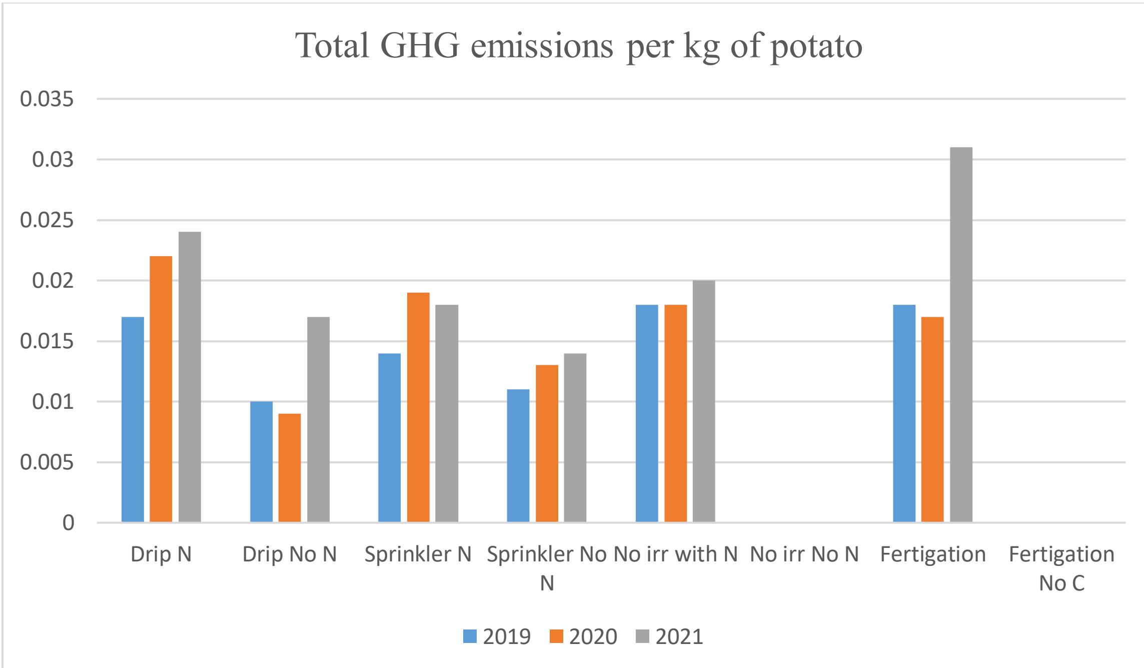

Total GHG Emissions per hectare
1200
1000
800
600
400
200
0
Drip N
Drip No N
Sprinkler N
Sprinkler No N
No irr with N
No irr No N
Fertigation
Fertigation no C
2019
2020
2021

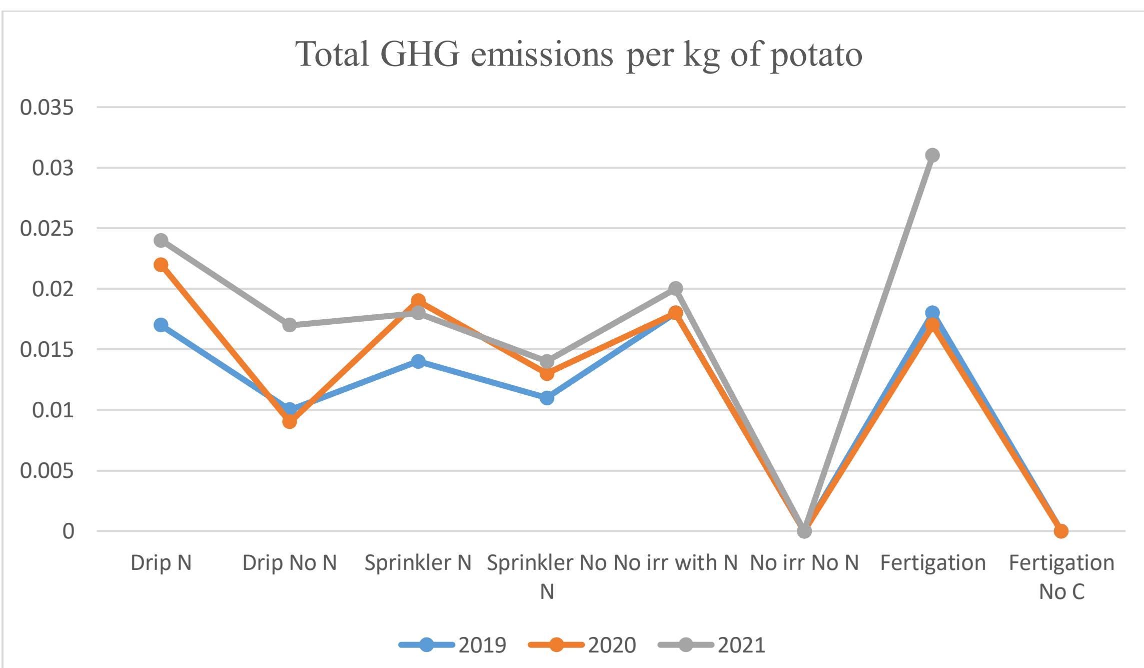

Total GHG emissions per kg of potato
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Drip N
Drip No N
Sprinkler N
Sprinkler No N
No irr with N
No irr No N
Fertigation
Fertigation No C
2019
2020
2021

In this table, we compare different irrigation strategies, based on their emissions of CO_2 per kg of potatoes that they produce each year to show a better comparison:

Strategy	2019 (KgCO2e/Kg of potato)	2020 (KgCO2e/Kg of potato)	2021 (KgCO2e/Kg of potato)
Drip irrigation with N Fertilization	0.017	0.022	0.024
Drip Irrigation Without Fertilization	0.010	0.009	0.017
Sprinkler irrigation with N Fertilization	0.014	0.019	0.018
Sprinkler irrigation Without Fertilization	0.011	0.013	0.014
No Irrigation with N Fertilization	0.018	0.018	0.020
No irrigation and No fertilization	0	0	0
Fertigation	0.018	0.017	0.031
Fertigation without Crops	0	0	0

Table 3.4: Total GHG Emissions for Different Irrigation Strategies (per Kg of potato) in Potato Production for 2019, 2020, and 2021

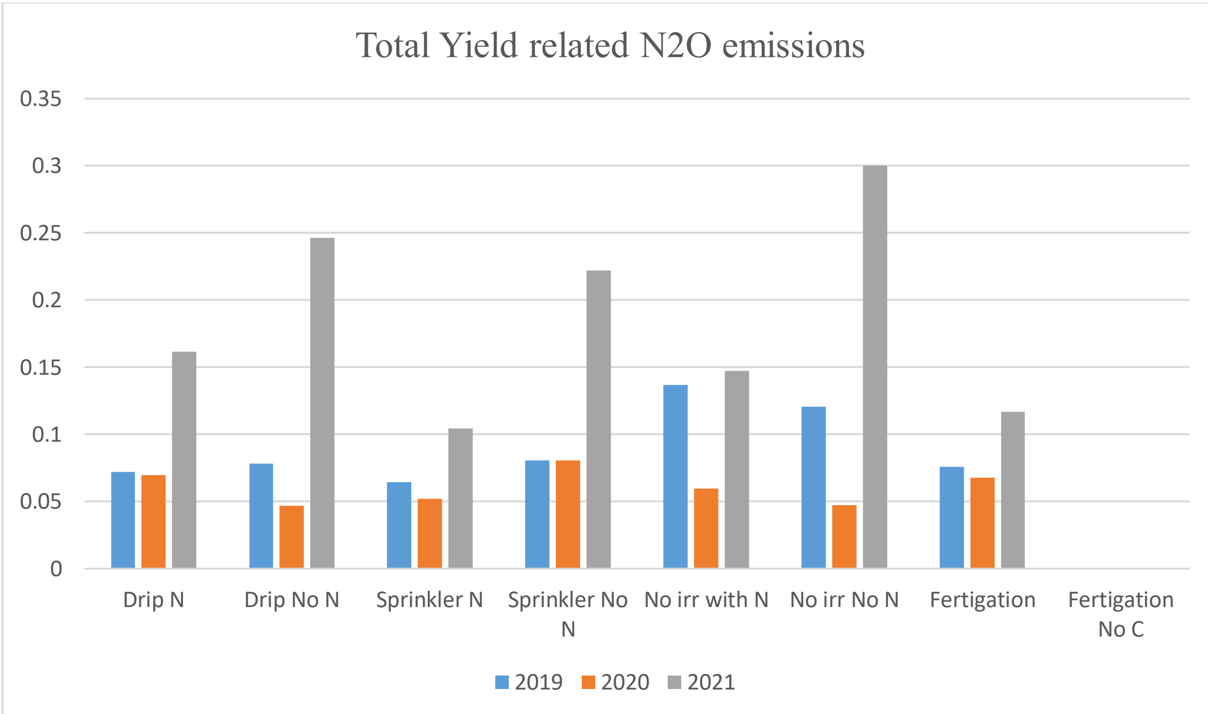

Total GHG emissions per kg of potato
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Drip N
Drip No N
Sprinkler N
Sprinkler No N
No irr with N
No irr No N
Fertigation
Fertigation No C
2019
2020
2021

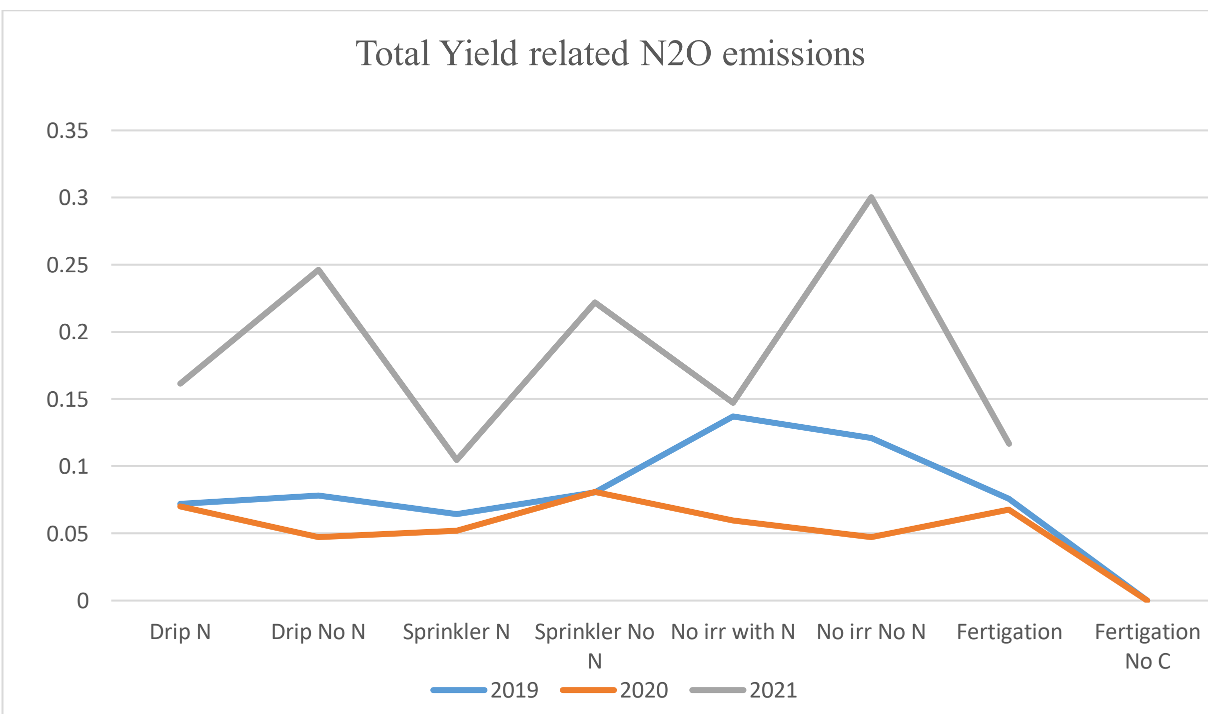

Total GHG emissions per kg of potato
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Drip N
Drip No N
Sprinkler N
Sprinkler No N
No irr with N
No irr No N
Fertigation
Fertigation No C
2019
2020
2021

If we only focus on the Nitrous Oxide emission (N2O) and their yield, the result will be different each year for each strategy. In the tables below, we have attached the yield related nitrous oxide for each strategy in the years of 2019, 2020 and 2021.

Strategy	Yield Related N2O 2019	Yield Related N2O 2020	Yield Related N2O 2021
Drip irrigation with N fertilization	0.072116031	0.069829	0.161673
Drip irrigation without N Fertilization	0.078302605	0.047075	0.246174
Sprinkler irrigation with N fertilization	0.0642417394	0.051998	0.104597
Sprinkler irrigation without N fertilization	0.08063525	0.080867	0.221978
No irrigation with N fertilization	0.137061896	0.059608	0.147297
No irrigation , No fertilization	0.120807905	0.047359	0.300265
Fertigation	0.075809035	0.067897	0.116638

Table 3.5: Total yield related N2O for Different Irrigation Strategies in Potato Production for 2019, 2020, 2021


Total Yield related N2O emissions
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Drip N
Drip No N
Sprinkler N
Sprinkler No N
No irr with N
No irr No N
Fertigation
Fertigation No C
2019
2020
2021


Total Yield related N2O emissions
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Drip N
Drip No N
Sprinkler N
Sprinkler No N
No irr with N
No irr No N
Fertigation
Fertigation No C
2019
2020
2021

Uncertainty Analysis

In this section, we will run an uncertainty test to figure out if the differences in the amount of greenhouse gas emitted by each strategy are significantly large or due to uncertainty, there are not that much distinguishable.

For this purpose, we run an uncertainty test once with 1% of uncertainty in out input data, and once with 10% uncertainty and see how it propagates to the output.

Strategy	Amount	Amount Uncertainty	EF	EF Uncertain	GHG	GHG Uncertainty
DN Machinery	163.2	1.632	2.68	0.0268	437.376	446.1673
DN set up	0.8	0.008	2.68	0.0268	2.144	2.187094
DN fertilization	150	1.5	3.52	0.0352	528	538.6128
DZ Machinery	163.2	1.632	2.68	0.0268	437.376	446.1673
DZ set up	0.8	0.008	2.68	0.0268	2.144	2.187094
SN Machinery	185	1.85	2.68	0.0268	495.8	505.7656
SN set up	1.4	0.014	2.68	0.0268	3.752	3.827415
SN fertilization	150	1.5	3.52	0.0352	528	538.6128
SZ Machinery	185	1.85	2.68	0.0268	495.8	505.7656
SZ Set up	1.4	0.014	2.68	0.0268	3.752	3.827415
No irr - N	150	1.5	3.52	0.0352	528	538.6128
FN Machinery	163.2	1.632	2.68	0.0268	437.376	446.1673
FN device	0.8	0.008	2.68	0.0268	2.144	2.187094
FN fertilization	147	1.47	3.52	0.0352	517.44	527.8405

Table 3.6: Data results with 1% Uncertainty

Strategy	Amount	Amount Uncertainty	EF	EF Uncertain	GHG	GHG Uncertainty
DN Machinery	163.2	16.32	2.68	0.268	437.376	529.225
DN set up	0.8	0.08	2.68	0.268	2.144	2.59424
DN fertilization	150	15	3.52	0.352	528	638.88
DZ Machinery	163.2	16.32	2.68	0.268	437.376	529.225
DZ set up	0.8	0.08	2.68	0.268	2.144	2.59424
SN Machinery	185	18.5	2.68	0.268	495.8	599.918
SN set up	1.4	0.14	2.68	0.268	3.752	4.53992
SN fertilization	150	15	3.52	0.352	528	638.88
SZ Machinery	185	18.5	2.68	0.268	495.8	599.918
SZ Set up	1.4	0.14	2.68	0.268	3.752	4.53992
No irr - N	150	15	3.52	0.352	528	638.88
FN Machinery	163.2	16.32	2.68	0.268	437.376	529.225
FN device	0.8	0.08	2.68	0.268	2.144	2.59424
FN fertilization	147	14.7	3.52	0.352	517.44	626.1024

Table 3.7: Data results with 10% Uncertainty

*GHG Uncertainty = (Amount + Amount with Uncertainty) * (EF + EF with Uncertainty)*

Judging by the result and the mean value of the original GHG emitted, we notice that having 1% uncertainty in our input data would not make much difference in the output, However, having 10% uncertainty affects the result significantly.

In both cases, we can still distinguish the differences between the strategies even with considering the uncertainties, so we conclude that the observed variations are not exclusively due to uncertainty but may reflect real differences between strategies.

4.Conclusion and Recommendations

In this section, we analyzed the results of the study and compared the greenhouse gas (GHG) emissions for various potato production strategies taken place in 2019, 2020, and 2021. We focused on understanding the environmental implications of these strategies and focused to identify the most environmentally sustainable approach while considering all the aspects.

4.1 Comparing GHG Emissions

1. **Drip Irrigation Strategies**: In general, using the drip irrigation, without nitrogen fertilization, consistently demonstrated lower GHG emissions compared to the other strategies such as fertigation. Drip irrigation appears to be an environmentally friendly choice, as it optimizes water usage and minimizes GHG emissions throughout the three years. Particularly, the "Drip Irrigation Without Fertilization" strategy showcased substantially lower GHG emissions, underscoring the environmental benefit of reduced fertilization.

2. **Sprinkler Irrigation Strategies**: While sprinkler irrigation is efficient for large fields and a variety of crops and has the most yield between all strategies, it resulted in higher GHG emissions, as observed in the "Sprinkler Irrigation with N Fertilization" strategy. The emissions from this strategy can be attributed to the use of machinery, higher water consumption, and fertilization practices. However, in 2021, it is noteworthy that the GHG emissions from sprinkler and drip irrigation were almost equal, indicating that climatic factors can significantly influence the results.

3. **No Irrigation Strategies**: The "No Irrigation with N Fertilization" strategy exhibited relatively low GHG emissions, but its practicality for potato cultivation could be limited due to potential yield reduction in regions with inadequate rainfall.
4. **Fertigation Strategies**: Fertigation, though efficient in nutrient management, displayed higher GHG emissions due to the increased use of machinery. The "Fertigation Without Crops" strategy had the lowest emissions, but its practicality is limited as it does not contribute to potato yield.

4.2 Balancing Yield and GHG Emissions

It is crucial to balance GHG emissions with the factors such as crop yield. When it comes to comparing the strategies based on their yields, there is a slight difference since sprinkler strategy has the highest yield among all. The "Drip Irrigation Without Fertilization" strategy stands out as a favorable choice, with relatively low emissions and reasonable crop productivity but for the year 2021, sprinkler irrigation without N fertilization is the most suitable option based on its productivity. This strategy along with drip irrigation effectively reduces the greenhouse gas emissions while providing a reasonable approach to potato cultivation. On the other hand, the "Fertigation" strategy, despite its potential to reduce emissions, may not be the most practical choice due to higher and more frequent machinery usage and comparable emissions.

In the context of **yield-related nitrous oxide (N2O) emissions**, it is generally better to have **low yield-related N2O emissions**. This means that for every unit of yield, you are emitting a smaller amount of N2O, which is a potent greenhouse gas. Lower yield-related N2O emissions is a sign that your agricultural practices are more environmentally efficient, since you are achieving higher yields while minimizing the impact on the environment.

High yield-related N2O emissions would imply that a significant amount of N2O is being released for each unit of yield, which is less sustainable from an environmental perspective. Reducing these emissions while maintaining or increasing yield is an important thing in sustainable agriculture.

So judging by the result of the yield related N2O for all the three years we notice these important facts which are:

1.Sprinkler Irrigation with N fertilization has the lowest yield related N2O in 2019

2.Drip Irrigation without N Fertilization has the lowest yield related N2O in 2020

3.Sprinkler irrigation with N fertilization has the lowest yield related N2O in 2021

This means, choosing Sprinkler and Drip irrigation, depending on the year is the best strategy concerning Nitrous oxide emissions and the crop yield. But if we take an average, overall based on N2O emissions, Sprinkler irrigation is the most suitable option.

In conclusion, while strategies like "Fertigation" show promise in reducing GHG emissions, the most sustainable and practical approach, considering yield and efficiency, appears to be "Drip Irrigation without N fertilization." This strategy minimizes environmental impact while ensuring a stable supply of potatoes for various agricultural practices. However, if we are using fertilization, sprinkler irrigation due to having much more yield is the optimal strategy.

This discussion provides valuable insights into the complex relationship between GHG emissions and potato production strategies, offering a foundation for environmentally conscious decision-making in the agricultural sector.

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